Title
Role of Zinc Fertilizers in Increasing Grain Zinc Concentration and Improving Grain Yield of Rice

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Introduction

Iron toxicity is one of the main nutritional disorders of lowland rice worldwide. Under flooding, ferrous ion (Fe^{2+}) in the soil solution increases sharply. Iron toxicity in rice also reflects deficiencies of other nutrients with a consequence in yield reduction (Dobermann and Fairhurst, 2000). Iron toxicity problems can be overcome by using Fe toxicity-tolerant genotypes and through soil, water and nutrient management practices. Published data in literature indicates that applications of P, K, and Zn together alleviate severity of Fe toxicity and increase growth and grain yield in rice (Audebert and Sahrawat, 2000 and Remírez et al., 2002). It was, however, not clear how each of these nutrients (P, K and Zn) contributed to the alleviation of Fe toxicity problem. Zinc and Fe compete during root uptake and shoot transport and therefore Zn deficiency induces Fe accumulation and toxicity in plants (Cakmak, 2000; Dobermann and Fairhurst, 2000).

Soil and/or foliar applications of Zn may also increase grain Zn concentration and thus contribute to grain nutritional quality for human beings. In rice, soil Zn application has been reported to increase grain yield whereas foliar-Zn application increased grain concentration of Zn (Wissuwa et al., 2008). Zinc deficiency is a well-documented nutritional and health problem in human populations in most of Asian countries where rice is the dominating staple food crop (Stein et al., 2007). Higher grain Zn concentration is also important for better seedling vigor and field establishment, particularly on Zn deficient soils (Cakmak, 2008). The objectives of this study were to evaluate the effectiveness of soil and foliar Zn applications in alleviating Fe toxicity and increasing grain Zn concentration in rice.

Materials and Methods

Zinc application on Fe toxicity

A field experiment was conducted on a Fe-toxic soil at the Rice and Commercial Crops Research Center **(**RCCRC) in Vientiane, Laos. A Fe-toxicity sensitive rice variety, TDK7, was used in the trails. Thirty-day-old seedlings were transplanted to 5 x 5 m plots, separated by bunds. The fertilizer treatments were controlled (nil Zn), KCl (Korn Kali) at a rate of 125 kg ha^{-1} (containing 40% K_2O, 6% MgO and 1.5% Zn) and $ZnSO_4.7H_2O$ at the rate of 50 kg ha^{-1} and applied at transplanting. Nitrogen application (100 kg urea ha^{-1}) was applied to all treatments at the panicle development. Plant growth was followed at tillering and flowering stages. At maturity, grain yield and yield components were determined.

A study of grain Zn in farmer's fields

In a second experiment conducted in four farmer's fields at Mae Tao village, Tak province in Thailand was used to study the effects of soil and foliar applied $ZnSO_4$ on grain Zn concentrations of rice. A popular Thai jasmine rice variety, KDML105 was grown in the four farmer's fields at Mae Tao village. Each field was treated by the basal N and P fertilizers. There were three Zn treatments: control (nil Zn), soil Zn application (50 kg ha^{-1} of $ZnSO_4$) and foliar Zn application (0.5% $ZnSO_4$). Soil Zn application was applied at tillering stage. Foliar Zn application was applied twice: before panicle development and one week after flowering.

Mineral nutrient analysis

For analysis of the targeted nutrients, the youngest emerged leaf blade (YEB) at tillering, and the flag leaves at the flowering stage were collected. Seeds collected at harvest were separated to brown rice and husk for their separate analysis. ICP-OES (Inductively Coupled Plasma-Optical Emission Spectroscopy) technique was used to analyze the mineral nutrients.

Result and discussion

At the tillering and flowering stages, the growth of rice variety TDK7 on a Fe toxic soil showed similar increases in response to the Zn-containing KCl (KornKali) and $ZnSO_4$ treatments (Table 1). Shoot dry weight was highest with $ZnSO_4$, followed by KornKali and the control treatment (no Zn and KCl applications). At maturity, straw and grain yield of the plants treated with KornKali and $ZnSO_4$ were almost similar and were much higher when compared to the control treatment. Grain yield was increased by nearly 35% with both Zn applications. The similar increasing effects on yield of Zn-containing KornKali and $ZnSO_4$ indicate that the increase in yield is caused by Zn and not K. Similarly, Sahrawat et al. (1996) showed that application of N did not affect rice yield on a Fe toxic soil, but a combination of N and Zn increased the yield 12-25%.

Table 1. Growth and yield of rice plants grown on a Fe toxic soil in Laos.

	Control	KornKali	$ZnSO_4$
Tillering			
Plant height (cm)	42.2 ± 1.2	45.2 ± 0.9	43.9 ± 1.4
Tiller number plant^{-1}	4.0 ± 0.4	4.3 ± 0.3	6.3 ± 0.5
Dry weight (g plant^{-1})	1.0 ± 0.1	1.3 ± 0.1	1.6 ± 0.2
Flowering			
Plant height (cm)	69.9 ± 2.7	76.9 ± 1.1	76.9 ± 3.1
Tiller number plant^{-1}	12.1 ± 0.5	12.1 ± 0.5	13.8 ± 0.5
Dry weight (g plant^{-1})	7.3 ± 0.8	9.2 ± 0.4	11.3 ± 1.3
Maturity			
Grain yield (ton ha^{-1})	1.7 ± 0.2	2.4 ± 0.2	2.3 ± 0.5
Grain weight (g plant^{-1})	8.4 ± 1.2	11.9 ± 1.3	11.7 ± 2.5
Straw weight (g plant^{-1})	6.9 ± 0.6	8.2 ± 0.5	8.5 ± 1.0

Iron toxicity seems to be associated with Zn deficiency after flooding as can be seen in low Zn concentrations of leaves at the tillering stage which are lower (range 17.7 -19.4 mg Zn kg^{-1}) than the critical level (< 20 mg Zn kg^{-1}, Dobermann and Fairhurst, 2000). Application of $ZnSO_4$ significantly increased the YEB and flag leaf Zn (Table 2). Iron concentrations of leaves at tillering ranged between 172 to 241 mg Fe kg^{-1} which was higher than the critical Fe toxicity levels (100-150 mg Fe kg^{-1}, Dobermann and Fairhurst, 2000). However, leaf Fe concentrations decreased at the flowering stage. Application of Zn fertilizers clearly reduced leaf concentrations of Fe (Table 2). This decrease was around 35 to 40 %. Iron and Zn concentrations of flag leaf showed negative correlation (R^2 = -0.637*; P<0.05). As reviewed by Cakmak (2000), a number of papers have been published in the past showing that Fe and Zn are antagonistic during root uptake and shoot transport, and consequently Zn deficient plants accumulate much higher concentration of Fe in leaves.

Table 2. Concentrations of Zn and Fe in leaves at the tillering and flowering stages in Laos.

	YEB at tillering		Flag leaf at flowering	
	Zn (mg kg^{-1})	Fe (mg kg^{-1})	Zn (mg kg^{-1})	Fe (mg kg^{-1})
Control	17.7 ± 0.3	241.5 ± 27.9	24.9 ± 0.7	140.0 ± 13.1
Kornkali	17.9 ± 0.7	172.2 ± 8.5	27.3 ± 0.4	117.4 ± 9.9
$ZnSO_4$	19.4 ± 0.6	221.2 ± 32.2	28.2 ± 0.9	102.1 ± 10.2

Application of $ZnSO_4$ has also increased Zn concentration of grain. However, there was no clear change in grain Fe concentration by Zn application. More Fe accumulated in husk, but not in brown rice (Table 3). This result is well in agreement with the recent results published by Zhang et al. (2008).

Table 3. Concentrations of Zn and Fe in rice seed in Laos.

	Unhusked rice	Brown rice	Husk
Zn (mg kg^{-1})			
Control	19.4 ± 0.5	21.9 ± 0.5	12.4 ± 0.5
Kornkali	20.7 ± 0.2	22.7 ± 0.8	14.7 ± 0.6
$ZnSO_4$	22.1 ± 0.8	24.8 ± 1.4	16.1 ± 1.1
Fe (mg kg^{-1})			
Control	33.4 ± 6.0	10.2 ± 0.5	152.4 ± 4.9
Kornkali	37.8 ± 2.0	9.2 ± 0.1	147.0 ± 4.8
$ZnSO_4$	38.9 ± 4.5	9.7 ± 1.0	146.2 ± 10.7

Application of Zn fertilizers to rice growing in farmer's fields showed that soil Zn application did not increase grain Zn concentration but foliar Zn application did (Fig. 1). In all farmers' fields foliar applied Zn significantly and consistently increased grain Zn concentration. Increases were from 20.5 to 45.5 mg Zn kg^{-1} in unhusked rice and from 20.8 to 27.7 mg Zn kg^{-1} in brown rice (Fig. 1). Very high Zn concentrations in unhusked rice might be related to contamination of husk caused by foliar Zn applications. Wissuwa et al. (2008) suggested that Zn uptake increased following soil Zn fertilizer applications but it accumulated in shoot tissue and not translocated to grain. It seems that foliar Zn application may be a practical way to increase Zn in rice grain.

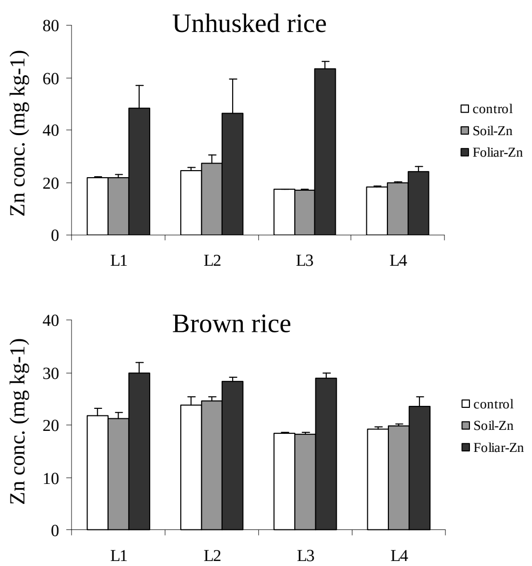

Figure 1. Concentration of Zn in rice seeds at 4 farmer's locations in Thailand.

The results of this study indicate that soil Zn application alleviates Fe toxicity problem, to some extent, by reducing accumulation of Fe in plant tissue. Foliar Zn application offers a simple and promising approach to increase Zn concentrations of rice grain. This effect is of great importance for human health in Asia where rice with very low grain Zn concentration is the dominating source of daily calorie intake.

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