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9. ABSTRACT

Next to nitrogen and phosphorus deficiencies, zinc deficiency is now the most important nutritional factor limiting the growth of wetland rice. This review reports the work done since 1967 at the International Rice Research Institute. Research has included diagnosis of Zinc deficiency, availability of zinc in flooded soils, and practical methods of correcting zinc deficiency. Zinc deficiency in soils is caused by high pH, continuous water-logging, low zinc content, high organic matter content, and high levels of fertilizer. Zinc deficiency is corrected by draining and drying the field, by dipping the seedlings in a 2% suspension of zinc oxide in water before transplanting, or by applying zinc sulfate to the soil. Organic matter should be avoided and fertilizers used prudently on zinc deficient soils. The report also discusses plant symptoms, soil tests, the effect of fertilizers, the use of zinc oxide and zinc sulfate, and varietal tolerance to zinc deficiency. It is suggested that further sutdy be done in the area of the availability of zinc in flooded soils in the hopes of finding long term corrective measures.

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ZINC DEFICIENCY IN RICE: A REVIEW OF RESEARCH AT THE INTERNATIONAL RICE RESEARCH INSTITUTE[1]

ABSTRACT

Next to nitrogen and phosphorus deficiencies, zinc deficiency is now the most important nutritional factor limiting the growth of wetland rice.

Analyses of the plant and the soil, together with plant symptoms, are useful tools in the diagnosis of a zinc deficiency problem. The characteristic symptoms are blanching at the base of the emerging leaves and discoloration of older leaves which varies from rusty brown to yellow. The critical level of zinc in the plant is 15 to 20 ppm. The level of available soil zinc, determined by a modified method, below which deficiency might occur is 1.0 ppm.

Zinc deficiency in soils is brought about by high pH, continuous waterlogging, low zinc content, high organic matter content, and high levels of fertilizer. A high pH decreases the solubility of zinc. Furthermore, in calcareous soils that contain free calcium carbonate and magnesium carbonate, zinc may be strongly adsorbed. Flooding decreases the concentration of water-soluble zinc to values as low as 0.03 ppm. In acid soils the decrease in concentration is due partly to the increase in pH following soil reduction. In calcareous and sodic soils, the decrease may be due to precipitation of zinc sulfide. The incorporation of organic matter and the use of high levels of fertilizers aggravate zinc deficiency in zinc-deficient soils.

Solubility criteria suggest the presence in flooded soils of the insoluble zinc compounds: zinc phosphate, zinc ammonium phosphate, zinc silicate, and zinc sulfide.

Zinc deficiency is corrected by draining and drying the field, by dipping the seedlings in a 2% suspension of zinc oxide in water before transplanting or by applying zinc sulfate to the soil. In direct-seeded rice the method of coating germinated seeds with zinc oxide is promising but needs to be tested. Varieties with tolerance to low available zinc may be used in combination with inexpensive amendment to increase rice yields in zinc-deficient areas.

Organic matter should be avoided and fertilizers used prudently on soils that are zinc deficient.

A better understanding of the mechanisms governing the availability of zinc in flooded soils will be useful in the search for corrective measures with long-term effects.

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[1]by Ruby Uy Castro, assistant scientist, International Rice Research Institute, Los Baños, Philippines. This paper was originally presented at the Joint FAO/IAEA Research Coordination Meeting on Isotope Aided Studies on Micronutrients in Rice Production with Special Reference to Zinc Deficiency, Manila, Philippines, May 1976.

ZINC DEFICIENCY IN RICE: A REVIEW OF RESEARCH AT THE INTERNATIONAL RICE RESEARCH INSTITUTE

No minor element problem in rice has received as much attention during the last few years as zinc deficiency. Next to nitrogen and phosphorus deficiencies it is now considered the most important nutritional factor limiting the growth of wetland rice. Zinc deficiency was first recognized by Nene (1966) as a field problem of rice on an alkali soil in India. It is reported in rice soils in Pakistan, Japan, the United States, Colombia, Chad, Nigeria, and the Philippines (Tanaka and Yoshida, 1970; Yoshida, et al., 1973; Yoshida and Tanaka, 1969). There are, for example, nearly 500,000 ha of zinc-deficient soils in the Philippines.

Because zinc deficiency is so widespread in wetland rice, the International Rice Research Institute (IRRI) has done considerable research on diagnosis of zinc deficiency, on availability of zinc in flooded soils and on practical methods of correcting zinc deficiency. This review reports the work done at IRRI since 1967.

DIAGNOSIS OF ZINC DEFICIENCY

Plant symptoms and plant and soil analyses are valuable diagnostic tools in identifying zinc deficiency.

Plant symptoms

Zinc deficiency is characterized by blanching at the base of the emerging leaves and by rusty brown discoloration in the older leaves. These symptoms appear 2 to 4 weeks after transplanting. Growth retardation usually accompanies the foliar symptoms. In mild cases, where plants recover, maturity is delayed and yield is low. In severe cases, plants may die (Forno et al., 1975b; Katyal, 1972; Yoshida et al., 1973; Yoshida and Tanaka, 1969).

Orticio and Ponnamperuma (1977) reported varietal differences in foliar symptoms. Although blanching was commonly observed, the later foliar symptoms varied from brown discoloration in the older leaves of sensitive varieties to slight yellowing in those of tolerant varieties.

Plant analysis

The content of zinc in the plant, when combined with visual observation and soil analysis, can prove useful in diagnosing zinc deficiency of rice. Plants can be analyzed for their zinc content by the method of Yoshida et al. (1972). Yoshida and Tanaka (1969) claim that the critical level of zinc

in the plant at 2 weeks after transplanting is 10 ppm while Katyal and Ponnamperuma (1974) set this value at 15 ppm at 4 weeks after transplanting. Other studies in this area indicate that 20 ppm in the plant is the level of zinc below which deficiency symptoms appear (Yoshida et al., 1973; Orticio and Ponnamperuma, 1977). In the straw at maturity, the critical level is 25 ppm (Katyal, 1972).

Soil tests

By the method of Trierweiler and Lindsay using ethylenediamine tetraacetic acid (EDTA) and ammonium carbonate as extractant (Trierweiler and Lindsay, 1969), the critical level of available zinc is 1.5 ppm (Katyal and Ponnamperuma, 1974).

Because of some practical disadvantages of the above method, Katyal and Ponnamperuma modified a hydrochloric acid extraction procedure as follows:

> Shake 10 g of soil with 20 ml of 0.05 N HCl for 5 minutes. Filter. Measure the zinc concentration in the filtrate by atomic absorption spectrophotometry and calculate zinc concentration in the soil.

The critical level of available soil zinc as determined by this method is 1.0 ppm (IRRI, 1973; Katyal and Ponnamperuma, 1974).

FACTORS THAT INFLUENCE ZINC AVAILABILITY

Zinc deficiency in wetland rice is most apt to occur on soils with a pH higher than 7.0, and, regardless of pH, on continuously wet or poorly drained soils, on soils with a low total zinc content such as sandy soils, and on soils with a high content of organic matter (IRRI, 1971, 1972; Yoshida et al., 1973; Yoshida and Tanaka, 1969). The occurrence of this nutritional problem has also been associated with the use of high levels of fertilizers (IRRI, 1972; Katyal, 1972; Katyal and Ponnamperuma, 1974).

Soil pH

In laboratory and greenhouse studies, the content of zinc in the plant was shown to be governed by soil pH. The higher the soil pH, the lower the plant's zinc content (Fig. 1). That is because the solubility of zinc in water decreases 100 times with every unit increase in pH (IRRI, 1971).

The interaction between zinc on the one hand, and magnesium and manganese on the other, provides another explanation for the occurrence of zinc deficiency on soils of high pH. Chemical analysis reveals that zinc-deficient plants have higher contents of magnesium and manganese than do healthy plants. Applying zinc not only corrected zinc deficiency and increased the zinc content of the plants but also depressed the contents of magnesium and manganese (Table 1). These observations suggest an antagonism between zinc and magnesium and manganese.

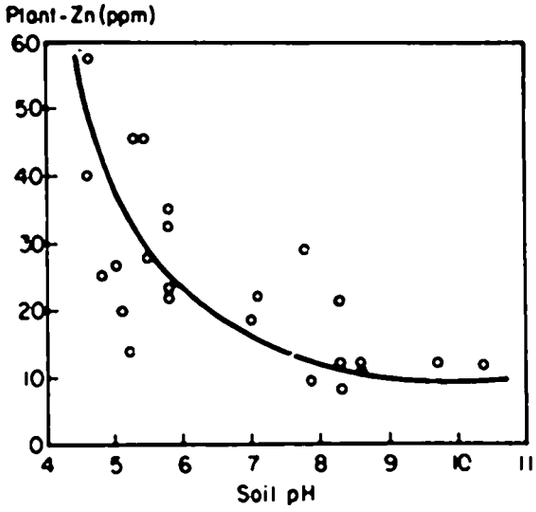

Fig. 1. Relationship between soil pH and plant zinc content.

Table 1. Effect of six zinc treatments on zinc deficiency, yield, and mineral composition of IR22 on Butuan clay.[a]

Treatment	Zn deficiency rating[b]	Yield (t/ha)		Composition			
		Grain	Straw	Zn (ppm)	Mn (ppm)	Mg (%)	K (%)
No Zn	4	4.5	5.9	11	481	0.47	2.38
ZnO (2% dip)	0	4.8	6.6	15	392	0.37	2.34
ZnO (10 ppm Zn)	0	4.9	6.1	18	384	0.39	2.56
$ZnCl_2$ (10 ppm Zn)	0	4.8	5.6	16	388	0.38	2.39
$ZnSO_4$ (10 ppm Zn)	0	5.0	6.3	18	383	0.37	2.16
1 spent dry cell/sq m	0	4.9	5.5	19	407	0.39	2.07
2 spent dry cells/sq m	0	5.2	7.4	21	413	0.36	2.07

[a]Source: Katyal and Ponnamperuma, 1974.

[b]0 = symptoms absent; 4 = symptoms most pronounced.

An equilibration study showed that the carbonates likely to be present in slightly alkaline soils, namely calcium carbonate, magnesium carbonate, and manganese carbonate, have high affinity for water-soluble zinc (Table 2). The zinc adsorbed in these carbonates are extractable in EDTA-ammonium carbonate reagent -- indicating that the adsorbed zinc is available to rice. That probably accounts for the transitory nature of zinc deficiency in some calcareous soils (IRRI, 1972; Katyal, 1972; Katyal and Ponnamperuma, 1974).

Table 2. Adsorption of zinc from an aqueous solution by three carbonates.[a]

Adsorbent	Zn adsorbed (%)
$MgCO_3$	100.0
$MnCO_3$	95.3
$CaCO_3$	67.4

[a]Source: Katyal and Ponnamperuma, 1974.

Water regime

Zinc deficiency occurs, regardless of pH, on continuously wet soils (IRRI, 1971, 1972; Yoshida et al., 1973).

On certain blocks of IRRI's experimental farm, which are cropped throughout the year and are continuously wet, zinc deficiency was encountered in the seventh crop year (IRRI, 1971; Yoshida et al., 1973). Air drying the soil from those blocks, followed by flooding, produced a dramatic increase in yield and increased the zinc content of straw (Table 3) (IRRI, 1971).

Table 3. Influence of some treatments on the growth and yield of IR22 on Maahas clay from a continuously cropped (continuously wet) area of the Institute farm.[a]

Treatment	Tillers (no.)	Straw (g/pot)	Grain (g/pot)	Zn in straw (ppm)
Mud	34	79	57	20
Mud + $ZnCl_2$	45	97	52	23
Mud + cellulose	19	47	42	16
Dried and kept at field capacity	29	86	34	67
Dried and flooded at planting	71	140	80	47

[a]Source: IRRI, 1971.

Rice plants were examined on 20 soils (pH values from 4.6 to 8.1) where a downward trend in yield after the fourth crop was observed. These soils had been kept continuously submerged for 3 years in pots and planted to rice in 8 successive seasons, with incorporation of rice stubble and

complete fertilizer each season. Typical symptoms of zinc deficiency were observed in 10 of the 20 soils. The addition of zinc chloride produced a dramatic response. Only two soils had dry-soil pH values above 6.9 at the start of the experiment. Zinc deficiency was visible on one soil that had an initial pH as low as 4.8 (IRRI, 1971).

My long-term study of the influence of water management on the growth and yield of rice provides further evidence that zinc-deficiency can result from continuous submergence of soils. In that study, three soils (Luisiana clay: pH 4.6, O.M. 2.9%; Maahas clay: pH 6.6, O.M. 2.0%; Pila clay loam: pH 7.6, O.M. 1.5%) were subjected to four water treatments using 220-liter drums. Two crops of rice were grown each year. Weeds and stubble, and nitrogen, phosphorus, and potassium fertilizers were incorporated before each crop was planted. Zinc deficiency was observed on the continuously flooded Pila clay loam during the third year, on the continuously flooded Maahas clay during the fourth year, and on the continuously flooded Luisiana clay during the fifth year. The zinc content in the active center leaf of zinc-deficient plants 8 weeks after transplanting was 7 to 9 ppm (Table 4). Even temporary soil drying (midseason soil drying) markedly increased the zinc content of the plant and prevented zinc deficiency (IRRI, 1972).

The occurrence of zinc deficiency on the perennially wet soils of the Banaue rice terraces (pH 4.9) is also dramatic evidence that zinc deficiency is possible even on acid soils if the soils are continuously waterlogged.

The changes in concentration of water-soluble zinc when a soil is flooded provide an explanation for the occurrence of zinc deficiency on poorly drained or waterlogged soils. On flooding, the concentration of water-soluble zinc decreases and reaches a value as low as 0.03 ppm (Table 5). In acid soils the decrease in concentration may be due partly to the increase in pH following soil reduction. The decrease in concentration of zinc in

Table 4. Influence of 4 water regimes on the zinc content of the active center leaf 8 weeks after transplanting and on grain yield of IR24 on three soils in drums outdoors in the 11th cropping season.[a]

Water regime[b]	Luisiana clay		Maahas clay		Pila clay loam	
	Zn in leaf (ppm)	Yield (g/drum)	Zn in leaf (ppm)	Yield (g/drum)	Zn in leaf (ppm)	Yield (g/drum)
Flood fallow						
no MSD	7.6	258	6.8	245	9.0	261
with MSD	16.2	241	16.2	253	14.1	199
Dry fallow						
no MSD	15.2	292	15.4	258	12.0	242
with MSD	17.2	226	18.1	264	20.1	187

[a]Source: IRRI, 1972.

[b]MSD = midseason soil drying.

Table 5. Kinetics of water-soluble zinc in 4 soils submerged for 5 weeks.[a]

Soil	pH	Water-soluble zinc (ppm)				
		1	2	3	4	5
Castañas clay	3.5	1.38	0.17	0.13	0.15	0.08
Luisiana clay	4.8	0.30	0.09	0.05	0.08	0.03
Maahas clay	6.6	0.18	0.08	0.04	0.06	0.03
Keelung silt loam	7.7	0.14	0.08	0.06	0.04	0.03

[a] Source: Ponnamperuma, 1975.

calcareous and sodic soils in spite of the decrease in pH may be due to the precipitation of zinc sulfide, which may occur after the peak of hydrogen sulfide (Ponnamperuma, 1975).

Organic matter content

Excess organic matter appears to inactivate soil zinc and retard its uptake by the rice plant (IRRI 1971, 1972; Yoshida et al., 1973; Yoshida and Tanaka, 1969). It is not surprising to note that zinc deficiency has been identified as one of the growth-limiting factors in peat soils or histosols (Lantin, 1976).

In a greenhouse experiment, cellulose aggravated zinc deficiency symptoms and drastically reduced the yield of rice in two zinc-deficient soils and induced mild symptoms in Pulilan sandy loam but not on some other soils (Table 6).

The effect of cellulose is probably related to the increase in partial pressure of carbon dioxide in the zinc-deficient soils e.g. Luna clay in Figure 2 (IRRI, 1971). Forno, et al. (1975b) observed an increase in concentration of both bicarbonate and organic acids in the soil solution of a zinc-deficient soil from Pakistan, which was treated with cellulose. In a culture solution study with isotope-labeled zinc they found that sodium carbonate caused a marked decrease in the Zn^{65} content of the shoots (Fig. 3) while acetic acid decreased the Zn^{65} content of both roots and shoots (Fig. 4) (Forno et al. 1975b).

Fertilizer level

In Pakistan, the use of the modern variety IR8 and high levels of fertilizer is believed to have caused the appearance of zinc deficiency. Extension workers in Agusan del Norte province, Philippines, reported that the incidence of zinc deficiency increased as the use of improved varieties and the accompanying good cultural practices became widespread.

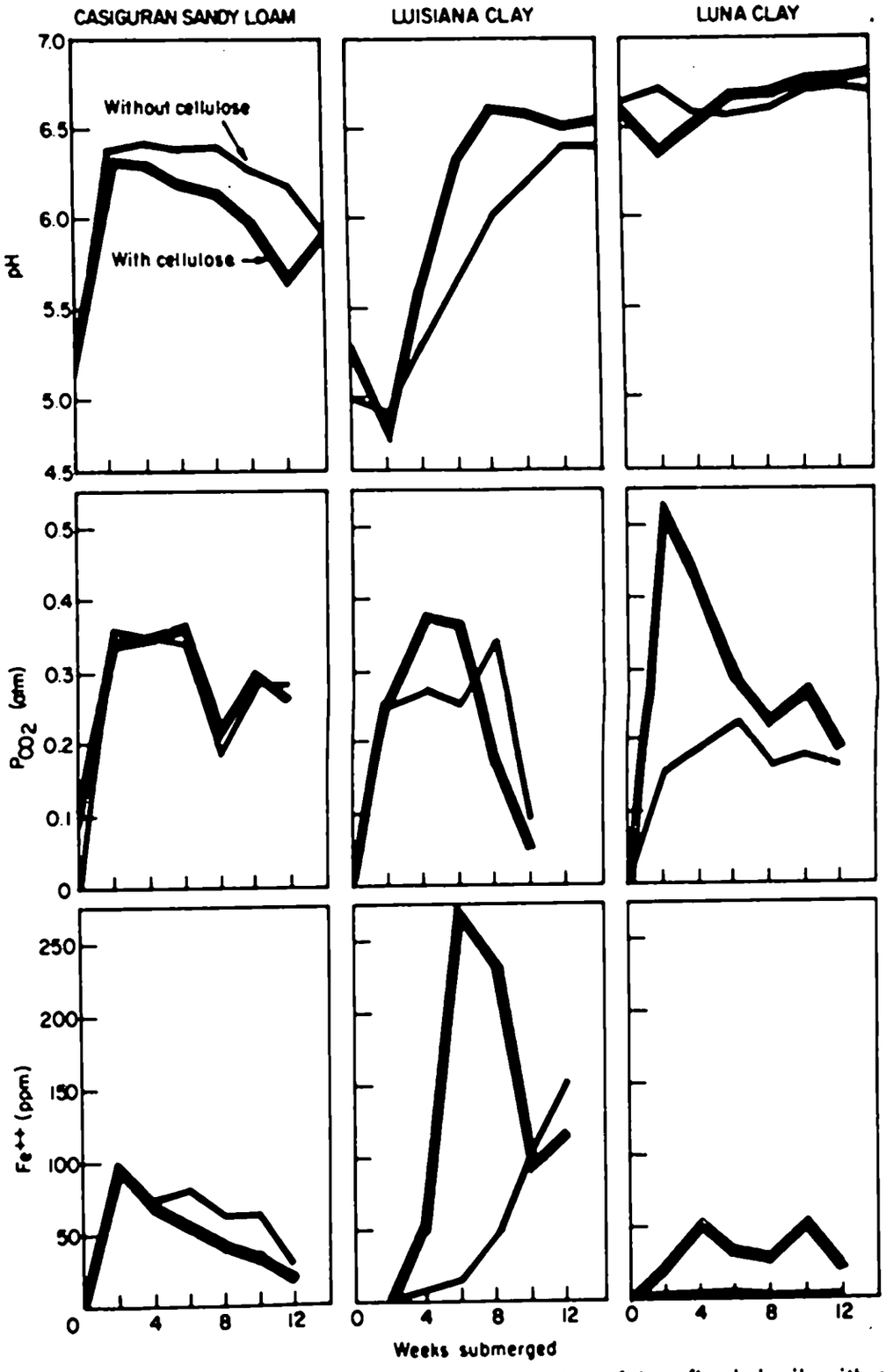

Fig. 2. Kinetics of the pH, P_{CO_2} and water-soluble iron of three flooded soils with and without 0.5 percent added cellulose.

Table 6. Organic matter and zinc deficiency.[a]

Soil	Added cellulose (%)	Straw (g/pot)	Grain (g/pot)	Zn in straw (ppm)	Zn deficiency rating[b]
Luisiana clay (pH 4.7; O.M. 3.2%)	0	50	35	45	0
	0.5	38	34	34	0
Casiguran sandy loam (pH 4.8; O.M. 4.4%)	0	76	73	33	0
	0.5	80	85	32	0
Maahas clay (pH 6.6; O.M. 2.0%)	0	63	49	47	0
	0.5	55	60	28	0
Pulilan fine sandy loam (pH 6.5; O.M. 2.3%)	0	53	44	19	0
	0.5	36	42	18	1
Butuan clay (Ampayon) (pH 6.8; O.M. 5.4%)	0	53	59	17	4
	0.5	53	38	13	4
Butuan clay (Luna) (pH 6.5; O.M. 5.3%)	0	50	56	22	4
	0.5	9	5	17	5

[a] Source: IRRI, 1971.
[b] Scale: 0 = symptoms absent; 5 = symptoms most pronounced.

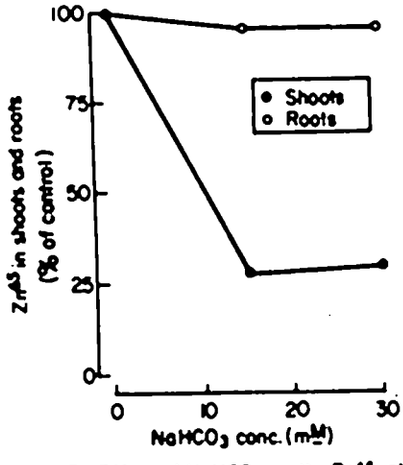

Fig. 3. Effect of $NaHCO_3$ on the Zn^{65} absorbed by the rice variety IR8 at pH 7.3.

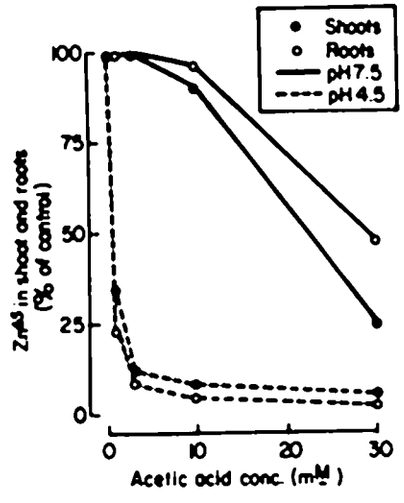

Fig. 4. Effect of acetic acid on the Zn^{65} absorbed by the rice variety IR8 at pH 4.5 and 7.5.

The effect of nitrogen, phosphorus, and potassium (NPK) fertilizer on the yield of IR20 and C4-63G was investigated in several locations in Agusan del Norte, which included established rice farms as well as an abandoned one. The NPK fertilizer depressed the rice yields both in the presence and in the absence of zinc treatment. The effect was more pronounced in the plants without zinc treatment than in the zinc-treated plants. The yield was lowest in the zinc-deficiency-susceptible variety C4-63G fertilized with NPK but without the zinc treatment (Table 7) (IRRI, 1973; Katyal, 1972; Katyal and Ponnamperuma, 1974).

In a pot experiment in the greenhouse, high levels of phosphorus fertilizer applied to the soil depressed zinc uptake (Table 8) (Katyal, 1972).

Table 7. Effect of Zinc and NPK fertilizers on the yield of IR20 and C4-63G, Ampayon, Butuan, Philippines, 1972 wet season.[a]

Treatment		Yield (t/ha)	
Zinc	NPK	IR20	C4-63G
No	No	2.4	2.9
No	Yes	1.9	0.9
Yes	No	5.4	4.0
Yes	Yes	5.0	3.6

[a] Source: Katyal and Ponnamperuma, 1974.

Table 8. Phosphorus fertilizer and depression of zinc uptake.[a]

Soil	P treatment (ppm)	Soluble zinc (mean for 10 wk) (ppm)	Plant Zinc (ppm)
Maahas clay	0	.05	25
	100	.05	15
	500	.04	17
Magalang clay loam	0	.10	22
	100	.06	18
	500	.05	18
Butuan clay (Ampayon)	0	.08	16
	100	.05	15
	500	.04	13

[a] Source: Katyal, 1972.

ZINC EQUILIBRIA

The concentration of water-soluble zinc in flooded soils influences the uptake of zinc by the rice plant. Therefore an understanding of the factors that affect its solubility may be useful in attempts to correct zinc deficiency.

If the bulk of the zinc in the solution of a flooded soil is in the form of Zn^{2+}, the following equilibria may influence its concentration.

$$3\ Zn^{2+} + 2\ PO_4^{3-} \rightleftharpoons Zn_3(PO_4)_2 \qquad pK_s = 32.03$$

$$Zn^{2+} + NH_4^+ + PO_4^{3-} \rightleftharpoons ZnNH_4PO_4 \qquad pK_s = 16.0$$

$$SiO_2 + Zn^{2+} + 2\ OH^- \rightleftharpoons ZnSiO_3 + H_2O \qquad pK_s = 21.03$$

$$Zn^{2+} + S^{2-} \rightleftharpoons ZnS \qquad pK_s = 22.80$$

$$Zn^{2+} + L \rightleftharpoons ZnL$$

where pK_s denotes the negative logarithm of the activity product constant and L stands for an organic ligand (IRRI, 1971).

If zinc phosphate is present in flooded soils, the value of the expression $[3\ pZn^{2+} + 2\ pPO_4^{3-}]$ should be constant and tend to 32.0, in spite of variations in the activities of the Zn^{2+} and PO_4^{3-} ions. Table 9 shows that zinc phosphate was present transitorily in the soils with peak pH values exceeding 6.6. In acid soils, the value of the expression deviated markedly from 32.0. Apparently zinc phosphate is not precipitated in acid solutions because the concentration of the PO_4^{3-} ion is too low.

Soil solutions contain Zn^{2+}, NH_4^+, and PO_4^{3-} ions. If the solubility product of zinc ammonium phosphate is exceeded, it should precipitate. If zinc ammonium phosphate is present in flooded soils, the value of the expression $[pZn^{2+} + pNH_4^+ + pPO_4^{3-}]$ should be constant and tend to 16.0, in spite of variations in the activities of the participating ions. Table 9 shows that zinc ammonium phosphate may be present transitorily in the soils whose solution pH values exceed 6.5. The equilibria with NH_4^+ and PO_4^{3-} ions explain why zinc deficiency is aggravated by fertilizer application.

Finely divided quartz is present in all soils. Besides, silica brought in by irrigation water may crystallize slowly, giving fine quartz crystals. Zinc ions in the soil solution may react with quartz and attain the equilibrium:

$$SiO_2 + Zn^{2+} + 2OH^- \rightleftharpoons ZnSiO_3 + H_2O \qquad pK_s = 21.03$$

then $2\ pH - pZn^{2+} = 6.97$

Zinc silicate was probably present in all soils at some stage, except in the two acid sulfate soils (Table 9) (IRRI, 1971). In Maahas clay irrigated with water high in silica, the solubility of zinc appears to be determined by zinc silicate.

A criterion for the presence of zinc sulfide is the constancy of the function $pZn^{2+} + pS^{2-}$ and its approximation to 22.8 (the pK_s value of zinc sulfide) in spite of variations in the activities of Zn^{2+} and S^{2-} ions. The values of pK_s obtained for zinc sulfide suggest that it was present in all the soils after the peak of hydrogen sulfide concentration (Table 10) (IRRI, 1973).

Table 9. Influence of soil properties on the residence time of zinc phosphate, zinc ammonium phosphate, and zinc silicate in flooded soils.

Soil	Peak value in soil solution			Residence time after submergence[a] (wk)		
	pH	P (ppm)	NH_4^+ (mmol/l)	$(Zn_3(PO_4)_2$	$ZnNH_4PO_4$	$ZnSiO_3$
Acid sulfate clay (Philippines)	6.20	2.85	7.33	-	-	0
Acid sulfate clay (Vietnam)	4.63	0.18	4.90	-	-	-
Luisiana clay	6.51	0.07	1.28	-	-	8 to 10
Kalayaan clay	6.64	2.36	4.70	3 to 8	2	10
Antipolo clay	6.82	0.07	1.02	-	-	1
Butuan clay	6.71	1.10	1.60	0	-	1 to 10
Maahas clay	6.61	0.39	1.11	-	3 to 5	0 to 10
Pila clay loam	6.71	6.63	1.61	1 to 3	-	2 to 10
Luna clay	6.86	0.27	2.69	-	0 to 2	4 to 10
San Pablo clay loam	6.76	2.10	1.60	0 to 4	2 to 6	1 to 10
Aggaie loam	6.75	0.39	6.11	0 to 4	1 to 4	8 to 10
Magalang loam	6.89	0.43	0.82	4	0 to 1	10

[a] Criteria used for the presence of the solids: Zn_3PO_4: $pK_s = 32.0 \pm 0.3$; $ZnNH_4PO_4$: $pK_s = 16 \pm 0.3$; $ZnSiO_3$: $\log Zn + 2\ pH = 7.0 \pm 0.3$.

Table 10. Mean values of the ionic product of ZnS (pK_{ZnS}) in the solution of 10 submerged soils from the H_2S peak to 10 weeks after submergence.

Soil	pH	O.M. (%)	Fe (%)	Mn (%)	H_2S peak (wk)	pK_{ZnS}
Calbon clay	7.0	1.8	1.0	.15	1	21.8
Maahas clay	6.6	2.0	2.2	.16	1	21.5
Luisiana clay	4.6	2.8	2.1	.06	3	21.6
Pila clay loam	7.6	1.5	0.3	.06	4	21.1
Keelung silt loam	7.9	6.9	2.3	.07	3	20.7
Silt loam (Korea)	4.8	3.2	0.5	.06	3	21.4
Acid sulfate clay (C)	3.4	6.6	2.6	.01	1	21.3
Acid sulfate clay (C) (limed)	5.5	6.6	2.6	.01	1	21.4
Acid sulfate clay (B)	3.6	6.3	0.1	0	3	21.2
Acid sulfate clay (B) (limed)	5.5	6.3	0.1	0	3	21.9

CORRECTION OF ZINC DEFICIENCY

Several methods of application and forms of zinc have been tested and found effective (Table 1) (IRRI, 1971, 1972; Katyal 1972; Katyal and Ponnamperuma, 1974; Yoshida et al., 1973; Yoshida and Tanaka, 1969) but the following methods are most widely accepted.

Draining and drying the field

If deficiency in zinc is caused mainly by prolonged submergence, draining and drying the field can prevent its occurrence (IRRI, 1971, 1972).

Use of zinc oxide

Correction of zinc deficiency by dipping the seedlings in a 2% suspension of zinc oxide in water is the most widely accepted practice in the Philippines because it is both cheap and convenient. Zinc oxide costs about US$2/kg. In the zinc-deficient soils of Agusan del Norte province in the Philippines, 4 t/ha can be obtained without the use of fertilizers for an additional US$2/ha spent each season on zinc oxide (IRRI, 1973; Katyal, 1972; Katyal and Ponnamperuma, 1974). I found in a preliminary greenhouse study that zinc deficiency can also be corrected by coating the germinated seeds with zinc oxide at the rate of 1% by weight of the dry seeds (Table 11). If applicable in the field, this method will cut the cost of materials by 50%. It is also a simple and inexpensive method of preventing zinc deficiency in direct-seeded rice (Castro, 1976).

Table 11. Influence of four methods of zinc application on the yield of E425 on a zinc-deficient soil.[a]

Treatment and planting method	Yield[b] (g/pot)	
	Straw	Grain
No zinc, transplanted	62 d	54 b
ZnO dip, transplanted	74 bc	83 a
ZnO as seed coating, transplanted	71 c	75 a
$ZnSO_4$ to seedbed, transplanted	79 ab	81 a
ZnO as seed coating, direct-seeded	83 a	67 ab

[a] Source: Castro, 1976. [b] Means followed by a common letter are not significantly different at the 5% level.

Use of zinc sulfate

Soil application of zinc sulfate at the rate of 40 to 50 kg/ha is an accepted practice in India, Pakistan, and the United States. If the zinc is not tied

up, one application should suffice for several seasons (Table 12) (IRRI, 1972, 1973; Katyal and Ponnamperuma, 1974). In a preliminary greenhouse study I found that zinc deficiency can be averted in transplanted rice by applying zinc sulfate to the seedbed at the rate of 5 g/sq m (Table 11). If applicable in the field, this method will cut down the amount of zinc sulfate required from 50 kg to 2.5 kg/ha (Castro, 1976).

Table 12. Residual available zinc after three successive crops[a] as affected by form and method of zinc application on Butuan clay.

Treatment	Residual available Zn (ppm)[b] after		
	1st crop	2nd crop	3rd crop
Control	1.0	1.0	1.4
ZnO (2% dip)	1.6	2.0	2.2
ZnO (10 ppm Zn)	8.5	7.6	6.4
$ZnCl_2$ (10 ppm Zn)	8.6	7.4	5.2
$ZnSO_4$ (10 ppm Zn)	7.4	6.4	6.2
1 spent dry cell/sq m	22.4	47.5	19.7
2 spent dry cells/sq m	37.2	100.0	36.1

[a] Source: Katyal and Ponnamperuma, 1974. [b] By the EDTA-$(NH_4)_2CO_3$ method of Trierweiler and Lindsay (1969).

VARIETAL TOLERANCE TO ZINC DEFICIENCY

Although zinc deficiency can be easily corrected by applying zinc to the soil or to the plant, inherent tolerance to zinc deficiency in rice will be a valuable trait, especially for the small farmers. Varietal differences in tolerance to zinc deficiency in rice soils have been recognized (Forno et al., 1975a; IRRI, 1973, 1974, 1975; Katyal, 1972). If the genetic sources of tolerance can be identified and the germ plasm used in developing improved varieties with tolerance to zinc deficiency, improved varieties suited to zinc-deficient soils can be bred. Use of such varieties in combination with inexpensive amendments should increase rice yield in these areas.

The varieties listed below were found more tolerant of zinc deficiency than others in IRRI greenhouse tests.

Chua daw	IR2681-118-1-6-2	IR4409-28-3
IR20	IR2681-163-5-2-2	IR4409-49-2
IR28	IR2688-39-4-23	IR4409-65-3
IR30	IR2793-30-3-2	IR4409-80-2
IR34	IR2793-80-2-2	IR4422-51-1
IR1514A-E666	IR2798-86-6-3	IR4427-18-3-2

IR1632-93-2-2
IR2061-628-1-6-4-3
IR2153-26-3-5-6
IR2307-112-3
IR2681-118-1-4
IR2798-115-2-3
IR2798-143-3-2
IR3478-4-3-1
IR3536-31-1
IR4409-9-2
IR4432-63-5
IR4432-103-6
IR5853-76
UCP 188

IMPLICATIONS FOR THE RICE CROP AND FUTURE RESEARCH

The results to date of zinc deficiency research in rice imply that soil management, judicious use of chemicals, and selection of varieties tolerant of zinc deficiency can overcome the zinc deficiency problem.

- The yield of rice on calcareous and alkali soils, on poorly drained soils, on soils with a low zinc content, and on soils high in organic matter can be increased by correcting zinc deficiency.

- The water regime of a soil profoundly affects the zinc nutrition of the rice plant. Prolonged submergence reduces zinc availability; soil drying increases it dramatically.

- Organic matter should be avoided and fertilizers should be used prudently on soils that are zinc deficient.

The availability of zinc in flooded soils is governed by a variety of factors. However, the mechanisms involved are not clearly understood. Future research toward a better understanding of these mechanisms will be useful in the search for corrective measures with long term effects. This will be specially useful in the management of histosols and peat soils where a single application of zinc is usually not adequate to correct the deficiency.

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