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Effects of Soil pH and Eh on Growth and Nutrient Uptake by Rice in a Flooded Oxisol of Sitiung Area of Sumatra, Indonesia

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Abstract

Rice grown on a flooded Sumatra Oxisol soils frequently exhibits poor growth and low yield. A study has been made of the effects of pH and redox conditions on growth and nutrient uptake by rice, and the relationship between nutrient release in the flooded soil and nutrient uptake by the rice plant. At pH 4.5 rice plants produced low plant height, low root dry weight, low shoot dry weight, slow relative growth rate, and short root length under both reducing and oxidizing conditions. Under both soil conditions these growth parameters tended to increase from pH 4.5 to 6.5 and then decrease at pH 7.5. The rice plants under reducing conditions showed a significantly higher score of orange leaf discoloration at pH 4.5 and 5.5 than at pH 6.5, and 7.5. At pH 4.5 the rice plants absorbed significantly high concentrations of Zn, Fe, Mn, Ca, Mg, and Al under reducing conditions. However, only the Fe content observed at pH 4.5 and 5.5 under reducing conditions was above the critical level of toxicity of 300 mg kg^{-1}, indicating that the rice plants may have suffered from Fe toxicity at these two pH levels.

Under oxidizing conditions, rice plants showed a significantly higher score of yellow leaf discoloration at pH 4.5 and 5.5 than at 6.5 and 7.5. Under oxidizing conditions, the Al content in the rice plants at all pH levels was above the critical level of Al toxicity of 300 mg kg^{-1}, indicating that the rice plants may have suffered from Al toxicity.

The contents of Cu, Zn, Mn, Ca, Mg, P and K in the rice plants at all pH and redox conditions were in the normal range except for Si which was found to be below the threshold deficiency value of 5%. A significant, high positive correlation was measured for the water-soluble Fe in soil and uptake by the rice plants under reducing conditions ($r = +0.962^{**}$). A significant, positive correlation was also measured for the water-soluble Al in the soil and uptake by the rice plants under oxidizing conditions ($r = +0.658^{*}$). A significant correlation was not measured for water-soluble Si in soil and uptake by the rice plants under both soil redox conditions.

In the Sumatra Oxisol soil Fe toxicity in rice appeared to occur under reduced soil conditions at pH values of 4.5 and 5.5, Al toxicity under oxidized conditions even at pH as high as 7.5, and Si deficiency under both soil redox conditions regardless of pH.

Introduction

Millions of hectares of soil in Indonesia are very strongly acid with soil pH frequently below 4.5. Sixty percent of these acid soils are classified as Oxisols (Typic Haplorthox) and have been utilized under shifting cultivation on semi-permanent subsistence agriculture (Driessen and Soepraptorahardjo, 1974).

Recently, Oxisols in the Sitiung area of Sumatra, Indonesia are rapidly being cleared for transmigrant farmers from the over-populated Indonesian islands of Java and Madura. In 1982 the Indonesian government introduced an irrigation project in these areas (Sitiung I and II) to support that transmigration program (Team LPT, 1979).

When the soil is flooded, the newly opened paddy field shows new problems for plant growth. Rice grown on these flooded soils frequently exhibits poor growth and leaf discolorations and gives low rice yields. This problem has not yet been identified and is probably due to physiological disorders caused by nutrient toxicity or deficiency as a result of flooding.

Flooding causes several biological and chemical changes of soil properties that are important to plant nutrition and growth (Redman and Patrick, 1965; Ponnamperuma, 1972; Turner and Patrick, 1968). Under reduced or flooded conditions, Fe^{3+} and Mn^{4+} ions are reduced to Fe^{2+} and Mn^{2+} (Gotoh and Patrick, 1972, 1974; Meek and Grass, 1975). Strongly acid soils can build up toxic concentrations of ferrous iron and thereby cause iron toxicity problems (Reddy and Patrick, 1983).

Under reduced conditions, pH is an important factor that controlling ferric and manganese concentrations (Gotoh and Patrick, 1972, 1974), but critical iron concentrations in the soil solution varies with the pH (Tanaka et al., 1966b). Lucas and Kneseck (1972)

noted that the availability of manganese is related to pH and increases markedly when the pH falls below 5.5.

Decreased soil Eh and associated changes in soil pH have important implications to nutrient transformations in soil solutions (Mahapatra and Patrick, 1969; Reddy and Patrick 1983). Recently, Patrick and Jugsujinda (1986) found that problems in wetland rice grown on a Sumatra Oxisol may be caused by Fe and Al toxicities Fe and Al and perhaps, deficiencies of Ca, P, K, and Mg in rice plants. Iron and Al contents in the plant were not related to those in the soils because the rice leaf samples were taken from plants in the field, whereas, the soil data were from controlled laboratory studies. Therefore in the present study, we conducted the experiments where the rice plants were grown under the controlled pH and Eh of soil suspension in laboratory conditions.

The objective of the present study is to identify adverse factors affecting growth of rice in Sitiung Transmigration areas of Sumatra, Indonesia, and ultimately contribute to management practices that will improve the productivity of these soils. Experimental procedures were designed to study rice growth and the potential for toxicities and deficiencies of various elements under flooded lowland and upland conditions of these soils.

Materials and Methods

The soil was collected from Sitiung Transmigration areas of Sumatra, Indonesia. These soils were classified as clayey, kaolinitic, isohyperthermic family of Typic Haplorthox. Some soil chemical and physical characteristics of the representative top soil layer (25 cm) are given in Table 1. Rice variety of IR-43, known as susceptible to Fe-toxicity, was used as plant indicator for both experiments.

Two experiments were conducted at the Laboratory for Wetland Soils and Sediments. Each was arranged in a completely randomized design with two replications. Treatments in experiment 1 consisted of two levels of redox conditions (reduced and oxidized) controlled

under four pH levels: 4.5, 5.5, 6.5, and 7.5. Treatments in experiment 2 consisted of four levels of soil Eh (-150, 0, +150 and +300 mv) controlled at a pH of 6.5.

1. Soil Incubation.

Glass dessicator bases (Pyrex 412230) were used to contain the soil suspension for the chemical-availability and plant-uptake studies (Fig. 1). Two hundred and fifty grams of air-dry soil containing 4g kg^{-1} finely ground rice straw (to provide an energy source for microbial activity) and 1750 ml deionized water were placed in and stirred with a magnetic stirrer. These vessels were used to contain the soil suspension for the chemical availability and plant uptake studies. In the first experiment, the soil was incubated under oxidizing and reducing conditions for three weeks by the method of Jugsujinda and Patrick (1977). In the second experiment, the soil was incubated under conditions of controlled redox potential and pH by the method of Reddy, Jugsujinda, and Patrick (1976).

2. Transplanting of Rice Seedlings.

At the end of the three-week incubation period a plexiglass plate with ten 30-day old rice seedlings, prepared as described by Jugsujinda and Patrick (1977), was transferred onto each vessel and sealed, as shown in figure 2. Nitrogen as urea, phosphorus as NaH_2PO_4 and potassium as KCl at rates of 100, 100 and 50 ppm, respectively, were added at transplanting. Deionized water was added to the soil suspensions every 1 or 2 days to replace the water lost by transpiration. The rice seedlings were allowed to grow under controlled pH and Eh for three weeks.

3. Controlling of Soil pH and Eh

After transplanting of rice seedlings, the pH of the soil suspension in both experiments was controlled at the desired pH values by adding either 1 N HCl or 1 N NaOH manually twice daily through the serum cap according to the treatments. In the first experiment, soil Eh was recorded after controling of the soil pH.In the second experiment, soil Eh was automatically controlled at the desired Eh values by the system as described by Reddy, Jugsujinda, and Patrick (1976).

4. Plant Growth and Assimilation Rate.

Plant growth parameters measured were: maximum root length, plant height, shoot and root dry weight, relative growth rate and assimilation rate. The assimilation rate of rice plants was measured with an ADC LCA-2 Portable Infrared Gas Analyzer at 0, 10, 15 and 20 days after transplanting.

5. Soil Analysis.

Samples of soil solutions were taken at harvesting (3 weeks after growing the rice plants). The samples were transferred to preweighed centrifuge bottles and immediately purged with N_2 gas for the samples to maintain reducing conditions, then centrifuged at 7000 rpm for 20 minutes. Fractionation for water-soluble, sodium acetate extractable, and citrate dithionite extractable or reducible forms of nutrients was performed successively by the following methods.

5.1. Water-soluble Fraction. After centrifuging, supernatants were filtered through 0.45 μm membrane filters under an inert atmosphere (Patrick and Henderson, 1980; Delaune et al., 1985). Subsamples of supernatants were acidified to pH 2 by adding 12 N HCl and stored for analysis. The remaining aliquot was used to determine electrical conductivity.

5.2. Sodium Acetate Extractable Fraction. One hundred ml of O_2-free 1 N sodium acetate (pH 4.0) was then added to the residual moist soil from water-soluble fractions while maintaining reducing conditions. This mixture was shaken for 1 hour on mechanical shaker and centrifuged at 7000 rpm for 20 minutes. The supernatants were filtered through 0.45 μm membrane filters as described previously and the aliquots stored for analysis.

5.3. Sodium-Citrate Dithionite Extractable Fraction. Sodium-citrate dithionite solutions (20%) were prepared just prior to each extraction as sodium-citrate dithionite loses reducing power with time. After sodium acetate extraction, a mixture of 10 g sodium citrate and 0.5 g sodium dithionite in 120 ml distilled deionized water was added to residual

soils in the centrifuge bottles. The bottles were then shaken for 18 hours and centrifuged and filtered as before. The mixture was centrifuged for 20 minutes at 7000 rpm. The supernatants were filtered through a 0.45 μm membrane filter and the aliquot stored for analysis.

Ion concentrations of all fractions were determined by Inductively Coupled Argon Plasma (ICAP) atomic emission spectrometer. Ion activities were calculated by the method of Lindsay (1979). Electrical conductivity (EC) of the water-soluble extract of the soil was measured with a Fisher Model 152 Conductivity Meter.

6. Plant Chemical Analysis.

At the end of the three-week experiment period, the shoots and roots of rice plants were harvested and dried separately at 70°C for 48 hours. The rice shoots and roots were weighed and chopped into fine pieces. One half gram subsamples were digested with 5 ml of high-purity nitric acid. Extracts were analyzed on the ICAP to determine the nutrient content of the shoots.

Results and Discussion

1. Soil Redox Potential (Eh).

The effect of soil pH on avereage values of redox potential of reduced and oxidized soil conditions (Experiment 1) are shown in Figure 3. When pH levels were controlled, the redox potential under reduced and oxidized soil conditions was shifted to more or less constant values at each pH level. Redox potential was constant at about +155, +55, -200, and -290 mv at pH 4.5, 5.5, 6.5, and 7.5, respectively under reducing conditions. In contrast, under oxidizing conditions, the redox potentials were constant at about +667, +616, +587, and +519 mv at pH 4.4, 5.5, 6.5, and 7.5, respectively.A redox potential value of +300 mv at pH 5.0 is ordinarily considered to be a boundary between oxidized and reduced conditions (Gotoh and Patrick, 1974). The results showed the difference in the potential values between pH 4.5 and 5.5 (one pH unit) was about 100 mv under

reducing conditions and 50 mv under oxidizing conditions. The theoretical value used to correct Eh data to pH 7.0 is 60 mv.

2. Plant Growth and Assimilation Rate.

2.1. Plant Growth. The effect of soil pH on rice growth under reducing and oxidizing conditions are shown in Table 2. All plants showed chlorotic symptoms, both those grown at pH 4.5 and 5.5 had leaf discoloration scores twice as high as those grown at pH 7.5. Under reducing conditions rice leaf blades showed oranging symptoms, roots had a heavy orange-brown coating on the tip and were blackened at the base. Average root length, root dry weight and shoot dry weight at pH 4.5 were significantly lower than at higher pH levels. Under oxidizing conditions, leaf blades showed yellowing symptoms and roots were reddish-brown at all pH levels. At pH 7.5 root length was significantly lower than at lower pH levels.

Shoot dry weight was high at pH 6.5 under both reducing and oxidizing conditions, 3.0 and 3.5 g/pot, significantly higher than at other pH levels. Plant height and relative growth rate of rice under oxidizing conditions were not significantly affected by soil pH. Under reducing conditions, however, these two growth parameters were affected by soil pH. At pH 4.5 plant height and relative growth rate were lowest, 31.8 cm and 0.3 g/pot/week. As soil pH increased, plant height and relative growth rate were significantly increased. The maximum plant height (35.4 cm) and relative growth rate (0.5 g/pot/week) were obtained at pH 6.5 (Table 2).

In experiment 2, where rice plants were grown under controlled soil Eh and pH, the chlorotic symptoms scores were less than one. Shoot-root ratio, shoot dry weight and relative growth rate were not affected by soil redox conditions, with the average values of 3.65, 5.32 g/pot and 0.41 g/pot/week, respectively (Table 3). Soil redox conditions did have a slight effect on root length, plant height and root dry weight. In this experiment, plant height, root dry weight and shoot dry weight were higher than in the first experiment.

The leaf discoloration and poor growth of rice plants that were observed in the first experiment may have been due to toxicity caused by a high intake of Fe in plant tissue under reducing conditions at pH 4.5 and 5.5 and by Al toxicity under oxidizing conditions at all pH levels.

A similar result for Fe toxicity was reported by Jugsujinda and Patrick (1977). Within a few weeks after transplanting, the impaired plants were retarded in growth, developed reduced numbers of tillers, produced sterile spikelets, roots are poorly developed and become black rather than red-brown. Except for an excessive content of Fe, all iron-toxic plants revealed low or deficient amounts of K and P, often of Zn, and sometimes of Ca and Mg. Iron toxicity is ascribed to a multiple nutritional soil stress (insufficient supply of K, P, Ca and Mg), rather than to high levels of active Fe under acid conditions (Ottow et al., 1983).

2.2. Assimilation Rate. The effects of soil pH on assimilations rate of rice grown under reducing and oxidizing conditions are shown in Table 4. Under reducing conditions the assimilation rates were not significantly different at all pH levels after 10 days. Maximum assimilation rates under all treatments were measured at 15 days. At 15 and 20 days, assimilations rates were significantly lower at pH 4.5 than at higher pH levels. Under oxidizing conditions, assimilations rates at 15 and 20 days were not significantly different. In experiment 2, the trend of assimilation rates was generally the same as in the first experiment (Table 5). Maximum assimilation rates were also found at 15 days after transplanting, but there was no significant difference among Eh levels.

Decreases in the assimilation rates at 20 days after transplanting were caused by development of chlorosis of leaves, which limited the regeneration of new leaves in the first experiment and affected by mutual shading of leaves in the second experiment. When a population experiences mutual shading for a long period, protein in the lower leaves decomposes due to a deficiency in energy source, and amide and amino acid content increases leading eventually to the production of ammonia. Under such conditions the

leaves lose their photosynthesizing capacity and die (Tanaka et al., 1966a). The life of leaves is therefore shorter if the population is mutually shaded, and even less or limited in root development, nutrient uptake and translocation through the shoot or leaves. Long and Hallgren (1985) reported that the highest assimilation rates by C_4 plants in the field are 32-66 umol $CO_2/m^2/sec$ under full sunlight and favorable conditions. Assimilation rates by rice in our laboratory conditions are 15-24 umol $CO_2/m^2/sec$, however.

3. Releases of Nutrient Elements in Soil, Their Contents in Rice Plants, and Their Relationships in Soil and Plant.

3.1. Forms of Release in Soil. Release of water-soluble (ws), sodium acetate extractable (ext), and citrate-dithionite extractable or reducible (red) forms of some selected nutrient elements in soil at different pH levels (Experiment 1), and at different Eh levels (Experiment 2) are shown in Tables 6-15.

3.1.1. *Copper, Zinc, and Molybdenum*. In the first experiment, the concentrations of ws-forms of Cu and Zn were affected by soil pH under both soil conditions. Concentrations of ws, ext and red-forms of Cu, Zn and Mo were higher under oxidizing than under reducing conditions at the same soil pH levels (Table 6).

Water-soluble Cu significantly increased with increasing soil pH, to a maximum of 4.7 mg/kg under reducing and 2.32 mg/kg under oxidizing conditions. But, concentrations of ext-Cu were significantly decreased with an increase of soil pH under reducing conditions.

Under reducing conditions, ws-Zn significantly decreased from 4.10 to 1.5 mg/kg with increasing soil pH. Under oxidizing conditions, however, ws-Zn increased to a high of 8.3 mg/kg at pH 7.5 with an increase of soil pH. Extractable Zn and red-Zn forms were not significantly affected by soil pH under either soil condition.

Under reducing conditions, soil pH had little effect on ws-Mo and ext-Mo, and no effect on red-Mo forms. Under oxidizing conditions these forms were slightly affected by soil pH, and the ws-Mo tended to increase with increasing soil pH.

Concentrations of extractable forms of Cu, Zn, and Mo under both soil conditions were higher than the water-soluble forms when comparison was made at the same pH levels.

In a recent study, Patrick and Jugsujinda (1986) also found that, after 60 days of flooding, concentrations of extractable forms of Cu, Zn, and Mo were higher than their water-soluble forms .

The high concentrations of all forms of Cu, Zn, and Mo in the soils under oxidizing conditions indicates that submergence resulted in decreases in the concentrations of Cu, Zn, and Mo in the soil solution. These results are in agreement with the findings of other workers (Reddy and Patrick, 1977, and Gambrell et al., 1980). Reddy and Patrick (1977) reported that chelated Cu, Zn, and Mo solution decreased with decreasing Eh from +500 mv (oxidized) to -200 mv (reduced). The instability of Zn and Cu chelates was attributed to chemical fixation (possibly with sulfide) of added Zn and Cu, and not due to chemical or microbial breakdown of metal chelate complex (Reddy and Patrick, 1983). Some of these metallic cations may be less mobile under reducing conditions because of possible precipitation with sulfide (Engler and Patrick, 1975). Under reducing conditions, Cu, Zn, and Mo were complexed by organic matter and also got adsorbed on exchange and organic sites (Sims and Patrick, 1978). This may explain why, in our study, high concentrations of all forms of Cu, Zn, and Mo were obtained under oxidixing conditions as compared to reducing conditions.

In experiment 2, except Mo, the concentrations of water-soluble, extractable and reducible forms of Cu, and Zn were not affected by soil Eh (Table 7). It may be explained that the range of soil Eh was narrow and it was not low enough to induce chemical fixation of Cu, Zn, and Mo.

In general, copper and Zn are subject to various chemical reactions which may increase or decrease solubility. Patrick, Mikkelsen and Wells (1985) reported that as a consequence of flooding, Cu and Zn availability is quite pH dependent, and their concentrations decrease

in solubility about 100 times per increase of one pH unit. Reddy and Patrick (1983) also reported that micro nutrients such as Zn, Cu, Mo, Co, and B were not readily involved in soil redox conditions, but their solubility and availability were affected by poor aeration.

3.1.2. *Iron and Manganese*. The concentrations of all forms of Fe and Mn were higher under reducing than under oxidizing conditions but pH had only a slight effect on reducible Fe and Mn forms under oxidizing conditions (Table 8). Under reducing conditions the concentration of all forms were significantly affected by soil pH under reducing conditions.

Under reducing conditions, concentrations of ws-Fe and ws-Mn forms were significantly decreased with increasing soil pH (1,231 to 220 mg/kg for Fe, and 111.5 to 4.45 mg/kg for Mn). Under the same conditions, concentrations of ext-Fe and ext-Mn were significantly increased with increasing of the soil pH. In this experiment, we also found that ext-Fe and ext-Mn forms were markedly higher than their water-soluble forms, especially under reducing conditions.

The decrease in Eh associated with flooding was responsible for the increase in ext-Fe and ext-Mn at the expense of their water-soluble forms (Gotoh and Patrick, 1974). Results reported by Patrick and Jugsujinda (1986) suggest that ws-Fe and ws-Mn were largely adsorbed on the exchange and organic sites in the soil, and only a small amount of Fe remained in water-soluble forms. Water-soluble Fe and Mn, which bond weakly to exchange and organic sites, are reported to be more available to rice plants (Sims and Patrick, 1978). Iron-toxicity, however, occurs when excessive soluble Fe accumulates in highly reduced soils (Patrick et al., 1985). Our results also indicate that potentially high levels of ext-Fe and red-Fe extracted from the soil might cause Fe-toxicity to rice plants, especially under reducing conditions and low pH.

In experiment 2, the concentrations of ws-Fe were significantly decreased when soil Eh was raised from 0 mv to +150 and +300 mv (51 and 18 mg/kg). Soil Eh had slight effect on ext-Fe, but had no effect on red-Fe (Table 9).

Soil Eh had a significant effect on ws-Mn and a slight effect on ext-Mn forms as both forms of Mn decreased throughout the Eh range of the experiment. Increasing soil Eh caused a significant increase in red-Mn. In our study, where soil pH was controlled at 6.5, Eh appeared to have marked effect on Fe and Mn. Gotoh and Patrick (1972, 1974), likewise, reported that both water-soluble and exchangeable Fe and Mn increased with a decrease in Eh and pH. At pH 5, the effect of Eh was minimal on Mn^{2+} solubility, while between pH 6 and 8 the conversions of insoluble Mn^{4+} to Mn^{+2} was dependent on both Eh and pH. Reducible Fe became unstable when Eh was between +300 and +100 mv at pH 6 and 7, and -100 mv at pH 8.

3.1.3. *Aluminum*. The concentration of all forms of Al were significantly affected by soil pH under oxidizing conditions, and higher than under reducing conditions (Table 10). Under oxidizing conditions the concentration of ws-Al was significantly decreased when soil pH was increased above 5.5. Under reducing conditions, the concentration of ws-Al was very low and was not affected by soil pH.

The high concentration of Al in the soil, especially under oxidizing conditions indicated that this soil has potential to cause Al-toxicity, regardless of soil pH. Hargrove (1986), who measured Al concentrations after oxidation, reported that Al-organic matter solubilized in the range of pH 5 to 7 and may be subject to plant uptake. This same mechanism may explain Al uptake and plant growth depression at near neutral soil pH values in this study.

Under controlled Eh in experiment 2, the concentration of Al in both ws and ext forms were significantly affected by soil Eh conditions, but soil Eh have no effect on red-Al forms. At Eh-150 mv, ws-Al was significantly lower than ws-Al at higher Eh levels (Table 11).

3.1.4. *Calcium and Magnesium*. In experiment 1 soil pH had little or no effect on the concentration of Ca and Mg forms under reducing and oxidizing conditions (Table 12). In general, concentrations of ws-Ca and ws-Mg under reducing conditions were higher

than under oxidizing conditions. The same results were observed in experiment 2 (Table 13).

Our results are similar to those of Patrick and Jugsujinda (1986) who found that extractable Ca and Mg were slightly higher than water-soluble Ca and Mg after flooding. Apparently, flooding had a little effect on distribution and concentration of Ca and Mg. This was expected because Ca and Mg do not undergo oxidation-reduction reaction like Fe and Mn.

Although Ca and Mg are not directly involved in soil redox conditions, their concentrations in the water-soluble form have been found to increase following flooding (Ponnamperuma, 1972, van Breeman, 1976).

3.1.5. *Phosphorus, Potassium and Silicon*. Concentrations of all forms of P were higher under oxidizing than reducing conditions. Extractable P was about 10-fold higher under oxidizing than under reducing conditions. The decrease in P with flooding (reduced) may be explained by adsorption-desorption processes which controlled its concentration in soil solution. Soil pH had a little effect on ws-P and ext-P and no effect at all on red-P under both conditions (Table 14). Concentration of ws-P under reducing conditions was significantly lower at pH 4.5 (2.05 mg/kg) and significantly increased with increasing soil pH.

Under oxidizing condition, soil pH had a significant effect on the all P forms. At pH 4.5 ws-P was 6.8 mg/kg and significantly lower than at higher pH levels. Water-soluble P gradually increases to 13.6 mg/kg at pH 7.5. An increase in ws-P with increasing soil pH, considered without regard to redox conditions, was found by other workers. Increasing soil pH increases the solubility of ferric phosphate and aluminum phosphate, but decreases the solubility of calcium phosphate (Lindsay and Morreno, 1960), and a decrease in pH favors the solubility of calcium phosphate as well as that of ferrous and manganous phosphate (Stumm and Morgan, 1970). Brady (1974) found that the maximum solubility of P in the soil occurs at the pH range of 6 to 7.

Patrick and Khalid (1974) reported that in Crowley silt loam soil (Typic Albaqualf) more P was adsorbed under reducing than under oxidizing conditions when P concentration in the soil was high. They attributed differences in behavior of phosphate under reducing and oxidizing conditions to changes brought about in ferric oxyhydroxide concentrations by soil reduction.

Like P, concentrations of all forms of K were lower under reducing than under oxidizing conditions (Table 14). Under reducing conditions, concentration of ws-K was not affected by soil pH, while concentration of ext-K was significantly increased at soil pH above 5.5. Under oxidizing conditions, each form of K was significantly affected by soil pH, and tended to increase with increasing soil pH up to 6.5. The ws-K and ext-K forms were higher under oxidizing than under reducing conditions. In a recent study, Patrick and Jugsujinda (1986) found that after flooding, however, water-soluble K was decreased by seven fold as compared to extractable form.

The concentrations of all Si forms were significantly affected by soil pH under both reducing and oxidizing conditions. Under reducing conditions concentration of Si was significantly lower at pH 7.5 as compared to pH 4.5, but under oxidizing conditions it increased significantly. Extractable Si forms were higher under oxidizing than under reducing conditions (Table 14). In experiment 2, where both soil Eh and pH were controlled ext-Si concentrations were significantly higher at Eh -150 and 0 mv (96.5 and 83.5 mg/kg) than at Eh +150 and 300 mv (47.5 and 24.5 mg/kg). Concentrations of ws-Si were lower at low Eh than at high Eh levels (Table 15).

In general, flooding increases the concentration of Si. Increases in soluble Si are associated with decreased pH, and the reduction of amorphous Al and ferric hydroxide forms in flooded soils (Patrick et al., 1985). Precipitation of iron causes a decrease in soluble SiO_2 concentration, and the reduction of ferri-silica complexes liberates silica. Therefore, reversible changes in the solubility of silica appear to be associated with the oxidation-reduction iron (Ponnamperuma, 1965). It has also been reported that the readily

soluble Si in soil is either adsorbed on exchange sites or combined with amorphous aluminum and ferrous hydroxide (Yoshida, 1981).

3.2. Nutrient Elements Contents in Rice Plants. Selected nutrient elements contents in the rice plants at the controlled pH levels of experiment 1 are shown in Table 16 and those at the controlled Eh levels of experiment 2 in Table 17.

3.2.1. *Copper, Zinc, and Molybdenum.* The content of Cu and Zn in the rice shoots tended to decrease with increasing pH under both reducing and oxidizing conditions, but stayed within the normal range. While Mo contents in the shoots were not affected by pH under reducing conditions it was significantly increased under oxidizing conditions (Table 16).

The critical levels for Zn deficiency and toxicity, 10-15 mg/kg and 1500 mg/kg are reported (Sedberry et al., 1971; 1978) and the critical levels for Cu in deficiency and toxicity are <6 mg/kg and 30 mg/kg (Yoshida 1981).

The Mo content under reducing conditions at all pH levels was less than 1.0 mg/kg, but under oxidizing conditions it ranged from 6.38 mg/kg at pH 4.5 to 9.58 mg/kg at pH 7.5. The critical levels for Mo deficiency and toxicity in the rice shoot have not been defined, but Patrick et al. (1985) suggest that the concentrations of Mo less than 2 mg/kg can be toxic to rice plants.

In experiment 2, the content of Cu, Zn, and Mo in the rice shoots significantly decreased with increasing Eh values (Table 17).

It has been reported that soil reduction depresses both the concentrations of Zn in the solution of flooded soils and Zn uptake by rice plants (IRRI, 1970). Decreased Zn uptake by rice plants may also be due to formation of sulfide and possibly production of organic complexing agents brought on by soil reduction as suggested by Ponnamperuma (1972).

3.2.2. *Iron and Manganese.* The content of Fe was higher under reducing than oxidizing conditions. Under both conditions the content of Fe decreased significantly as

the soil pH was raised from 4.5 to 6.5, and thereafter remained insignificant decrease (Table 16).

Increased concentration of Fe in the soil caused by intense reduction and low pH appear to increase Fe uptake by rice plants. Gotoh and Patrick (1974) also found that the content of Fe was highly pH dependent. Poor growth of plants which was observed especially at pH 4.5 and 5.5 under reducing conditions may have been due to the high amount of Fe in the rice shoots (5,304 and 674 mg/kg). At these two pH levels the plants may have suffered from Fe toxicity, as the Fe content is higher than threshold toxicity level of 300 mg/kg as reported by Yoshida (1981). Ponnamperuma (1972), and van Breeman and Morman (1978) reported that the combination of high concentrations of soluble Fe and low pH cause Fe toxicity to plants. Iron content above 300 mg/kg in the leaf blade has also been reported to be toxic to the rice plants (Tanaka et al., 1966b; IRRI, 1969).

The content of Mn in the rice shoot was significantly higher at pH 4.5 than at higher pH levels under both soil conditions and tended to decrease with increasing pH levels (Table 16). The Mn content in the rice shoots was well below the critical levels for Mn toxicity of 2,500 mg/kg (Yoshida, 1981). Tadano and Yoshida (1978) suggested that a high manganese content in the rice tissue is frequently associated with high yields. In this study, however, pH 4.5 gave the highest Mn contents, but shoot dry weights were very low. This may have been due to the high content of Fe and Al in the rice plants.

Studies conducted on Mn availability to rice have often been contradictory. Some investigators (Clark et al., 1957; Chaundry and McLean,1963; Jugsujinda and Patrick, 1977; and Patrick and Jugsujinda, 1986) have reported that flooding a soil greatly increased Mn uptake by rice while others (Sinewirante and Mikkelsen, 1961) reported that it caused a decrease in uptake. Patrick and Fontenot (1976) found that flooding had little or no effect on Mn uptake by rice.

In experiment 2, Soil Eh had a significant effect on Fe content (Table 17), but Fe content in the shoots was below the critical level for Fe-toxicity. The symptoms of Fe-

toxicity therefore did not occur. It may be that the level of soil pH controlled at 6.5 was not low enough to induce Fe-toxicity. Soil Eh did not affect on Mn content in the shoots.

3.2.3. *Aluminum*. The content of Al was higher under oxidizing than under reducing conditions. The Al content in the rice shoots under oxidizing conditions decreased from 709 mg/kg at pH 4.5 to 655 mg/kg at pH 7.5 (Table 16). Since these values are higher than threshold toxicity level of 300 mg/kg reported by Yoshida (1981), the rice plants may have suffered Al-toxicity at all pH levels under oxidizing conditions.

Wagatsuma (1984) found direct relationship between Al-uptake and Al in the medium, but others have found no relationship (Succoff and Ohno, 1986 and Jugsujinda et al., 1985). In experiment 2, peculiarly, although soil Eh was controlled and pH maintained at 6.5, Al content in the shoots at all Eh levels was still higher than threshold level for Al toxicity. The average Al content ranged from 693 mg/kg at -150 mv to 713 mg/kg at +150 mv (Table 17). These high Al concentrations in the soil may have enhanced the release of Al to the soil solution.

3.2.4. *Calcium and Magnesium*. Calcium content ranged from 1,816 to 5,297 mg/kg (0.18 to 0.53 %) under reducing conditions and from 1,768 to 2,990 mg/kg (0.18 to 0.30 %) under oxidizing conditions. Magnesium content ranged from 2,905 to 3,867 mg/kg (0.29 to 0.39 %) under reducing conditions and from 2,177 to 3,221 mg/kg (0.22 to 0.32 %) under oxidizing conditions (Table 16). Both Ca and Mg contents were above the critical levels (0.15 % and 0.10 %) for deficiencies of these nutrients (Tanaka and Yoshida,1970 and Yoshida,1981). Calcium and Mg are displaced from cation exchange sites during flooding, which increases their concentration in the solution (Patrick et al., 1985). Moreover, Ca and Mg deficiencies seldom occur in flooded rice because wetland soils and irrigation water are usually well-supplied with these elements.

In experiment 2, soil Eh had little effect on Ca and Mg content and their uptake by rice plants. The Ca content in the shoots ranged from 1,924 to 3,581 mg/kg (0.19 to 0.36%), and Mg content from 2,524 to 3,888 mg/kg (0.25 to 0.39%) (Table 17).

3.2.5. *Phosphorus, Potassium, and Silicon*. Phosphorus content in the rice shoots under reducing and oxidizing conditions were not affected by soil pH, but P content in the shoots were higher under reducing than under oxidizing conditions, with average values of 4,157 mg/kg (0.42%) and 2,449 mg/kg (0.25%), respectively (Table 16). These values were above the threshold deficiency levels of 0.1% as reported by Tanaka and Yoshida (1970).

Ottow et al. (1983) observed that the P content of rice leaves with clear symptoms of Fe toxicity ranged from 0.1 to 0.2%. In the present study, the shoot P apparently was adequate. This may be due to release of P during incubation period. Patrick et al. (1985) reported that saturating the soil with water increases the availability of P to rice crops.

Soil pH significantly affects the content of K in rice shoots under oxidizing, but not under reducing conditions. The content of K in the rice shoots under reducing and oxidizing conditions was about equal when compared at the same pH level, indicating that oxidation-reduction conditions have no effect on K content in rice shoots. The K content recorded under reducing conditions ranged from 25,261 mg/kg (2.5 %) at pH 4.5 to 19,004 mg/kg (1.9 %) at pH 7.5; while under oxidizing conditions it ranged from 25,211 mg/kg (2.5 %) at pH 4.5 to 16,685 mg/kg (1.7 %) at pH 7.5. These values were above the 1.0% critical levels of K deficiency (Tanaka and Yoshida, 1970).

The content of Si in the rice shoots was not affected by soil pH under either soil condition (Table 16). These contents are below the 5% threshold deficiency level (Tanaka and Yoshida, 1970). Yoshida (1981) reported that the application of silicates in the field was beneficial for rice growth when silica content of straw residue was below 11 %, but in solution culture the addition of silicon had little effect on vegetative growth when silica content in the leaves was as low as 0.07% (Yoshida, 1981) and applications of Si had no effect on rice growth and yield when its content in green leaves was above 1.25% (Yoshida, 1981).

In experiment 2, the contents of P, K, and Si in the rice shoots were not affected by soil Eh (Table 17). Their contents were 3,730 mg/kg (0.37 %), 2,284 mg/kg (0.23 %), and 336 mg/kg (0.037 %), respectively. The content of Si was still lower than threshold deficiency levels, and therefore the rice plants may have been suffering from Si deficiency in both experiments. The results reported by Patrick and Jugsujinda (1986) also indicate that rice grown in Sumatra Oxisol was Si-deficient.

3.3. Relationships Among Selected Nutrient Elements in the Soil and Their Uptake by Rice Plants.

3.3.1. *Copper, Zinc, and Molybdenum*. Concentrations of water-soluble Cu in the soil were negatively correlated with uptake by rice plants under both reducing and oxidizing conditions under oxidizing conditions (Table 18). Extractable Cu, however, were positively correlated with their rice uptake (Table 19). No relationships between Mo uptake and ws-Mo, or between ext-Mo and Mo uptake were observed under reducing conditions, but both forms were positively correlated with Mo uptake under oxidizing conditions (Tables 18 and 19). In experiment 2, there was no relationship between water-soluble and extractable Cu and Zn and their uptake by rice. Uptake of Cu and Zn were positively correlated with ws-Fe and Mn and negatively correlated with ws-Mo, Si, P and Al. Uptake of Mo was positively correlated with ws-Fe, ws-Mn and ext-Mo, and negatively correlated with ws-Si, P and Al (Tables 20 and 21).

3.3.2. *Iron and manganese* The uptake of Fe was significantly related to ws-Fe concentrations (r= +0.962**) and Fe^{2+} activity (r= +0.976**) under reducing, but not under oxidizing conditions (Tables 18 and 22). There was no relationship between ws-Mn, ext-Mn, or Mn^{2+} activity and Mn uptake under reducing conditions, whereas under oxidizing conditions Mn uptake was significantly related to ws-Mn (r= +0.99**) and Mn^{2+} activity (r= +0.934**) (Table 18, 19 and 22).

In experiment 2, there were no correlations between ws-Mn and Mn-uptake, or between ext-Mn and Mn-uptake by rice. Water-soluble and extractable Fe, were positively correlated with Fe uptake by rice (r= +0.873**, +0.864**) (Tables 20 and 21).

3.3.3. *Aluminum*. Aluminum uptake by rice plants was positively correlated with ws-Al (r= +0.658*), but had no relationships to Al^{3+} activity under oxidizing conditions. Also, no relationships between Al uptake and ws-Al, or between Al-uptake and Al^{3+} activity were observed under reducing conditions. In experiment 2, water-soluble Al and ext-Al were not correlated to Al uptake by rice (Tables 20 and 21).

3.3.4. *Calcium and Magnesium*. Under oxidizing conditions, ws-Ca and Ca^{2+} activity were negatively correlated with Ca uptake (r= -0.881** and -0.692*). No relationship was observed between ws-Ca, ext-Ca or Ca^{2+} activity in the soil to Ca uptake by rice plants grown under reducing conditions. Also, no relationship between ws-Mg, ext-Mg or Mg^{2+} activity to Mg uptake was observed under either conditions (Tables 18, 19 and 22). In experiment 2, water-soluble and extractable Ca and Mg had no relationship with their uptake by rice plants (Tables 20 and 21).

3.3.5. *Phosphorus, Potassium, and Silicon*. The phosphorus uptake by rice plants under reducing conditions was positively correlated with ws-P and negatively correlated with water-soluble forms of Zn, Fe, Mn, Ca, Mo and Si (Table 18). Under reducing conditions, P uptake was negatively correlated with activities of Zn^{2+}, Fe^{2+}, and Mn^{2+}, but positively correlated with Ca^{2+} activity (Table 22). Under oxidizing conditions, only the activity of Ca^{2+} was negatively correlated to P uptake.

No relationships between K uptake and ws-K, and between K uptake and ext-K in the soil were observed under either soil condition. K uptake was negatively correlated with ws-P under reducing conditions. The uptake of K under oxidizing conditions was negatively correlated with water-soluble forms of Cu, Zn, Ca, Si and P. Activities of Zn^{2+} and Ca^{2+} were negatively and ws-Al and Al^{3+} activity were positively correlated with K

uptake. Also, no relationships between Si uptake and ws-Si, ext-Si, and Si^{4+} activities was observed under either soil condition (Tables 18, 19 and 22).

In experiment 2, no relationships between P, K, and Si uptake by rice plants and their water-soluble forms were observed. Extractable P, Si, Mo, Mg, Fe, and Zn was positively correlated with P uptake, while K uptake was positively correlated with ext-Zn and ext-Fe (Tables 20 and 21).

Summary and Conclusions

To study metals and nutrients release and their uptake by rice in a flooded Oxisol of Sitiung Transmigration area of Sumatra, we conducted two laboratory experiments. In the first experiment, rice plants were grown in reduced and oxidized soil suspensions with pH levels controlled at 4.5, 5.5, 6.5, or 7.5. In the second experiment, rice plants were grown on the soil suspension with pH was controlled at 6.5 and the Eh controlled at -150, 0, +150, and +300 mv.

In the first experiment, at pH 4.5 the reduced soil released significantly higher amounts of water-soluble Zn, Fe, Mn, and Mo concentrations into the soil solution than at pH 5.5, 6.5, and 7.5. Under reducing conditions and at pH 4.5, the rice plants also absorbed significantly higher concentrations of Zn, Fe, and Mn as well as Ca, Mg, and Al. The contents of Fe observed at pH 4.5 was 5304 mg/kg, and at pH 5.5 was 674 mg/kg under reducing conditions, both were above the critical level of Fe toxicity of 300 mg/kg, indicating that the rice plants may have suffered from Fe toxicity at these two pH levels.

Under oxidizing conditions the soil released significantly higher amounts of water-soluble Al and Mn at pH 4.5 than at other pH levels. The content of Al in the rice plants ranged from 709 mg/kg at pH 4.5 to 655 mg/kg at pH 7.5 and both were above the critical level of Al toxicity of 300 mg/kg. Therefore, rice plants may also have suffered from Al toxicity at all pH levels under the oxidizing conditions.

The concentration of other elements were in normal range in the rice plants grown at all pH levels and redox conditions except Si, which was found to be below the threshold deficiency value of 5 %. Silicon was not affected by soil pH under either condition.

Correlation coefficients indicating the relationship between water-soluble Fe in the soil and uptake of Fe, Cu, Zn and P by rice plants under reducing conditions were +0.962**, +0.762**, +0.785**, and -0.803**, respectively. Under oxidizing conditions, the correlations between water-soluble Al in the soil and the uptake of Cu, Zn, Fe, Mn, Ca, Mg, Al, and K were +0.909**, +0.906**, -0.797**, +0.793**, +0.958**, +0.612*, +0.658* and +0.928*, respectively.

At pH 4.5 reduced soil conditions produced significantly lower plant height, root dry weight, shoot dry weight, relative growth rate, and shorter root length than at higher pH levels. Under reducing conditions, however, these growth parameters increased significantly from pH 4.5 to 6.5 and then decreased at pH 7.5. Plant height and relative growth rate were not significantly affected by pH under oxidizing conditions.

Leaf discoloration under both conditions was significantly higher at pH 4.5 and tended to decreased with increasing pH. Under reducing conditions, rice leaves exhibited oranging symptoms, and under oxidized conditions, yellowing.

The activity of Fe^{2+} in the soil was positively correlated with Mg, Si, and P uptake by rice under reducing conditions, and Fe uptake was negatively correlated with Ca, Mg, Si, P, and K activity. Under oxidizing conditions, on the the other hand, Al activity was positively correlated with Cu, Zn, Fe, Mn, Ca, and K uptake, but was negatively correlated with Ca and Si activity.

In the second experiment, where pH was controlled at 6.5, water-soluble Fe concentration was significantly higher at low Eh levels (141 and 109 mg/kg) than at higher Eh (51 and 18 mg/kg). The concentration of water-soluble Al and P were low at lower Eh than at higher Eh levels. These results were consistent with the results obtained from the first experiment.

The content of the various elements in the rice shoots was in the normal range, except Al which was also found to be higher than the critical level for toxicity, and Si which was lower than the critical level for deficiency at all Eh levels. The content of Cu, Zn, Fe, Ca, Mg, Mo, and Al were affected by Eh, but Mn, Si, P, and K were not. In this experiment there was no Fe toxicity recorded because the soil pH was not low enough to cause the toxicity.

The shoot dry weight, relative growth rate, and shoot root ratio were not affected by soil Eh levels studied. Root length, however, was significantly increased whereas plant height, and root dry weight were significantly decreased at Eh of 0 mv. Plants grown at Eh +150 and +300 mv showed significantly higher assimilation rates at 15 and 20 days after transplanting than at lower Eh values.

Leaf discoloration appeared to be more pronounced at pH 4.5 and 5.5 than at higher pH levels under both soil conditions. Water-soluble Fe was negatively correlated with P uptake and positively correlated with Fe uptake. Iron uptake by rice was positively correlated with leaf discoloration under reducing conditions.

The findings of the present study identify problems of Fe toxicity in lowland (reducing conditions), Al toxicity in upland soils (oxidizing conditions), and Si deficiency for rice under both soil conditions in the flooded Sumatra Oxisol. It may be concluded from the foregoing results that factors limiting growth of rice appeared to be Fe toxicity at pH 4.5 and 5.5 under reducing conditions and Al toxicity at all pH levels under oxidizing conditions. Si deficiency was observed in both experiments regardless of soil conditions and pH levels studied.

It is suggested that future research be directed towards alleviating the Fe toxicity in lowland, Al toxicity in upland, and Si deficiency in both soils of the Sitiung Transmigration Areas of Sumatra, Indonesia. More specifically, research projects should be conducted in the field to evaluate: (i) water management practices; drained versus undrained, (ii) kinds

of soil amendments and fertilizers; chemical versus organic matter additions, and (iii) Fe-tolerant rice varieties.

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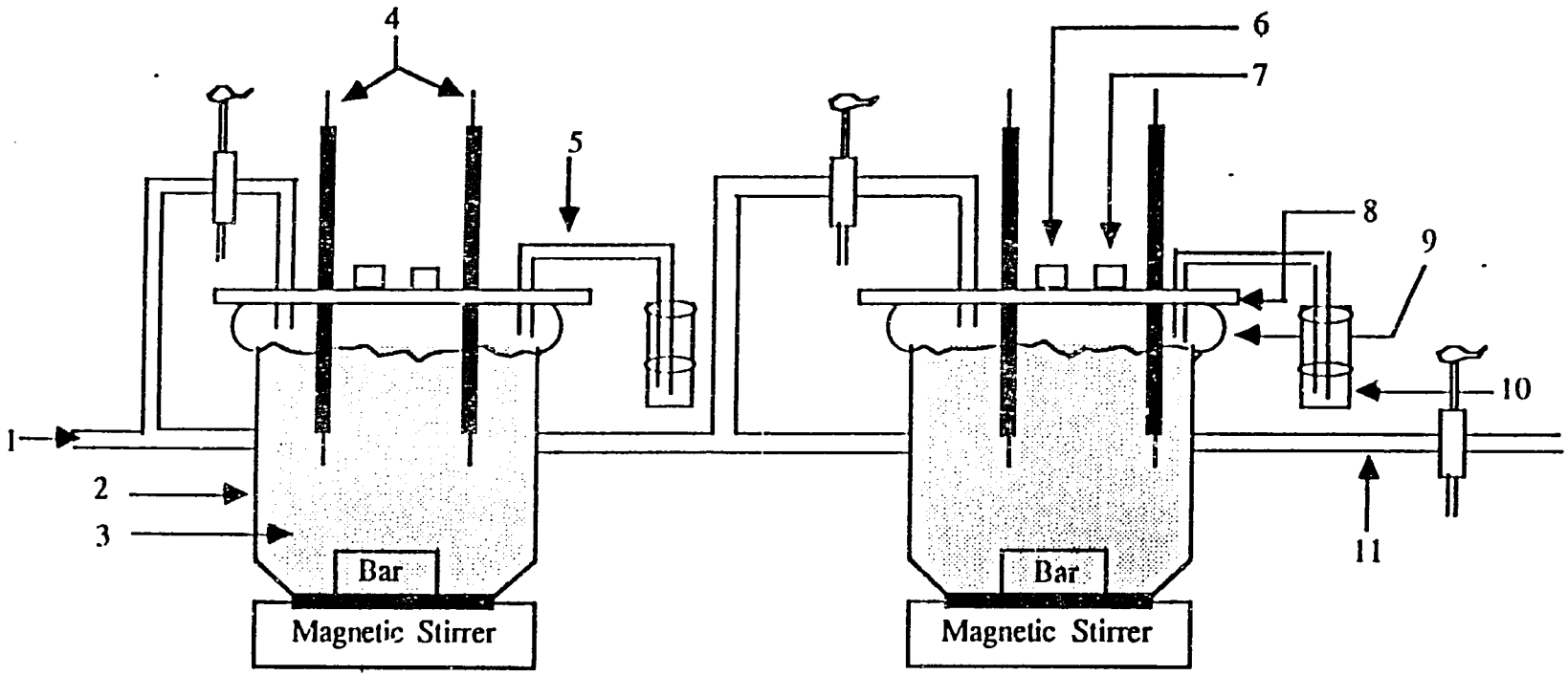

1. Gas Inlet
2. Desiccator Base
3. Soil Suspension
4. Platinum Electrodes
5. Gas Outlet
6. Rubber Stopper
7. Serum Cap
8. Plexiglass Plate
9. Plastic Rubber Seal
10. Distilled Water
11. Gas Pipe

Fig. 1. The apparatus for incubation of the soil suspension at controlled pH or redox potential conditions .

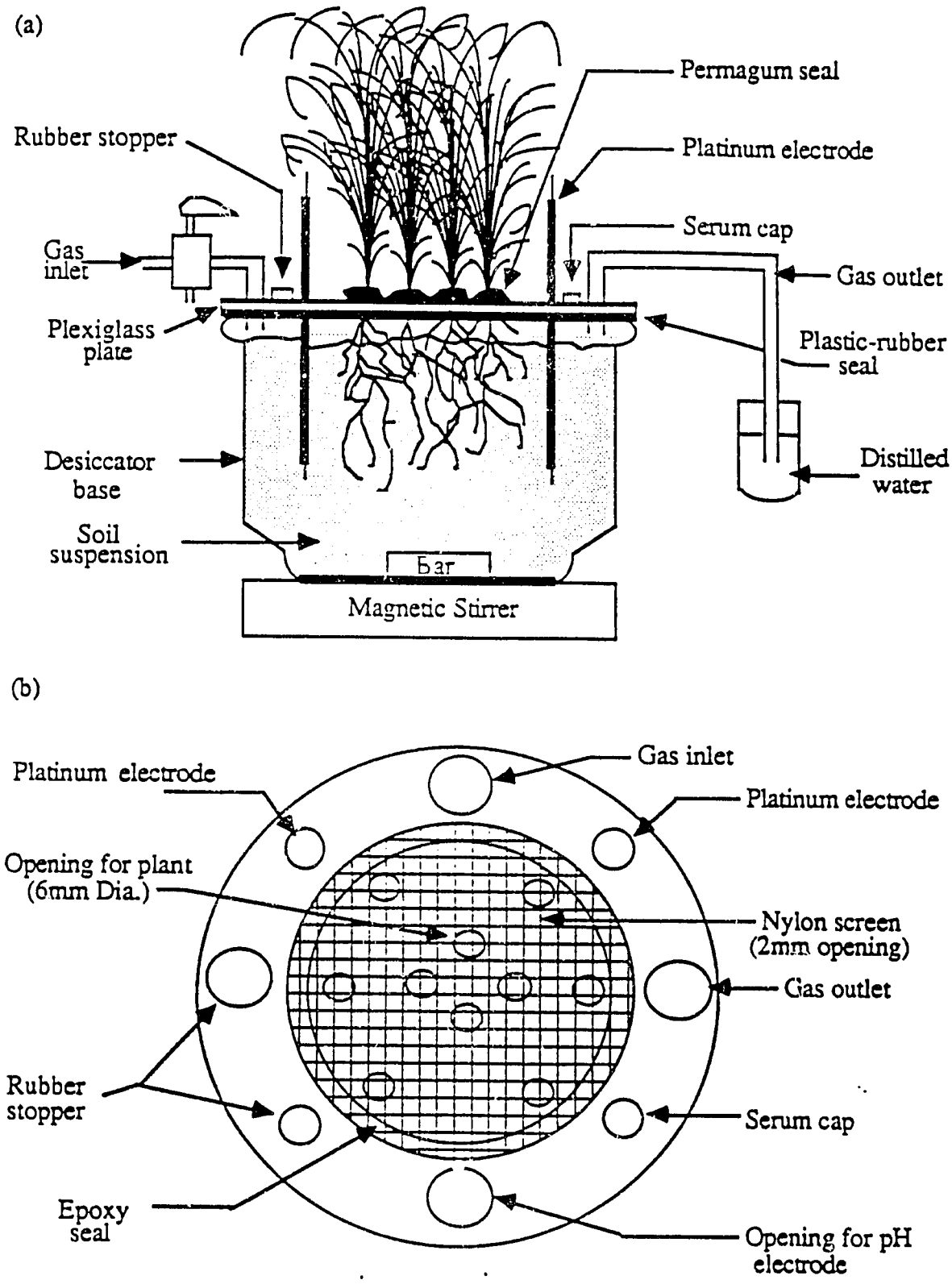

Fig. 2. Diagram of growth set up after transplanting rice (a) and a plexiglass plate (b) designed for use in supporting rice seedlings in controlled system

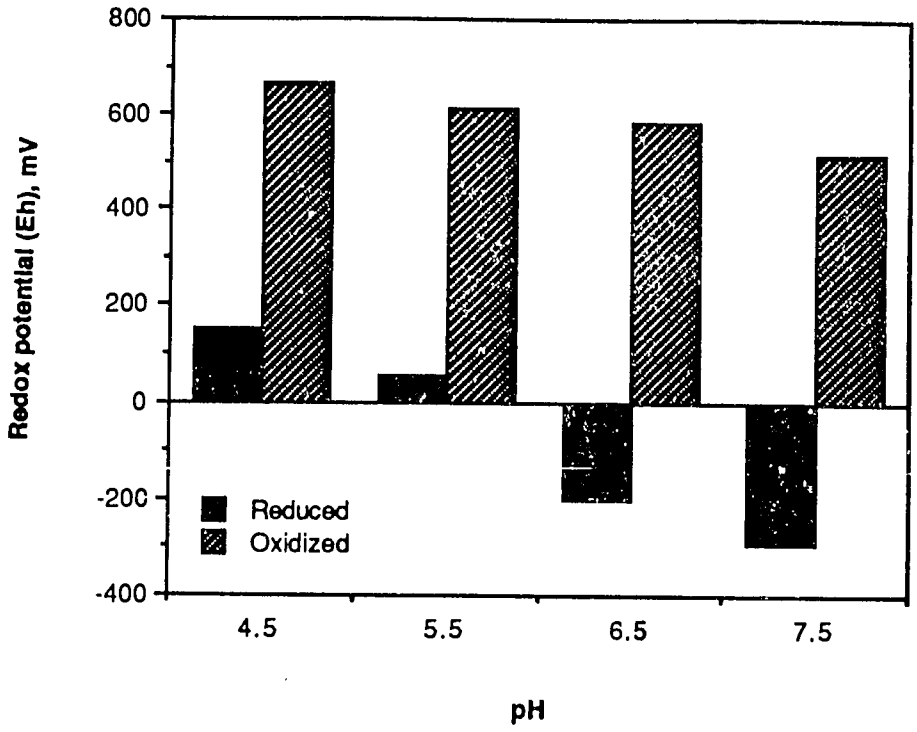

Figure 3. Effect of soil pH on average values of redox potential (Eh) of reduced and oxidized soil conditions.

Table 1. Some soil chemical and physical characteristics of the representative top soil layer (25 cm).

Soil characteristics	Value	
pH (1:1 soil:water ratio)	4.1	
Organic matter	2.3	%
C/N ratio	10.3	
CEC-clay	15.5	me/100 g
Extractable Ca (1N NH4OAc, pH 4.0)	0.6	me/100 g
Extractable Mg (1N NH4OAc, pH 4.0)	0.9	me/100 g
Extractable K (1N NH4OAc, pH 4.0)	0.3	me/100 g
Extractable Na (1N NH4OAc, pH 4.0)	0.1	me/100 g
Extractable Al (1N NH4OAc, pH 4.0)	3.1	me/100 g
Extractable Fe (DPTA-TEA)	69.0	mg/kg
Extractable Mn (DPTA-TEA)	36.0	mg/kg
Extractable Zn (DPTA-TEA)	0.6	mg/kg
Extractable Cu (DPTA-TEA)	0.8	mg/kg
Sand	31.9	%
Silt	11.9	%
Clay	56.2	%

Table 2. Effect of soil pH on leaf discolorations and growth parameters of rice plants grown under reduced and oxidized soil conditions in a flooded Oxisol.*

pH	Red	Ox	Red	Ox	Red	Ox
	Leaf ** discoloration score		Root lenght (cm)		Plant height (cm)	
4.5	2.4 a	2.4 a	15.5 c	15.4 c	31.8 c	33.0 a
5.5	2.1 b	2.1 b	18.9 b	18.5 b	32.8 bc	35.0 a
6.5	1.3 c	1.2 c	21.0 a	20.4 a	35.4 a	37.4 a
7.5	1.1 c	1.1 c	22.0 a	14.5 d	34.8 ab	34.4 a
	root dry weight (g/pot)		Shoot dry weight (g/pot)		Shoot/ root ratio	
4.5	0.8 d	0.7 b	1.8 d	2.7 b	2.3 a	3.8 d
5.5	1.0 c	0.7 b	2.4 c	3.4 a	2.4 a	4.8 a
6.5	5.3 a	0.8 a	3.0 a	3.5 a	2.4 a	4.6 b
7.5	1.1 b	0.7 b	2.5 b	2.4 c	3.3 a	3.4 c
	Relative growth rate (g/pot/week)					
4.5	0.3 b	0.5 a				
5.5	0.4 a	0.6 a				
6.5	0.5 a	0.6 a				
7.5	0.5 a	0.5 a				

* Mean separation in a column by Duncan Multiple Range Test at 5% level.
** Leaf discoloration rating: 0 = normal, 1 = 25%, 3 = 50%, 5 = 75%, and 7 = 100% leaf discolration, respectively.

Table 3. Growth parameters of the rice plants grown in a flooded Oxisol at pH 6.5 and varied Eh level.*

Eh (mV)	Growth parametrs					
	Root lenght (cm)	Shoot/ root ratio	plant height (cm)	Root dry wt. (g/pot)	shoot dry wt. (g/pot)	Relative growth rate (g/pot/week)
-150	18.6 b	3.57 a	51.3 a	1.61 a	5.75 a	0.43 a
0	21.2 a	3.95 a	48.6 b	1.29 b	5.09 a	0.39 a
+150	18.9 b	3.59 a	52.3 a	1.48 a	5.29 a	0.41 a
+300	19.6 ab	3.48 a	52.6 a	1.49 a	5.15 a	0.39 a

* Mean separation in a column by Duncan Multiple Range Test at 5% level different.

Table 4. Average assimilation rates of rice plants grown in a flooded oxisol under reduced and oxidized conditions at varied pH levels.*

	Days after transplanting**					
pH	10		15		20	
	--- CO2 umol/m2/sec.---					
	Red	Ox	Red	Ox	Red	Ox
4.5	8.9 a	10.7 c	15.6 b	19.6 b	12.5 b	18.2 b
5.5	9.5 a	12.5 c	21.0 a	22.0 a	20.4 a	17.6 b
6.5	12.4 a	19.0 a	22.5 a	24.2 a	20.4 a	22.9 a
7.5	10.8 a	15.6 b	21.7 a	18.0 b	19.9 a	18.6 b

* Means separation in a column by Duncan Multiple Range Test at 5% level different.

** Assimilation rate at 0 days after transplanting = 11.1 CO2 umol/m2/sec.

Table 5. Average assimilation rates of rice plants grown in a flooded Oxisol at pH 6.5 and varied Eh level.*

Eh	Assimilation rate (CO_2 umol/m2/sec)		
(mV)	10DF**	15DF	20DF
-150	8.16 b	19.2 a	17.8 b
0	8.70 ab	21.2 a	18.7 ab
+150	7.27 b	20.6 a	20.2 a
+300	12.27 a	20.4 a	19.2 a

* Means separation in a column by DMRT at 5% level different

** DF = days after transplanting

Table 6. Average concentrations of water-soluble, sodium acetate extractable, and citrate dithionite extractable forms of Cu, Zn, and Mo in a flooded Oxisol under reduced and oxidized conditions at varied pH levels. *

pH	Water-soluble		Sodium acetate extractable		Citrate dithionite extractable	
	Red	Ox	Red	Ox	Red	Ox
			Copper, mg/kg			
4.5	0.20 c	3.95 bc	4.9 a	26.4 ab	0.57 a	45.5 a
5.5	0.70 b	3.45 c	1.8 b	26.3 a	0.67 a	35.6 a
6.5	0.80 b	4.45 ab	1.2 bc	32.9 a	0.60 a	35.6 a
7.5	2.35 a	4.70 a	0.6 c	21.2 b	0.67 a	29.5 a
			Zinc, mg/kg			
4.5	4.10 a	2.40 d	18.6 a	25.0 a	15.8 a	18.5 a
5.5	2.70 b	3.70 c	20.5 a	27.2 a	16.7 a	12.5 b
6.5	0.70 d	6.30 b	14.5 a	25.9 a	17.9 a	23.2 a
7.5	1.50 c	8.30 a	22.4 a	22.2 a	18.4 a	21.0 a
			Molybdenum, mg/kg			
4.5	0.26 a	0.94 b	0.7 b	21.8 c	4.2 a	24.1 b
5.5	0.09 b	1.15 a	0.7 b	26.2 ab	3.9 a	28.6 a
6.5	0.06 b	1.27 a	0.7 b	28.0 a	3.1 a	30.1 a
7.5	0.05 b	1.09 ab	0.9 a	23.1 bc	3.6 a	24.2 b

* Mean separation in a column for each nutrient element by Duncan Multiple Range Test at 5% level different.

Table 7. Average concentrations of water-soluble, sodium acetate extractable, and citrate dithionite extractable forms of Cu, Zn and Mo in a flooded Oxisol at pH 6.5 under varied Eh levels.*

Eh (mV)	Water-soluble	Sodium acetate extractable	Citrate dithionite extractable
		Copper, mg/kg	
-150	2.30 a	8.5 a	12.3 a
0	2.79 a	5.76 a	8.6 a
+150	1.78 a	14.66 a	13.3 a
+300	2.36 a	5.52 a	8.7 a
		Zinc, mg/kg	
-150	2.25 a	21.3 a	9.88 a
0	3.46 a	15.6 a	7.83 a
+150	2.53 a	18.1 a	13.15 a
+300	2.67 a	14.2 a	8.84 a
		Molybdenum, mg/kg	
-150	0.05 b	1.66 a	4.10 a
0	0.10 b	1.51 a	3.44 a
+150	0.22 a	0.51 b	1.46 b
+300	0.12 b	0.49 b	1.39 b

* Means separation in a column for each nutrient element by Duncan Multiple Range Test at 5% level different.

Table 8. Average concentrations of water-soluble, sodium acetate extractable, and citrate dithionite extractable forms of Fe, and Mn in a flooded Oxisol under reduced and oxidized conditions at varied pH levels. *

pH	Water-soluble		Sodium acetate extractable		Citrate dithionite extractable	
	Red	Ox	Red	Ox	Red	Ox
			Iron, mg/kg			
4.5	1231 a	1.85 b	747.5 d	102.0 bc	11510 a	4913 a
5.5	586 b	5.25 a	1068.5 c	119.0 a	10448 ab	4422 a
6.5	244 c	6.15 a	1479.5 b	112.0 ab	9008 b	4699 a
7.5	220 c	6.65 a	1715.5 a	90.5 c	8651 b	3825 b
			Manganese, mg/kg			
4.5	111.15 a	2.70 a	53.1 b	26.5 b	24.1 ab	110.3 a
5.5	41.65 b	1.05 c	67.6 b	26.0 b	27.5 a	112.5 a
6.5	16.25 c	1.35 b	97.8 a	28.9 ab	22.8 b	100.1 ab
7.5	4.45 d	1.15 bc	116.1 a	32.0 a	22.9 ab	86.8 b

* Mean separation in a column for each nutrient element by Duncan Multiple Range Test at 5% level different.

Table 9. Average concentrations of water-soluble, sodium acetate extractable, and citrate dithionite extractable forms of Fe and Mn in a flooded Oxisol at pH 6.5 under varied Eh levels.*

Eh (mV)	Water-soluble	Sodium acetate extractable	Citrate dithionite extractable
		Iron, mg/kg	
-150	141 a	1123 a	864 a
0	109 a	556 b	1310 a
+150	51 b	138 c	1170 a
+300	18 b	173 bc	940 a
		Manganese, mg/kg	
-150	3.90 a	31.7 a	2.76 c
0	2.71 ab	24.5 a	2.84 c
+150	1.70 ab	38.2 a	15.68 a
+300	0.76 b	13.8 a	10.22 b

* Means separation in a column for each nutrient element by Duncan Multiple Range Test at 5% level different.

Table 10. Average concentrations of water-soluble, sodium acetate extractable, and citrate dithionite extractable forms of Al in a flooded Oxisol under reduced and oxidized conditions at varied pH levels. *

pH	Water-soluble		Sodium acetate extractable		Citrate dithionite extractable	
	Red	Ox	Red	Ox	Red	Ox
			Aluminum, mg/kg			
4.5	3.99 ab	25.3 a	499 a	691 a	2954 a	1309 b
5.5	3.55 b	23.6 a	338 b	693 a	2630 ab	1582 a
6.5	3.76 b	19.9 b	330 b	647 a	2475 b	1485 ab
7.5	5.46 a	11.2 c	477 a	519 b	2273 b	1020 c

* Mean separation in a column by Duncan Multiple Range Test at 5% level different.

Table 11. Average concentrations of water-soluble, sodium acetate extractable, and citrate dithionite extractable forms of Al in a flooded Oxisol at pH 6.5 under varied Eh levels.*

Eh (mV)	Water-soluble	Sodium acetate extractable	Citrate dithionite extractable
		Aluminum, mg/kg	
-150	17.8 c	596 a	508 a
0	72.7 b	541 a	530 a
+150	167.5 a	286 b	660 a
+300	116.1 ab	246 b	673 a

* Means separation in a column by Duncan Multiple Range Test at 5% level different.

Table 12. Average concentrations of water-soluble, sodium acetate extractable, and citrate dithionite extractable forms of Ca, and Mg in a flooded Oxisol under reduced and oxidized conditions at varied pH levels. *

pH	Water-soluble		Sodium acetate extractable		Citrate dithionite extractable	
	Red	Ox	Red	Ox	Red	Ox
			Calcium, mg/kg			
4.5	35.90 b	17.98 bc	290 c	590 c	94.5 b	170 b
5.5	51.39 a	14.35 c	431 b	820 a	115.5 a	199 a
6.5	54.28 a	24.85 ab	499 b	796 a	96.0 ab	195 ab
7.5	53.48 a	30.72 a	594 a	714 b	97.0 ab	167 b
			Magnesium, mg/kg			
4.5	12.34 a	2.66 a	52.5 c	87 b	18.3 a	16.4 a
5.5	23.28 a	2.60 a	80.0 b	112 a	16.0 a	18.3 a
6.5	24.67 a	4.16 a	95.5 b	123 a	16.1 a	19.5 a
7.5	24.98 a	4.44 a	122.5 a	110 a	17.5 a	20.3 a

* Mean separation in a column for each nutrient element by Duncan Multiple Range Test at 5% level different.

Table 13. Average concentrations of water-soluble, sodium acetate extractable, and citrate dithionite extractable forms of Ca and Mg in a flooded Oxisol at pH 6.5 under varied Eh levels.*

Eh (mV)	Water-soluble	Sodium acetate extractable	Citrate dithionite extractable
		Calcium, mg/kg	
-150	22.5 a	380 a	142 ab
0	21.5 a	348 a	157 a
+150	22.0 a	531 a	124 ab
+300	33.0 a	394 a	75 b
		Magnesium, mg/kg	
-150	3.30 a	48 a	23.5 ab
0	1.99 a	44 a	27.0 a
+150	4.37 a	49 a	16.5 ab
+300	2.67 a	45 a	10.0 b

* Means separation in a column for each nutrient element by Duncan Multiple Range Test at 5% level different.

Table 14. Average concentrations of water-soluble, sodium acetate extractable, and citrate dithionite extractable forms of P, K, and Si in a flooded Oxisol under reduced and oxidized conditions at varied pH levels. *

pH	Water-soluble		Sodium acetate extractable		Citrate dithionite extractable	
	Red	Ox	Red	Ox	Red	Ox
			Phosphorus, mg/kg			
4.5	2.05 d	6.8 d	13.5 b	158 b	199 a	186 b
5.5	5.05 c	9.0 c	11.5 b	193 a	179 a	319 a
6.5	9.50 a	11.9 b	11.5 b	201 a	168 a	330 a
7.5	7.20 b	13.6 a	17.5 a	168 b	169 a	266 b
			Potassium, mg/kg			
4.5	13.4 a	48.7 c	44.2 c	1071 c	nd**	1168 b
5.5	20.6 a	61.2 b	69.7 c	1325 ab	nd	1392 a
6.5	19.0 a	70.3 a	125.1 b	1388 a	nd	1470 a
7.5	19.0 a	60.2 b	209.4 a	1185 bc	nd	1195 b
			Silicon, mg/kg			
4.5	45.9 a	33.5 b	39.5 b	122 c	395 a	348 b
5.5	26.5 b	39.0 b	51.0 b	145 bc	379 ab	395 ab
6.5	20.5 c	47.0 a	56.0 b	173 b	336 b	416 a
7.5	17.9 c	52.0 a	127.5 a	244 a	107 c	367 ab

* Mean separation in a column for each nutrient element by Duncan Multiple Range Test at 5% level different.

** nd = non detectable.

Table 15. Average concentrations of water-soluble, sodium acetate extractable, and citrate dithionite extractable forms of P, K, and Si in a flooded Oxisol at pH 6.5 under varied Eh levels.*

Eh (mV)	Water-soluble	Sodium acetate extractable	Citrate dithionite extractable
		Phosphorus, mg/kg	
-150	1.19 b	19.5 a	74.3 a
0	2.21 b	17.5 ab	84.8 a
+150	5.44 a	10.5 b	73.7 a
+300	4.12 ab	10.0 b	57.9 a
		Potassium, mg/kg	
-150	53.5 b	126.5 b	121.5 a
0	95.6 ab	237.5 b	158.5 a
+150	128.2 a	546.0 a	28.0 b
+300	120.8 a	30.0 b	28.5 b
		Silicon, mg/kg	
-150	41 c	96.5 a	449 a
0	61 bc	83.5 a	531 a
+150	117 a	47.5 b	249 b
+300	83 b	24.5 c	197 b

* Means separation in a column for each nutrient element by Duncan Multiple Range Test at 5% level different.

Table 16. Average nutrient content of rice shoot grown in a flooded oxisol under reduced and oxidized conditions at varied pH levels.

pH	Nutrient concentration, mg/kg					
	Red	Ox	Red	Ox	Red	Ox
	Cu		Zn		Fe	
4.5	20.5 a	20.3 a	110.8 a	65.9 a	5304 a	106 a
5.5	16.1 b	17.4 b	59.5 b	44.0 b	674 b	95 b
6.5	9.3 c	15.7 c	51.2 c	24.9 c	208 c	91 c
7.5	9.6 c	16.0 c	38.7 d	22.7 c	144 c	90 c
	Mn		Ca		Mg	
4.5	809 a	916 a	5297 a	2990 a	3867 a	2792 ab
5.5	640 b	315 b	3721 b	2367 b	3352 ab	3221 a
6.5	630 b	184 c	3202 bc	2094 b	2913 b	2587 bc
7.5	491 c	109 d	1816 c	1768 c	2905 b	2177 c
	Mo		Si		P	
4.5	0.30 a	6.38 d	125 a	513 a	4016 a	2362 a
5.5	0.04 a	7.41 c	206 a	507 a	4220 a	2643 a
6.5	0.79 a	8.16 b	205 a	518 a	4295 a	2488 a
7.5	0.35 a	9.58 a	187 a	464 a	4097 a	2302 a
	Al		K			
4.5	183 a	709 a	25261 a	25211 a		
5.5	118 b	688 ab	18176 b	21485 b		
6.5	101 b	680 ab	26091 a	19032 c		
7.5	104 b	655 b	19004 b	16685 d		

* Means separation in a column for each nutrient element by Duncan Multiple Range Test at 5% level different.

Table 17. Average nutrient content in rice shoots grown in a flooded Oxisol under varied redox levels at pH 6.5.*

Eh (mV)	Nutrient content, mg/kg					
	Cu	Zn	Fe	Mn	Ca	Mg
-150	17.9 a	72.3 a	250 a	894 a	3581 a	3888 a
0	18.5 a	55.7 ab	232 ab	1227 a	3315 ab	3610 a
+150	8.1 b	26.7 b	146 bc	880 a	1924 b	2524 b
+300	10.2 ab	30.1 b	141 c	859 a	2644 ab	2963 ab
	Mo	Si	P	Al	K	
-150	1.18 a	359 a	4292 a	693 b	24649 a	
0	1.51 a	347 a	4051 a	682 b	22696 a	
+150	0.81 b	390 a	3255 a	713 a	21264 a	
+300	0.78 b	369 a	3321 a	689 b	22764 a	

* Means separation in a column for each nutrient element by Duncan Multiple Range Test at 5% level different.

Table 18. Simple correlation coefficients for the relationships between water-soluble nutrients in the soil and nutrient uptake by rice in a flooded Oxisol under reduced and oxidized conditions over all pH levels.

Water-soluble nutrient	Nutrient uptake										
	Cu	Zn	Fe	Mn	Ca	Mg	Mo	Si	P	Al	K
Reduced											
Cu	-0.737**	-0.898**	-0.643*	ns	-0.828**	ns	ns	ns	ns	ns	ns
Zn	+0.798**	ns	+0.876**	ns	ns	ns	-0.622*	ns	-0.852**	ns	-0.710**
Fe	+0.762**	+0.785**	+0.962**	ns	ns	ns	ns	ns	-0.803**	ns	ns
Mn	+0.762**	+0.843**	+0.976**	ns	+0.643*	ns	ns	ns	-0.750**	ns	ns
Ca	ns	-0.711**	-0.934**	ns	ns	+0.644*	ns	ns	-0.850**	ns	ns
Mg	ns	ns	-0.680*	ns	ns	ns	ns	ns	ns	ns	ns
Mo	+0.668*	+0.833**	-0.978**	ns	+0.629*	ns	ns	ns	-0.746**	ns	ns
Si	+0.733**	+0.670*	-0.875**	ns	ns	ns	ns	ns	+0.726**	ns	ns
P	-0.803**	ns	-0.868**	ns	ns	ns	ns	ns	+0.809**	ns	+0.670*
AL	ns	ns	ns	-0.686*	ns	ns	ns	ns	ns	ns	ns
K	ns	ns	-0.651*	ns	+0.720**	ns	ns	ns	ns	ns	ns
Oxidized											
Cu	-0.750**	-0.815**	-0.684*	ns	-0.778**	-0.757**	ns	ns	ns	ns	-0.774**
Zn	-0.786**	-0.985**	-0.626*	-0.897**	-0.867**	ns	ns	ns	ns	ns	-0.820**
Fe	ns	-0.836**	ns	-0.957**	ns	ns	+0.785**	ns	ns	ns	ns
Mn	ns	+0.625*	ns	+0.999**	ns	ns	-0.832**	ns	ns	ns	ns
Ca	-0.838**	-0.877**	-0.753**	-0.635*	-0.881**	+0.787**	ns	ns	ns	ns	-0.854**
Mg	ns	+0.665*	ns	ns	-0.629*	ns	ns	ns	ns	ns	ns
Mo	ns	-0.630*	ns	-0.797**	ns	ns	+0.961*	ns	ns	ns	ns
Si	-0.738**	-0.947**	ns	-0.906**	-0.764**	ns	ns	ns	ns	ns	-0.745**
P	-0.715**	-0.987**	ns	-0.943**	-0.804**	ns	ns	ns	ns	ns	-0.744**
AL	+0.909**	+0.906**	-0.797**	+0.793**	+0.958**	+0.612*	ns	ns	ns	0.658*	+0.928**
K	ns	-0.622*	ns	-0.771**	ns	ns	+0.925**	ns	ns	ns	ns

*,** Significance at the 0.05 and 0.01 levels of probability, respectively.
ns = not significant.

Table 19. Simple correlation coefficients for the relationships between NaOAc extractable nutrients in the soil and nutrient uptake by rice in a flooded Oxisol under reduced and oxidized conditions over all pH Levels.

NaOAc extract. nutrient	Nutrient uptake										
	Cu	Zn	Fe	Mn	Ca	Mg	Mo	Si	P	Al	K
Reduced											
Cu	+0.695*	+0.865**	+0.986**	ns	+0.638*	ns	ns	ns	-0.754**	ns	ns
Zn	ns	ns	ns	-0.783**	ns	ns	-0.630*	ns	ns	ns	-0.653*
Fe	-0.861**	-0.802**	-0.844**	ns	-0.659*	ns	ns	ns	-0.701*	ns	ns
Mn	-0.846**	-0.750**	-0.773**	ns	ns	ns	ns	ns	+0.716*	ns	ns
Ca	-0.797**	-0.884**	-0.886	ns	-0.755**	ns	ns	ns	+0.622*	ns	ns
Mg	-0.798**	-0.883**	-0.835**	ns	-0.782**	ns	ns	ns	ns	ns	ns
Mo	ns	-0.628*	ns	-0.794**	ns	ns	ns	ns	ns	ns	ns
Si	-0.697*	-0.845**	ns	ns	-0.811**	ns	ns	ns	ns	ns	ns
P	ns	ns	ns	-0.738**	ns	ns	ns	ns	ns	ns	ns
AL	ns	ns	ns	-0.653*	ns	ns	ns	ns	ns	ns	ns
K	ns	-0.807**	ns	-0.785**	-0.803**	ns	ns	ns	ns	ns	ns
Oxidized											
Cu	+0.808**	ns	+0.879**	ns	+0.669*	+0.910**	ns	+0.828**	+0.854**	+0.873**	+0.767**
Zn	+0.754**	ns	+0.793**	ns	+0.711*	+0.761**	ns	+0.690*	+0.677*	+0.758**	+0.758**
Fe	+0.865**	ns	+0.931**	ns	+0.798**	+0.977**	ns	+0.893**	+0.918**	+0.944**	+0.855**
Mn	-0.849**	-0.832**	-0.718*	-0.718*	-0.809**	ns	ns	ns	ns	ns	-0.824**
Ca	ns	ns	ns	-0.683*	ns	ns	+0.912**	ns	+0.708*	ns	ns
Mg	ns	-0.637*	ns	-0.827**	ns	ns	+0.946**	ns	ns	ns	ns
Mo	ns	ns	ns	ns	ns	+0.624*	+0.848**	+0.749**	+0.783**	+0.733**	ns
Si	+0.891**	-0.924**	-0.772**	-0.830**	-0.935**	+0.644*	ns	ns	ns	ns	-0.908**
P	ns	ns	ns	ns	ns	+0.688*	+0.879**	+0.791**	+0.832**	+0.778**	ns
AL	+0.910**	+0.833**	+0.853**	+0.681*	+0.964**	+0.777**	ns	+0.638*	ns	+0.745**	+0.942**
K	ns	ns	ns	ns	ns	ns	+0.910**	+0.649*	+0.750**	+0.683*	ns

*,** Significance at the 0.05 and 0.01 levels of probability, respectively.
ns = not significant.

Table 20. Simple correlation coefficient for the relationship between concentrations of water-soluble nutrients and uptake by rice in a flooded Oxisol at pH 6.5 over all Eh levels.

Water-soluble nutrient	Nutrient uptake					
	Cu	Zn	Fe	Mn	Ca	Mg
Cu	ns	ns	ns	ns	ns	ns
Zn	ns	ns	ns	ns	ns	ns
Fe	+0.775**	+0.864**	+0.873**	ns	+0.670*	+0.765*
Mn	+0.622*	+0.932**	+0.865**	ns	+0.684*	+0.694*
Ca	ns	ns	ns	ns	ns	ns
Mg	ns	ns	ns	ns	-0.635*	ns
Mo	-0.638*	-0.689*	ns	ns	-0.672*	-0.708**
Si	-0.818**	-0.750**	-0.730*	ns	-0.785**	-0.844**
P	-0.832**	-0.727**	-0.830**	ns	-0.919**	-0.873**
Al	-0.832**	-0.795**	-0.787**	ns	-0.779**	-0.862**
K	ns	ns	ns	ns	ns	ns

	Mo	Si	P	Al	K
Cu	ns	-0.706*	ns	ns	ns
Zn	ns	ns	ns	-0.628*	ns
Fe	+0.779**	ns	+0.762**	ns	ns
Mn	+0.700*	ns	ns	ns	ns
Ca	ns	ns	ns	ns	ns
Mg	ns	ns	ns	ns	ns
Mo	ns	ns	ns	ns	ns
Si	-0.696*	ns	ns	ns	ns
P	-0.678*	ns	ns	ns	ns
Al	-0.722**	ns	+0.699*	ns	-0.666*
K	ns	ns	ns	ns	ns

*,** Significance at the 0.05 and 0.01 levels of probability, respectively.
ns = not significant

Table 21. Simple correlation coefficients for the relationships between the concentration of NaOAc extractable nutrients and nutrient uptake by rice grcwn in a flooded Oxisol at pH 6.5 over all Eh levels.

NaOAc extract. nutrient	Nutrient uptake					
	Cu	Zn	Fe	Mn	Ca	Mg
Cu	ns	ns	ns	ns	ns	ns
Zn	ns	ns	+0.685*	ns	ns	+0.627*
Fe	+0.837**	+0.829**	+0.864**	ns	+0.802**	+0.907**
Mn	ns	ns	ns	ns	ns	ns
Ca	-0.705*	ns	-0.666*	ns	-0.821**	-0.703*
Mg	-0.622*	+0.889**	ns	ns	-0.766**	-0.641*
Mo	+0.931**	+0.834**	+0.909**	+0.626*	+0.842**	+0.883**
Si	+0.794**	+0.816**	+0.809**	ns	+0.629*	+0.738**
P	+0.862**	+0.868**	+0.832**	+0.633*	+0.815**	+0.845**
AL	+0.824**	ns	+0.861**	ns	+0.709*	+0.790**
K	ns	ns	ns	ns	ns	ns
	Mo	Si	P	Al	K	
Cu	ns	ns	ns	ns	ns	
Zn	ns	ns	+0.823**	ns	+0.779**	
Fe	+0.637*	ns	+0.823**	ns	+0.666*	
Mn	ns	ns	ns	ns	ns	
Ca	ns	ns	ns	ns	ns	
Mg	ns	ns	+0.772**	ns	ns	
Mo	+0.931**	ns	+0.791**	ns	ns	
Si	+0.847**	ns	+0.705*	ns	ns	
P	+0.798**	ns	+0.702*	ns	ns	
AL	+0.851**	ns	ns	ns	ns	
K	ns	ns	ns	ns	ns	

*,** Significance at the 0.05 and 0.01 levels of probability, respectively.
ns = not significant.

Table 22. Simple correlation coefficients for the relationships between ion activity and nutrient uptake in a flooded Oxisol under reduced and oxidized conditions over all pH levels.

Ion activity (mole/L)	Nutrient uptake (mg/pot)										
	Cu	Zn	Fe	Mn	Ca	Mg	Mo	Si	P	Al	K
Reduced											
Zn	+0.689*	ns	+0.863**	ns	ns	ns	-0.626*	ns	-0.891**	ns	-0.758**
Fe	+0.716**	+0.768**	+0.976**	ns	ns	ns	ns	ns	-0.827**	ns	ns
Mn	+0.743**	+0.846**	+0.982**	ns	+0.644*	ns	ns	ns	-0.753**	ns	ns
Ca	-0.838**	-0.867**	-0.840**	ns	-0.717**	ns	ns	ns	+0.614*	ns	ns
Mg	-0.819**	-0.873**	-0.847**	ns	-0.762**	ns	ns	ns	ns	-0.622*	ns
Si	ns	+0.719**	+0.954**	ns	ns	ns	ns	ns	-0.782**	ns	ns
P	-0.939**	-0.695*	-0.799**	ns	ns	ns	ns	ns	ns	ns	ns
Al	-0.788**	-0.718**	ns	ns	-0.713**	ns	ns	ns	ns	ns	ns
K	ns	-0.617*	-0.625*	ns	ns	ns	ns	ns	ns	-0.670*	ns
Oxidized											
Zn	-0.831**	-0.932**	-0.710**	-0.848**	-0.932**	ns	ns	ns	ns	ns	-0.876**
Fe	ns	-0.742**	ns	-0.899**	-0.620*	ns	+0.713**	ns	ns	ns	ns
Mn	ns	+0.710*	ns	+0.934**	ns	ns	-0.835**	ns	ns	ns	ns
Ca	-0.900**	-0.790**	-0.868**	ns	-0.951**	-0.882**	ns	-0.668*	-0.670*	-0.782**	-0.923**
Mg	ns	ns	ns	ns	-0.682*	ns	ns	ns	ns	ns	ns
Si	ns	-0.752**	ns	-0.885**	-0.699**	ns	ns	ns	ns	ns	ns
P	-0.708*	-0.902**	ns	-0.912**	-0.872**	ns	ns	ns	ns	ns	-0.766**
Al	+0.835**	+0.867**	+0.724**	+0.692**	+0.782**	+0.630*	ns	ns	ns	ns	+0.828**
K	ns	ns	ns	-0.768**	ns	ns	+0.660*	ns	ns	ns	ns

*,** Significance at the 0.05 and 0.01 levels of probability, respectively.
ns = not significant.