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Effects of Liming, Soil-Moisture Regimes, Application of Sulfur and Some Micronutrients on Nutrients Availability in Soil-Plant System and Yield of Rice in Acid Alluvial Soil

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Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

Original Research Article

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ABSTRACT

The productivity of wetland rice is constrained by the reduced availability of sulfur (S) and micronutrients like boron (B), copper (Cu), and zinc (Zn) in acid alluvial soil of West Bengal, India. A greenhouse study was conducted for two seasons (wet and winter 2007) using acid alluvial soil (Inceptisol, Durgapur, Silty loam) to evaluate the effects of liming, soil moisture regime and application of sulfur, boron, copper and zinc on the availability of applied nutrients, growth and yield of rice. The effects of application of lime (2.0 t/ha) over no lime; alternate flooding and drying (AFD) over continuous flooding (CF) and moisture regime maintained at field capacity (FC); and nutrients viz., S, B, Cu and Zn on growth and yield of rice were assessed. Rice cv. International Rice 36 (IR 36) was grown with N:P:K applied at the rate of 60:30:30 mg /kg of soil. S, B, Cu, and Zn were applied at the rate of 10, 0.5, 1.5 and 5 mg/kg of soil, respectively. Application of 22.4 kg S, 1.12 kg B, 3.36 kg Cu, and 11.2 kg Zn/ha significantly enhanced the growth and yield of rice over control in alluvial soil. Yield response of rice to the application of S, B, Cu and Zn was further improved (22.15%) by liming and alternate flooding and drying during the growing season.

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1. INTRODUCTION

The productivity of rice in India is oscillating around 2 tons per hectare under rainfed condition [1] however; the estimated yield potential of the crop is 15 tons per hectare [2].

There is a large variation among national average yield with a factor of 5 to 6 tons per hectare among industrialized and developing countries [3]. World rice production in 2008 was approximately 661 million tons and about 90 percent produce in Asia [4]. In submerged acid soils, the reduced availability or deficiency of S and micronutrients has often been made up by their soil application at appropriate rates to boost the production of rice. The multi-nutrient stress of rice grown in Fe toxic soil has been improved by use of balanced fertilization [5]. In majority of Indian soils, application of Zn at the rate of 11kg Zn per hectare has been found to be adequate for rice [6]. The deficiency of Cu in some Indian soils has been successfully corrected for rice crop by its soil application at an optimal rate of 12.5kg Cu per hectare. In B deficient soils of eastern and northern India, spectacular responses of cereals including rice have been obtained by the soil application of B at 0.5-2.5kg/ha [7].

Management of Sulfur nutrition of rice varies depending whether the soil is submerged. Sulfur deficiency has emerged as an important factor-affecting yield and grain quality of rice. In S deficient soils of India, soil application of S at the rate of 20-40 kg/ha has been found to be highly economical for rice [8]. Research is needed to develope optimal sulfur nutrient management for the emerging water saving production system where soil redox potential system fluctuates over time, affecting the mineralization of organically bound sulfur and changing the stability of reduced or oxidized forms of sulfur [9].

Periodic lime addition is recommended for naturally acidic agricultural soil as soil pH affect nutrient availability and the toxicity of elements such as Al [10]. Al toxicity problems will be enhanced during drought period as soil becomes oxidized and pH falls [11]. Air dry acid alluvial soil contain toxic concentration of aluminum and Al toxicity problem will be enhanced during drought period as soil become oxidized and pH fall [12]. Alluvial soil contained a high level of exchangeable Al under air dry conditions [13]. In order to increase the availability of micronutrients to rice, one could try to manipulate some of the factors that affect the availability of micronutrients in soils, such as pH by liming, redox potential by irrigation and drainage [14]. Rice yield can be enhanced threefold by draining the soil for 9 days 1 month after planting. The water-soluble Fe content is considerably reduced by flooding and draining, and this reduction in soluble Fe substantially increased the grain yield of rice. There is limited work on how liming changes the concentration of iron, manganese and aluminum in acid soils and controls the changes in pH and Eh, which in turn effect the availability of micronutrient and sulfur to rice under varying soil moisture regime. Considering the above facts, a pot experiment under greenhouse conditions was carried out to evaluate the effects of liming, soil moisture regime and application of S and few selected micronutrients (B, Cu and Zn) on soil and plant availability of S, B, Cu and Zn as well as on growth and yield of rice.

2. MATERIALS AND METHODS

2.1 Characterization of Soil

The growth and yield responses of rice were assessed in two seasons wet (June to September) and winter (November to February) season, 2007-08 in a controlled greenhouse experiment with the acid alluvial soil (Inceptsols, sub-order or great group is USTEPTS, Durgapur Silty loam). Bulk soil samples of Durgapur Clay loam soils were collected from the surface layer (0-20 cm) of the rice fields at Durgapur, West Bengal, India. The soils were air dried and processed. A uniform quantity of 5 kg processed soil was taken and filled in a series of plastic pots. Some soil physico-chemical properties were selected and given in Table 1. The pH, organic carbon and organic matter of soil is 5.2, 5.4 g kg^{-1} and 9.31 g kg^{-1} respectively. Soil particle size was examined by hydrometer method [15]. Soil pH was measured in a 1:2.5 soil to distilled water ratio using pH meter and soil cation exchange capacity was measured by using ammonium accetate leachate method [16]. The soil and ambient temperature was 27-29ºC and 25-27ºC in wet and 19-21ºC and 18-20ºC in winter respectively. Organic carbon and organic matter was determined by rapid titration method [17]. Total content of S, B, Cu, Zn, Fe, Mn and Al in this soil were determined using anhydrous Na_2CO_3 fusion method [16]. Available S in exchangeable form was determined by 0.15% $CaCl_2$ extractable method [18]. Soil available B was determined by hot water extractable method [19]. Soil available Cu, Zn, Fe and Mn were estimated in exchangeable and organic bonded form by 0.005 MDTPA (pH 7.3) extractable method [20]. Soil available Al in exchangeable form was determined by 1 N KCL extractable method [21]. Lime requirement in alluvial soil were evaluated by pH buffer method. The equilibrium pH method for lime requirement was adopted considering the buffer capacity of soil [16]. For each treatment combination, the levels of N, P and K were applied at 120 kg/ha N, 60 kg/ha P_2O_5 and 60 kg/ha K_2O. N, P, K, S, Zn, Cu and B were applied respectively in the form of Analar grade urea ($CO(NH_2)_2$), potassium di-hydrogen orthophosphate (KH_2PO_4), potassium chloride (KCl), calcium sulfate (Ca SO_4, $2H_2O$), zinc sulfate (Zn SO_4, $7H_2O$) copper sulfate (Cu SO_4, $5H_2O$) and borax ($Na_2B_4O_7$, $10H_2O$) respectively. All the treatments were replicated thrice in the experiment. Ten numbers of 10 days old rice seedlings of rice cv. IR-36, were transplanted in each plastic pot. After seven days, the numbers of plants were thinned to 4. Three moisture regims were maintained i.e. field capacity (FC), continuous flooding (F) and alternate flooding and drying (AFD). At field capacity 25% moisture and in continuous flooding 5±1 cm standing water were maintained. In AFD condition the soil was flooded with 5±1 cm standing water for 8 days followed by 50% moisture condition for seven days. Field Capacity (FC) and Alternate Flooding and Drying (AFD) soil moisture regimes were maintained with the help of tensiometers placed upto 10 cm. The details of the treatments are enumerated below:

2.1.1 Treatments

Main Treatments

L_0 = Soil without liming
L_1 = Soil with liming at the rate of 2 tons ha^{-1}

Sub-Treatments

FC = Field Capacity (0-30 kPa soil matric potential)

CF = 5±1 Flooding
AFD = Alternate Flooding (5±1) and Drying (30 kPa soil matric potential)

2.1.2 Sub-sub Treatments

C = Control (without S, B, Cu and Zn)
S = at the rate of 10 mg kg^{-1} soil

S+B at the rate of 10 mg S kg^{-1} soil + 0.5 mg B kg^{-1} soil
S+Cu at the rate of 10 mg S kg^{-1} soil + 1.5 mg Cu kg^{-1} soil
S+Zn at the rate of 10 mg S kg^{-1} soil+ 5 mg Zn kg^{-1} soil
S+B+Cu+Zn at the rate of 10 mg S + 0.5 mg B+ 1.5 mg Cu + 5 mg Zn per kg soil

Table 1. Physico-chemical properties of soil (0-20 cm)

Sl no.	Properties	Value
1	Sand %	49.0
2	Silt %	31.2
3	Clay %	19.8
4	pH	5.2
5	CEC (Cmolckg^{-1})	7.19
6	Organic carbon (g kg^{-1})	5.4
7	Organic matter (g kg^{-1})	9.31
8	Total S (mg kg^{-1})	303
9	Total B (mg kg^{-1})	18.02
10	Total Cu (mg kg^{-1})	12.50
11	Total Zn (mg kg^{-1})	25.39
12	Total Fe (mg kg^{-1})	12500
13	Total Mn (mg kg^{-1})	167
14	Total Al (mg kg^{-1})	48650

2.2 Soil and Plant Analysis

Soils and plants were analysed 60 and 120 days after rice planting for soil availability and plant concentration of S, B, Cu, and Zn. After 60 days of planting, 2 rice plants from each treatment combination were harvested for the analysis of available micronutrients and sulfur. About 50 grams soil sample was also collected from each treatment combination for the analysis of available micronutrients and sulfur. Finally after the attainment of maturity, the remaining two rice plants were harvested, threshed and sampled separately for grain and straw. Soil samples weighing 50 g were collected at the harvest time from each treatment combination. The samples of soil, plant (after 60 days) grain and straw were analyzed for available sulfur and micronutrients.

The plant samples including the straw and grains of rice plants, were washed with double distilled water, dried in air and then in oven at 70ºC, and ground by pestle and mortar. One gram processed plant sample was taken in a 100 ml conical flask and digested with a diacid mixture (HNO_3: $HClO_4$::10: 4) on hot plate for the analyses of sulfur, copper, zinc, iron and manganese. For boron, 0.5 g processed plant sample was taken in a quartz dish and dry ashed in muffle furnace at 550ºC overnight and cooled. 10 ml of 0.1 M HCl was added in the quartz dish to dissolve the dry ash. The solution was covered by glass and allowed to stand for 4 hours. Subsequently, it was filtered into a test tube. The diacid extract of plant sample was analyzed for copper, zinc, iron and manganese with the help of Atomic Absorption Spectrophotometer (Pye-Unicam-SP-9, 800, made in U.K). For boron, 0.1 M hydrochloric acid extract was analyzed calorimetrically with the help of autoanalyser (CFA system 4, Chemlab, made in U.K.) by using Azomethine – H indicator [22]. The plant extract was analyzed for sulfur by the turbidimetric method using a colorimeter. A series of known five standards of S, B, Cu, Zn, Fe, Mn and Al were used to compare as reference of the soil and plant samples.

2.3 Statistical Analyses

Statistical analyses were performed with the help of the MSTAT computer package to estimate the regression equations relating dependent variables with independent variables. In order to test the significance of different treatments individually as well as in combinations, ANOVA was performed on the experimental data for the split-split plot design by the method described by Gomez and Gomez [23]. The comparisons between the treatment means were tested and least significant difference (LSD) were calculated at 5% and 1% level of significance.

3. RESULTS AND DISCUSSION

3.1 Growth and Yield of Rice

The growth and yield of rice under FC moisture regime were significantly lower (40.3% from flooding and 45.5% from AFD moisture regimes) than those under flooding and AFD moisture regimes. Although soil and plant availability of S, B, Cu, Zn, Fe and Mn were higher under FC than F moisture regime, the growth and yield of rice increased under F regime due to increased availability of moisture and macronutrients. Higher growth and yield of rice under AFD than F regime are attributed to the greater availability of S, B, Cu and Zn under AFD compared to F moisture regime (Tables 2, 3, 4, 5). The growth responses of rice to liming (5% more from unlimed soil), soil moisture regime and application of S, B, Cu and Zn are, presented in Table 6. The responses of yield attributes: 1000 grain weight and straw yield per plant, to liming were not favourable. The grain yield per plant in limed soil was not significantly higher than that in unlimed soil in wet season. However, in winter season the grain yield per plant in limed soil was significantly higher than unlined soil. This unfavourable response of growth and yield parameters of rice to liming in alluvial soil is ascribed to the decreases in soil and plant availability of S, Cu and Zn, (Table 2, 4, 5) due to liming.

The growth and yield parameters of rice were significantly affected by soil moisture regime. The maximum growth and yield of rice were observed under AFD moisture regime closely followed by those under continuous flooding (F) in alluvial soils (Table 6).

The data presented in Table 6 reveal that the growth and yield of rice in acid alluvial soil of West Bengal, India, responded significantly to the application of S, B, Cu and Zn either singly or in combination. Grain yield per plant of rice under the treatments of S, S+B, S+Cu, S+Zn, S+B+Cu+Zn were significantly higher (9, 14, 17, 16 and 20% respectively) compare to control in alluvial soil. In alluvial soil the treatments of S+B, S+Cu, S+Zn and S+B+Cu+Zn treated plots resulted in higher grain yield than other treatments. The maximum grain yield in alluvial soil occurred under S+B+Cu+Zn closely followed by that under S+Cu. The results on the yield responses of rice to the application of S and micronutrients thus indicate that application of Cu and Zn in alluvial soil, are essential for the maximum yield of rice as it is reported [1] that in perennial S deficient soils of India, soil application of S at the rate of 20-40 kg/ha through S containing fertilizers has been found to be highly economical for rice.

Table 2. Effects of liming, soil moisture regime and application of S and micronutrients on S content of soil and rice plant in alluvial soil (wet & winter season, 2007-08)

Treatments	Concentration of sulfur (mg kg^{-1})					
	Soil (120 days) (after 120 days)		Straw (after 120 days)		Grain (after 120 days)	
	Wet	Winter	Wet	Winter	Wet	Winter
Unlimed	27.46	27.79	2210	2171	1764	1715
Limed	18.14	18.88	2004	1834	1555	1446
LSD (0.05)	**0.97**	**0.40**	**10.42**	**10.22**	**18.80**	**12.07**
Field Capacity	23.46	24.02	2193	2063	1858	1743
Flooding	21.81	22.41	2030	1937	1540	1466
Alternate flooding and	23.12	23.57	2098	2009	1579	1532
LSD (0.05)	**0.10**	**0.15**	**7.08**	**3.98**	**6.82**	**8.24**
Control	17.45	17.23	1956	1894	1574	1523
S	21.93	22.13	2140	2043	1718	1568
S + B	25.26	25.74	2131	2049	1675	1597
S + Cu	25.60	26.49	2117	2036	1672	1604
S + Zn	22.03	23.23	2130	1966	1645	1599
S + B + Cu + Zn	24.50	25.17	2168	2029	1671	1591
LSD (0.05)	**0.27**	**0.30**	**10.58**	**6.06**	**7.57**	**7.36**

Table 3. Effects of liming, soil moisture regime and application of S and micronutrients on B content of soil and rice plant in alluvial soil (wet & winter season, 2007-08)

Treatments	Concentration of boron (mg kg^{-1})					
	Soil (120 days) (after 120 days)		Straw (after 120 days)		Grain (after 120 days)	
	Wet	Winter	Wet	Winter	Wet	Winter
Unlimed	0.31	0.29	27.79	26.29	23.54	22.68
Limed	0.45	0.41	28.45	27.24	25.55	23.41
LSD (0.05)	**0.01**	**0.01**	**0.09**	**0.22**	**0.11**	**1.11**
Field Capacity	0.38	0.34	28.02	26.71	23.78	22.89
Flooding	0.37	0.33	27.45	26.11	23.48	22.09
Alternate flooding and drying	0.40	0.37	28.88	27.47	26.36	24.16
LSD (0.05)	**0.002**	**0.01**	**0.34**	**0.35**	**0.10**	**0.43**
Control	0.37	0.34	25.13	24.94	22.66	20.79
S	0.35	0.32	25.32	23.23	22.64	20.71
S + B	0.45	0.39	33.02	30.56	27.12	26.06
S + Cu	0.33	0.30	26.33	26.01	23.81	22.74
S + Zn	0.31	0.29	26.60	26.19	23.78	23.13
S + B + Cu + Zn	0.46	0.45	32.30	29.65	27.26	24.85
LSD (0.05)	**0.01**	**0.01**	**0.36**	**0.71**	**0.15**	**0.36**

Table 4. Effects of liming, soil moisture regime and application of S and micronutrients on Cu content of soil and rice plant in alluvial soil (wet & winter season, 2007-08)

Treatments	Concentration of copper (mg kg^{-1})					
	Soil (120 days) (after 120 days)		Straw (after 120 days)		Grain (after 120 days)	
	Wet	Winter	Wet	Winter	Wet	Winter
Unlimed	1.466	1.46	10.02	9.19	6.58	6.11
Limed	0.99	0.99	8.78	8.25	5.96	5.24
LSD (0.05)	**0.04**	**0.02**	**0.05**	**0.02**	**0.15**	**0.04**
Field Capacity	2.04	2.056	11.48	10.21	7.16	6.16
Flooding	0.78	0.78	7.74	7.28	5.29	4.95
Alternate flooding and drying	0.85	0.84	8.98	8.67	6.37	5.91
LSD (0.05)	**0.02**	**0.02**	**0.08**	**0.02**	**0.05**	**0.03**
Control	0.72	0.74	9.11	7.69	5.98	4.41
S	0.70	0.69	8.50	8.24	5.64	5.39
S + B	0.67	0.66	8.24	8.45	5.15	5.81
S + Cu	2.30	2.32	10.90	9.99	7.70	6.85
S + Zn	0.63	0.62	8.12	7.62	5.23	5.02
S + B + Cu + Zn	2.82	2.32	11.53	10.33	7.93	6.57
LSD (0.05)	**0.02**	**0.01**	**0.06**	**0.02**	**0.06**	**0.03**

Table 5. Effects of liming, soil moisture regime and application of S and micronutrients on Zn content of soil and rice plant in alluvial soil (wet & winter season, 2007-08)

Treatments	Concentration of Zinc (mg kg^{-1})					
	Soil (120 days) (after 120 days)		Straw (after 120 days)		Grain (after 120 days)	
	Wet	Winter	Wet	Winter	Wet	Winter
Unlimed	2.13	2.04	57.49	47.25	24.92	22.59
Limed	1.19	1.19	48.84	43.84	21.94	20.15
LSD (0.05)	**0.08**	**0.05**	**0.39**	**0.08**	**0.14**	**0.53**
Field Capacity	2.10	2.02	59.39	47.06	24.79	22.78
Flooding	1.29	1.27	49.11	43.83	21.49	19.53
Alternate flooding and drying	1.59	1.54	50.99	45.74	24.00	21.81
LSD (0.05)	**0.02**	**0.01**	**0.15**	**0.06**	**0.11**	**0.35**
Control	0.73	0.52	43.48	42.34	21.49	20.80
S	0.62	0.60	41.76	42.50	21.56	22.15
S + B	0.69	0.67	51.25	42.27	21.62	18.69
S + Cu	0.75	0.73	50.61	41.02	22.10	17.50
S + Zn	3.41	3.52	66.37	52.80	27.00	24.76
S + B + Cu + Zn	3.74	3.63	65.51	52.34	26.80	24.34
LSD (0.05)	**0.04**	**0.03**	**0.18**	**0.13**	**0.12**	**0.46**

Table 6. Effects of liming, soil moisture regime and application of Sulfur and micronutrients on growth and yield of rice in alluvial soil (wet and winter Season, 2007-08)

Treatments		Plant height at panicle initiation		Number of tillers per plant		Number of grains per panicle		1000 grain weight (g)		Straw yield per plant (g)		Grain yield per plant (g)	
		Wet	Winter	Wet	Winter	Wet	Winter	Wet	Winter	Wet	Winter	Wet	Winter
Liming	Unlimed	101.3	87.5	9.0	12	128	112	21.31	21.86	12.91	25.38	12.47	17.14
	Limed	106.1	92.8	9.0	11.0	157	118	21.19	21.79	11.96	22.14	12.77	18.47
LSD (0.05)		**0.44**	**0.14**	**0.24**	**0.34**	**4.70**	**1.96**	**0.14**	**0.18**	**0.08**	**0.17**	**0.32**	**0.17**
Soil moisture regime	Field Capacity	99.8	85.0	7.0	11.0	116	104	19.59	20.17	9.92	20.75	8.47	11.63
	Flooding	103.6	91.7	10	11.0	148	115	21.66	22.19	13.13	25.09	14.15	19.98
	AFD	107.8	93.8	10	12.0	164	127	22.50	23.13	14.26	25.44	15.24	21.81
LSD (0.05)		**1.00**	**0.92**	**0.36**	**0.56**	**6.63**	**1.22**	**0.14**	**0.12**	**0.25**	**0.24**	**0.21**	**0.23**
Applications of nutrients	Control	99.2	86.6	8.0	10.0	131	107	20.03	20.50	11.40	21.66	11.00	15.46
	S	103.9	88.8	9.0	11.0	137	112	21.10	21.74	12.22	22.13	12.18	16.83
	S + B	102.6	91.2	9.0	12.0	145	115	21.36	21.98	12.47	23.23	12.33	18.39
	S + Cu	104.2	90.7	9.0	12.0	150	115	21.32	21.93	12.48	23.89	13.22	18.67
	S + Zn	105.4	92.0	9.0	12.0	143	121	21.53	22.16	12.63	25.57	12.85	18.63
	S + B + Cu + Zn	106.9	91.7	11.0	14.0	150	123	22.15	22.66	13.43	26.06	14.13	18.84
LSD (0.05)		**0.46**	**0.60**	**0.32**	**0.44**	**3.73**	**1.25**	**0.25**	**0.19**	**0.39**	**0.26**	**0.66**	**0.26**

3.2 Nutrients Availability

In continuous flooding there was increase in pH value approaching to neutral in acid alluvial soils. In submersed acid soil under rice cultivation due to low redox potential (Eh) and pH around 7 lead to non availability of S, Cu and Zn [24].

3.3 Sulfur

It is seen from the tables that liming at the rate of 2 tons ha^{-1} significantly decreased S concentration in alluvial soil. S concentration in rice plant after 60 days of growth period as well as in straw and grain at harvest were also significantly reduced due to liming. S concentration in soil, plant, straw and grain was also significantly affected by soil moisture regime in alluvial soil. S concentration in soil under flooding was significantly lower than those under FC and AFD moisture regimes. The concentration of S under FC was, in general, significantly higher than those under AFD. Sulfur deficiency has found as an important that affects yield and grain quality of rice. In S deficient soils of India, soil application of S at the rate of 20-40 kg/ha has been found to be highly economical and beneficial for rice [8]. A similar study is conducted by Bell and Dell, 2008 [9] and found that in submerged soil access to sulfur is limited by the slower mineralization of organically bound sulfur and shallow root system with more than 90% of root confined to the top 20 cm of the soil. Low redox potential causes reduction of sulfates to sulfides, some of which are toxic (H_2S) and other low in solubility (FeS, ZnS). Moreover the slower mineralization of organically bound sulfur decreases the availability of sulfur to rice in submerged soils. Hence, sulfur deficiency has increase in prevalence in wet land rice under changing.

3.4 Boron

The data on concentration of Hot water soluble B in soil as well as in plant, straw and grains as analysed in wet and winter season experiments are presented in Table 3. It is apparent from the tables that the concentration of available B in soil, plant, straw and grains were significantly increased by the application of the lime at the rate of 2 tons ha^{-1} in and alluvial soils as it is also suggested [21] that periodic lime addition is recommended for naturally acidic agricultural soil as soil pH affect nutrient availability and the toxicity of elements such as Al. In response to effect of liming the plant available concentration of S, Cu, Zn, Fe and Mn decreased in alluvial soil. However, the concentration of plant available B was not significantly affected by liming in alluvial soil. The availability of B may increase with increase in pH due to either liming or flooding of soil in the neutral range of pH [22]. Spectacular responses of cereals including rice have been obtained by B application at the rate of 0.5-2.5 kg/ha in B deficient soils of eastern and northern India [7]. Increases in B concentration in limed soils are attributed to the increase in pH on liming. The concentration of B in rice plant, straw and grains was also significantly affected by soil moisture regime. B concentration under flooding was significantly lower (5% probability level) than those under FC and AFD soil moisture regimes in alluvial soil. AFD moisture regime induced significantly higher concentration of available B in soil, rice plant, straw and grains compared to flooding and FC regimes in alluvial soil. This increase in B concentration in soil and rice plant under AFD may be ascribed to decrease in available Fe under this moisture regime.

3.5 Copper

Application of lime at the rate of 2 tons ha^{-1} significantly decreased the concentration of available Cu in alluvial soil (Table 4). In alluvial soil due to high clay and organic matter content, the soil fractions of available Cu are more strongly adsorbed and not becoming available to rice plant. Due to this the Cu concentration in straw and grains decreased on liming in alluvial soil. The availability of Cu in soil and rice plant was significantly influenced by soil moisture regime. In alluvial soil, the concentration of Cu in soil, plant, straw and grain was significantly lower under flooding than FC and AFD moisture regimes. The flooded rice soils may develop unfavourable soil conditions that reduce the availability of Cu due to high concentration of iron, manganese, sulfide and dissolved carbon dioxide. As the redox potential decreases under flooding condition, insoluble sulfides of Cu may be formed, which make these elements unavailable to rice plant [24]. However, when the submerged soils are drained off and redox potential increases, the formation of insoluble sulfides is restricted and as a result the availability of Cu increases [24]. Such increase in redox potential, which occurs under FC and AFD moisture regimes, helps decrease the soil and plant availabilities of Fe and Mn. Due to decrease in the availability of Fe and Mn, the reduction in the availability of B, Cu and Zn as affected by Fe and Mn is also restricted. The concentration of available Cu under AFD moisture regime was significantly higher than that under flooding. The maximum concentration of Cu in soil, plant, straw and grain was however observed under field capacity regime.

3.6 Zinc

Application of lime at the rate of 2 tons ha^{-1} significantly decreased the available concentration of Zn in soil and rice plant after 60 days of growth period in alluvial soil (Table 5). Soil availability of Zn after 120 days of growth period was also significantly lower in limed than unlimed soil. As the redox potential decreases under flooding condition, insoluble sulfides of Zn is generated, which is responsible for unavailablity of these elements to rice plant [22]. Zinc uptake can be inhibited by strong adsorption of Zn^{2+} on Fe hydroxide precipitate as iron plaque on rice root [25]. The trends of Zn availability in rice straw and grains as affected by liming in alluvial soil were similar to those observed with Cu. The concentration of Zn in rice straw and grain on maturity was significantly lower in limed than unlimed alluvial soil. As discussed for Cu, the organic complexed and amorphous fractions of Zn, which were adsorbed on Fe and Mn hydroxides in alluvial soil, were more strongly adsorbed and not easily available to rice plant due to high clay and organic matter content. Soil and plant availability of Zn was also significantly affected by soil moisture regime. The available concentration of Zn in soil, plant, straw and grains was significantly lower under flooding than FC and AFD regimes in alluvial soil. Zn concentration under AFD was significantly higher than flooding. However, FC regime induced the maximum availability of Zn in soil and rice plant.

Application of Zn at the rate of 5 mg kg^{-1} of soil along with S significantly enhanced the concentration of Zn in soil, rice plant, straw and grains over control in alluvial soils and the similar finding is also reported [6] that application of Zinc at the rate of 11.2 kg per hectare is adequate for rice. Application Zn along with S, B and Cu also significantly enhanced Zn availability in soil, plant, straw and grain.

3.7 Relationships of Nutrients Availability in Soil and Plant

The soil available concentration of S, B, Cu and Zn under different treatments of nutrient applications: S, S+B, S+Cu, S+Zn, S+B+Cu+Zn in limed and unlimed soils were regressed with their concentration in rice plant after 60 days of growth. The linear correlation coefficients for these relationships are presented in Table 7 for alluvial soil. In alluvial soil 0.15% $CaCl_2$ extractable S was highly significantly related with plant concentration of S in limed soil, but the relationship was not highly significant in unlimed soil when S was applied along with B or Cu or Zn or with the combination of B, Cu and Zn [25]. The results indicate that in unlimed soil where the S availability is relatively high, S possibly forms complexes with micronutrients [9]. Hot water extractable B was highly significant related with the plant concentration of B unlimed and limed alluvial soil, particularly under the treatments where B was applied either with S or with the combination of S, Cu and Zn. Similar was the trend observed with Zn. This table also indicates that in case of Cu and Zn, the values of correlation coefficient for the relationships of DTPA extractable soil concentration and plant concentration increased generally on liming.

The available soil concentration of S, B, Cu and Zn under different nutrient applications: S, S+B, S+Cu, S+Zn, S+B+Cu+Zn in limed and unlimed soils were also regressed with their concentration in rice straw and grains [24]. The linear correlation coefficients for these relationships are presented in Table 8 for alluvial soil. As observed with the plant concentration of S, the S concentration in rice straw and grains was also highly significant related with 0.15% $CaCl_2$ extractable S in unlimed alluvial soil. However, in limed soil the relationships became weaker when S was applied with Zn or particularly in grains [25]. Hot water extractable B was found to be highly significantly related with concentration of B in straw and grains under the treatments where B was applied either singly or combination with other nutrients in limed and unlimed alluvial soil.

In general, similar were the trends observed for the relationships of plant concentration of Cu and Zn with DTPA extractable Cu and Zn [24].

The findings of these regression analyses indicate that the available soil concentration of S, B, Cu and Zn extracted respectively by 0.15% CaCl2, hot water and DTPA, were significantly related with their concentration in plant, straw and grains of rice. This confirms the suitability of these extractants in acid alluvial soil. Significant relationships between soil and plant concentration under different treatments of S, B, Cu and Zn applications also point to the favorable response of rice plants to the application of S, B, Cu and Zn.

Table 7. Linear correlation coefficients (r) for the relationships of soil available S, B, Cu and with their concentration in rice plant after 60 days of growth in alluvial soil (wet season, 2007-08)

Concentration of available nutrient in soil	**Application of Nutrients**				
	S	**S + B**	**S + Cu**	**S + Zn**	**S + B + Cu + Zn**
	Concentration in plant				
	Unlimed				
	Sulfur				
0.15% $CaCl_2$ – extractable S	0.769***	0.543*	0.539*	0.471*	0.474*
	Boron				
Hot water – extractable B	0.420	0.643**	0.700**	0.695**	0.892***
	Copper				
DTPA – extractable Cu	0.527*	0.291	0.912***	0.676**	0.892***
	Zinc				
DTPA – extractable Zn	0.624**	0.419	0.635**	0.888***	0.873***
	Limed				
	Sulfur				
0.15% $CaCl_2$ – extractable S	0.753***	0.917***	0.897***	0.794***	0.873***
	Boron				
Hot water – extractable B	0.721***	0.926***	0.589*	0.209	0.819***
	Copper				
DTPA – extractable Cu	0.982***	0.917***	0.906***	0.917***	0.892***
	Zinc				
DTPA – extractable Zn	0.822***	0.864***	0.755***	0.793***	0.737***

, ** and * significant at the 0.05, 0.01 and 0.001 probability levels, respectively.*

Table 8. Linear correlation coefficients (r) for the relationships of available S, B, Cu and Zn concentration in rice straw and grain in alluvial soil (wet season, 2007-08)

Concentration of available nutrient in soil	Application of Nutrients									
	S	S+B	S+Cu	S+Zn	S+B+Cu+Zn	S	S+B	S+Cu	S+Zn	S+B+Cu+Zn
	Concentration in straw					Concentration in grain				
	Unlimed									
	Sulfur									
0.15% $CaCl_2$ – extractable S	0.586*	0.615**	0.641**	0.598**	0.730***	0.474*	0.368	0.379	0.301	0.293
	Boron									
Hot water – extractable B	0.922***	0.660**	0.376	0.004	0.797***	0.939***	0.906***	0.286	0.038	0.945***
	Copper									
DTPA – extractable Cu	0.953***	0.928***	0.814***	0.967***	0.888***	0.894***	0.731***	0.888***	0.806***	0.890***
	Zinc									
DTPA – extractable Zn	0.762***	0.082	0.394	0.984***	0.965***	0.828***	0.922***	0.916***	0.792***	0.793***
	Limed									
	Sulfur									
0.15% $CaCl_2$ – extractable S	0.909***	0.913***	0.880***	0.943***	0.935***	0.594**	0.762***	0.769***	0.530*	0.823***
	Boron									
Hot water – extractable B	0.305	0.978***	0.077	-0.040	0.941***	0.218	0.730***	0.390	0.317	0.754***
	Copper									
DTPA – extractable Cu	0.976***	0.911***	0.880***	0.884***	0.930***	0.724***	0.712***	0.884***	0.776***	0.930***
	Zinc									
DTPA – extractable Zn	0.838***	0.481*	0.660**	0.890***	0.864***	0.909***	0.752***	0.746***	0.963***	0.978***

, ** and * significant at the 0.05, 0.01 and 0.001 probability levels, respectively.*

4. CONCLUSION

Soil available concentration of S, B, Cu and Zn under different treatments of nutrient application; S, S+B, S+Cu, S+Zn, S+B+Cu+Zn in limed and unlimed soils was, in general, significantly related with their plant concentration. In case of Cu and Zn, the relationship of DTPA extractable soil concentration with their plant concentration became stronger on liming. The significant relationships between soil and plant concentration under different treatments of S, B, Cu and Zn applications indicated favorable response of rice plants to the application of S, B, Cu and Zn and also confirmed the suitability of 0.15 CaCl2 and hot water as extractants of respectively S and B and 0.005 M DTPA (pH 7.3) as extractant of Cu and Zn in alluvial soil. Application of lime at the rate of 2.0 t/ha significantly increased plant height, number of tillers per plant and shoot height per plant in laterite soil. The grain yield in limed soil was not significantly higher than unlimed soil in wet Season. However, in winter season, the grain yield per plant was higher in limed than unlimed soil. The growth and yield parameters of rice were significantly affected by soil moisture regime. The maximum growth and yield of rice was observed under AFD moisture regime closely followed by F in alluvial soil. Application of S along with B, Cu and Zn in alluvial soil helped attaining the maximum grain yield of rice under AFD moisture regime. Application of S, B, Cu and Zn respectively at the rate of 22.4, 1.12, 3.36 and 11.2 kg/ha significantly enhances the growth and yield of rice over control alluvial soils. The yield response of rice to the application of S, B, Cu, Zn is improved by liming the soil and maintaining the moisture regime of alternate flooding and drying.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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