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Interaction effects of phosphorus and zinc on yield and nutritional quality of rice (*Oryza sativa*)

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Received: June 2019; Revised accepted: December 2020

ABSTRACT

A field experiment was conducted at Nadia, West Bengal, to evaluate the effect of different levels of phosphorus (P) and zinc (Zn) on the yield, soil P and Zn availability, P and Zn nutritional quality and also Zn recovery efficiency of boro rice (*Oryza sativa*). Combined application P and Zn enhanced increased the yield of rice, recording the highest in P₈₀Zn₁₀ treatment (P @ 80 kg/ha and Zn @ 10 kg/ha). Results showed significant increase in P : Zn ratio, grain phytic acid (PA) content and PA : Zn molar ratio with simultaneous decrease in Zn content and uptake by rice, Zn harvest index (Zn-HI), relative transfer of Zn from root to grain and also soil phosphatase activity (PA) in rice with P application up to the highest level (80 kg P/ha). The availability of applied Zn in soil was also reduced to some extent with higher rates of P application. However, Zn application significantly increased Zn content and uptake by rice and reduced the P : Zn ratio, grain PA content and PA : Zn ratio and ultimately enhanced the bioavailability of zinc in rice grains.

Key words: Inseptisol, Interaction, Phosphorus, Phytic acid, Rice, Zinc uptake

West Bengal, the rice bowl of the country (Chatterjee *et al.*, 2008) is one of the leading states for rice cultivation (accounting 5.46 million ha) in India. There is a need to step up the productivity of rice in West Bengal to meet the growing population of 91.28 million (Census of India, 2011), which could be achieved by intensification of rice cultivation rather than increasing the area. But with the intensification of rice cultivation and introduction of high-yielding varieties, coupled with concomitant usage of high doses of chemical fertilizers and low amount of organic manures over a period of time, the soils have been depleted of several micronutrients, especially that of zinc (Zn). Zinc deficiency has emerged as one of the major constraints in improving crop yields and reportedly covers 49% cultivated area of India and about 30% in West Bengal (Singh, 2009).

As in the case with plants and soils, Zn deficiencies are also the most widespread micronutrient deficiencies in humans and is the fifth most important risk factor of human disorders (Cakmak, 2008) affecting one-third of the world's population (approximately two billion people), particularly in developing countries where cereal grains are the staple food (for calorie and protein intake) with low concentration of bio-available Zn (Biesalski, 2013). An estimated 30% of the world's population experiences inadequate dietary Zn intake (Brown and Wuehler, 2000).

The increased use of phosphorus (P) fertilizers as well as fertilizers with less Zn-containing impurities can exacerbate Zn deficiency (Loneragan and Webb, 1993). Part of the P added to soil in fertilizer and manure is used by the plant in the year of application, while a substantial part accumulates in the soil as residual P, which contributes to P in the soil solution and be taken up by crops for many years. Continuous practice of farmers with higher doses of fertilizer application and rice cultivation leads to significant build-up of available phosphorus (Kuligod *et al.*, 2009). Excessive P fertilizer application can reduce Zn availability in soil (Mondal and Hazra, 2018) forming Zn₃(PO₄)₂.H₂O deposits. High soil P content can also inhibit Zn translocation from root to straw, especially to leaves, and leads to Zn deficiency in most of the crops (Alloway, 2008). There is also evidence that soil P has a

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negative effect on grain Zn concentration (Mondal *et al.*, 2017) and bioavailability.

Hence, the present investigation was undertaken to evaluate P–Zn interaction at various levels of phosphorus application with different levels of zinc, in soil and plant through field experiment by growing *boro* rice.

MATERIALS AND METHODS

The field experiment was conducted in New Alluvial soil (Aeric Haplaquept) at Central Research Farm of the Bidhan Chandra Krishi Viswavidyalaya, Gayeshpur, Nadia, West Bengal (22°58' N and 88°29' E) by growing rice (var. 'IET 4786') during the *boro* season of 2014 and 2015. Soil at the experimental site was Inceptisol and had sandy loam texture, pH 7.06, organic carbon 5.8 g/kg, available N 242.37 kg/ha, available P 32.41 kg/ha, available K 138.16 kg/ha and available Zn 0.796 mg/kg.

The experiment was laid out in factorial randomized block design with 3 replications and 12 treatment combinations, i.e. 3 treatments of Zn (0, 5 and 10 kg Zn/ha) applied through ZnSO₄·7H₂O and 4 treatments of P (0, 40, 60 and 80 kg P/ha) through single superphosphate. The Zn and P fertilizer was applied in soil at the time of land preparation through broadcast, followed by surface incorporation. Twentyfive-day-old rice seedlings were transplanted in the first fortnight of February in both the years. Nitrogen and potassium fertilizers were applied as per the recommended dose (100 and 60 kg/ha through urea and muriate of potash, respectively) in all the plots (size: 5 m × 4 m) of the experimental field. Half of the dose of nitrogen and entire amount of K were applied at the time of transplanting and the other half at tillering stage. The crop was grown by following the standard recommended practice and was harvested in the first fortnight of May during both the years.

Soil samples (0–15 cm) were collected at harvesting stage from each plot and were air-dried, ground, sieved through 2-mm nylon sieve and stored in for subsequent analysis. The available N in soil samples were determined by alkaline permanganate method (Subbiah and Asija, 1956). Soil-available P was extracted from the soil with 0.5 M NaHCO₃ (Olsen *et al.*, 1954) and available K in soil was determined by 1 N ammonium acetate using flame photometer (Hanway and Heidel, 1952). Available Zn in soil samples was extracted with DTPA-extractant and analysed in atomic absorption spectrophotometer (GBC Avanta) (Lindsay and Norvell, 1978).

Plant samples were harvested plot-wise and the yield was recorded separately for grain and straw after threshing, cleaning and air-drying. Representative samples of both grain, straw and root were collected and the samples were thoroughly washed with dilute hydrochloric acid followed

by distilled water, air-dried and further dried at 60°C until acquiring constant weight, ground in a Wiley Mill, sieved through 40 mesh sieve and stored for further analysis. The rice grain, straw and root samples were digested in a 3 : 10 mixture of perchloric and nitric acid and P concentration in the digest was determined by vanado-molybdo-phosphoric yellow colour method (Jackson, 1973) using spectrophotometer and Zn concentration in atomic absorption spectrophotometer. Phytic acid content of the grains was also estimated by extracting phytins (Ca or Mg phytates) with trichloroacetic acid (TCA) with subsequent precipitation of Fe-phytate on addition of FeCl₃ and measuring Fe concentration in the form of Fe (NO₃)₃ using atomic absorption spectrophotometer assuming a Fe : P ratio of 4 : 6 (Wheeler and Ferrel, 1971).

Zinc harvest index (Zn-HI) was calculated as Zn uptake by grain divided by Zn uptake by the total above-ground biomass. The phytic acid : Zn (PA : Zn) molar ratio, an indicator for Zn bioavailability in the harvested grains (Roohani *et al.*, 2012) was calculated by using 660 and 65 as molecular weight of phytic acid and Zn, respectively

$$\text{PA : Zn molar ratio} = \frac{\text{Phytic acid content (in mg/kg)}/660}{\text{Zn content (in mg/kg)}/65}$$

The zinc-use efficiency (ZUE) or apparent Zn recovery was calculated by subtracting Zn uptake in control plot from Zn treated plot per unit amount of Zn applied.

$$\text{ZUE (\%)} = \frac{[\text{Zn uptake in Zn treated plot (g/ha)} - \text{Zn uptake in control plot (g/ha)}]}{\text{Amount of Zn fertilizer applied (g/ha)}} \times 100$$

All the data obtained from 2 years study were statistically analysed using the F test for factorial randomized block design (Gomez and Gomez, 1984) and standard error of means (SEm±) and critical difference (CD) at 5% level of significance were calculated for determination of significance of difference between treatment means. The analysed data of the experiment were also pooled for the two years (2014 and 2015) are presented.

RESULTS AND DISCUSSION

Phosphorus and Zinc availability in soil

Application of Zn significantly increased the amount of DTPA-extractable Zn content in post-harvest soil (Table 1), confirming the findings of Shaheen *et al.* (2007), whereas application of P at higher rates caused a decrease in the applied soil Zn but the availability of native soil Zn showed no such change in its amount. Application of P fertilizer may lead to the formation of insoluble Zn₃(PO₄)₂ compound in soil solution (Das *et al.*, 2005) possessing solubility of 1.7 × 10⁻⁴ to 2.88 × 10⁻⁸/ml⁻¹ (Clever *et al.*, 1992),

causing such decrease in the amount of Zn. Phosphorus addition may increase negative charges at the soil colloidal surface leading to increased sorption of Zn (Cakmak, 2004).

Soil-available P was increased with the application of P fertilizer. On the other hand, availability of soil P was decreased with the application of Zn at both the levels which may be due to the antagonistic effect between Zn and P in soils forming insoluble compounds, $Zn_3(PO_4)_2$ resulting in the low amount of P in the available pool (Das *et al.*, 2005).

Yield of rice

Application of Zn as well as P at all the levels significantly increased the dry-matter yield of grain and straw of rice. Addition of P @ 80 kg/ha increased the grain yield by 9.95% and straw yield by 16.26% over the control, and Zn @ 10 kg/ha increased the yield of grain by 11.31% and straw by 7.77% over the control (Table 2). Our results confirm the findings of Saha *et al.* (2015) and Ghasal *et al.* (2015).

The highest yield was obtained when both P and Zn were combined together at their respective highest levels, i.e. treatment $P_{80}Zn_{10}$ where the yield of grain was increased by 23.28 % and straw by 25.79% over the control (P_0Zn_0). The beneficial effects of P and Zn perhaps led to higher yield due to their combined application (Lal *et al.*, 2001).

Zinc content in rice

Concentration of Zn both in grain, straw and root of rice increased significantly with the application of Zn (Table 3) and the increase was 8.86% in grain, 10.14% in straw and 118.44% in root over the control at 10 kg/ha level of Zn. Addition of P fertilizer, on the other hand, progressively retarded the Zn concentration both in grain, straw and root, irrespective of various levels of Zn application and the effect was more prominent at the higher levels of P application. Gao *et al.* (2011) reported that, Zn concentration in straw and root of durum wheat was significantly decreased with higher rates of P fertilization. Increasing P application rates decreased the root physiological function and morphology (Tang and Skibsted, 2017) decreasing the Zn absorption by root and subsequently lowers the Zn concentration in straw (Zhang *et al.*, 2015). The reduced Zn concentration in wheat grain affected by P application was reported earlier by Zhang *et al.* (2012). The decrease in rhizospheric mycorrhizal colonization by P applications possibly explains the Zn reduction. Although the absolute value of Zn concentration in root was much higher than that in straw and grain, the relative decrease in Zn concentration due to P application in root (20.27 %) was slight lower than that in straw (30.50 %) and grain (30.07 %), indicating the need of increased level of Zn application when P is used at higher level for rice cultivation.

Uptake of Zinc by rice

The application of Zn significantly increased the Zn

Table 1. Effect of phosphorus and zinc application on the availability of Zn and P in post-harvest soil of rice

Treatment	Available soil Zn (mg/kg)				Available soil P (kg/ha)			
	Zn ₀	Zn ₅	Zn ₁₀	Mean	Zn ₀	Zn ₅	Zn ₁₀	Mean
P ₀	0.676	0.902	1.006	0.861	23.46	22.82	22.63	22.97
P ₄₀	0.676	0.878	0.991	0.849	24.68	24.13	23.87	24.23
P ₆₀	0.677	0.840	0.961	0.826	25.73	25.19	25.13	25.35
P ₈₀	0.675	0.771	0.916	0.788	26.49	26.33	26.16	26.33
Mean	0.676	0.848	0.969		25.09	24.62	24.45	24.72
SEm±	P: 0.014		Zn: 0.012	P × Zn: 0.025	P: 0.308		Zn: 0.266	P × Zn: 0.533
CD (P=0.05)	P: 0.042		Zn: 0.036	P × Zn: NS	P: 0.902		Zn: NS	P × Zn: NS

Table 2. Effect of phosphorus and zinc application on the grain and straw yield of rice

Treatment	Grain yield (t/ha)				Straw yield (t/ha)			
	Zn ₀	Zn ₅	Zn ₁₀	Mean	Zn ₀	Zn ₅	Zn ₁₀	Mean
P ₀	2.40	2.58	2.67	2.55	5.29	5.51	5.69	5.50
P ₄₀	2.46	2.63	2.73	2.61	5.50	5.72	5.89	5.70
P ₆₀	2.61	2.78	2.90	2.76	5.85	6.07	6.30	6.07
P ₈₀	2.64	2.81	2.96	2.81	6.13	6.39	6.66	6.39
Mean	2.53	2.70	2.81		5.69	5.92	6.14	
SEm±	P: 0.015		Zn: 0.013	P × Zn: 0.026	P: 0.038		Zn: 0.033	P × Zn: 0.066
CD (P=0.05)	P: 0.045		Zn: 0.039	P × Zn: NS	P: 0.111		Zn: 0.096	P × Zn: NS

uptake by rice grain 18.53%, straw 18.58% and root 167.04% over the control at 10 kg/ha level of Zn application (Table 4). An increase in the availability of Zn in soil due to increase in solubility in soil solution and/or stimulation of root absorption perhaps led to increase in Zn uptake (Jiang *et al.*, 2008).

Although P application increased the dry-matter yield of grain, straw and root, the uptake of Zn by the same recorded a declining trend and this decrease was significant at higher dose of P application. The decrease in the concentration of Zn, which was more prominent in case of grain and straw, may be due to decrease in translocation and decrease in availability of the element in soil. The decrease in Zn uptake may be partly due to mycorrhizal colonization (Ryan and Angus, 2003).

Harvest index of Zn in rice

Consistent with earlier report (Shivay *et al.*, 2010), Zn application had no effect on harvest index of zinc (Zn-HI) of rice, whereas application of P caused a significant decrease in the Zn-HI of rice (Table 5), previously reported by Zhang *et al.* (2015), indicating that P application results in increased Zn accumulation in straw but not in grain, when sufficient Zn is available in soil.

Relative transfer of Zn from root to straw and from straw to grain of rice

Relative transfer of Zn from root to straw and from straw to grain was estimated as uptake of Zn in straw divided by uptake of Zn in root and uptake of Zn in grain divided by uptake of Zn in straw, respectively. Application of Zn significantly decreased the transfer coefficient of Zn

Table 3. Effect of phosphorus and zinc application on Zn content in grain, straw and root of rice

Treatment	Grain Zn concentration (mg/kg)				Straw Zn concentration (mg/kg)				Root Zn concentration (mg/kg)			
	Zn ₀	Zn ₅	Zn ₁₀	Mean	Zn ₀	Zn ₅	Zn ₁₀	Mean	Zn ₀	Zn ₅	Zn ₁₀	Mean
P ₀	27.77	29.17	29.96	28.97	36.42	38.40	39.80	38.20	48.74	77.89	102.0	76.21
P ₄₀	26.18	27.50	28.46	27.38	34.46	36.26	37.87	36.19	46.45	73.61	97.70	72.58
P ₆₀	22.97	24.21	25.04	24.07	30.39	32.27	33.50	32.05	41.67	68.25	91.76	67.23
P ₈₀	19.09	20.26	21.04	20.13	25.29	26.66	28.21	26.72	36.24	59.38	86.65	60.76
Mean	24.00	25.28	26.13		31.64	33.40	34.84		43.27	69.78	94.53	
SEm±	P: 0.24	Zn: 0.21	P × Zn: 0.41		P: 0.58	Zn: 0.51	P × Zn: 1.01		P: 1.17	Zn: 1.01	P × Zn: 2.03	
CD (P=0.05)	P: 0.70	Zn: 0.60	P × Zn: NS		P: 1.71	Zn: 1.48	P × Zn: NS		P: 3.44	Zn: 2.98	P × Zn: NS	

Table 4. Effect of phosphorus and zinc application on the uptake of Zn by grain, straw and root of rice

Treatment	Grain Zn uptake (g/ha)				Straw Zn uptake (g/ha)				Root Zn uptake (g/ha)			
	Zn ₀	Zn ₅	Zn ₁₀	Mean	Zn ₀	Zn ₅	Zn ₁₀	Mean	Zn ₀	Zn ₅	Zn ₁₀	Mean
P ₀	66.80	73.61	78.37	72.92	193.1	211.9	226.7	210.6	40.24	74.38	106.2	73.61
P ₄₀	64.62	71.17	76.05	70.61	189.5	207.6	223.0	206.7	39.73	73.45	105.4	72.85
P ₆₀	59.91	65.99	71.06	65.65	177.8	195.9	211.1	194.9	39.03	71.96	103.8	71.59
P ₈₀	50.44	56.28	61.10	55.94	155.2	170.5	187.8	171.1	36.75	68.23	100.5	68.50
Mean	60.44	66.76	71.64		178.9	196.5	212.1		38.93	72.00	104.0	
SEm±	P: 0.65	Zn: 0.56	P × Zn: 1.13		P: 4.04	Zn: 3.50	P × Zn: 7.00		P: 1.55	Zn: 1.34	P × Zn: 2.68	
CD (P=0.05)	P: 1.91	Zn: 1.66	P × Zn: NS		P: 11.85	Zn: 10.27	P × Zn: NS		P: 4.54	Zn: 3.93	P × Zn: NS	

Table 5. Effect of phosphorus and zinc application on the zinc harvest index (Zn-HI) and transfer coefficient of Zn from root to straw and from straw to grain of rice

Treatment	Zn-HI				Transfer coefficient of Zn from root to straw				Transfer coefficient of Zn from straw to grain			
	Zn ₀	Zn ₅	Zn ₁₀	Mean	Zn ₀	Zn ₅	Zn ₁₀	Mean	Zn ₀	Zn ₅	Zn ₁₀	Mean
	P ₀	0.257	0.258	0.257	0.257	5.13	3.17	2.41	3.57	0.346	0.356	0.353
P ₄₀	0.254	0.255	0.254	0.255	5.18	3.21	2.42	3.60	0.341	0.349	0.348	0.346
P ₆₀	0.252	0.252	0.252	0.252	5.04	3.12	2.34	3.50	0.337	0.344	0.343	0.341
P ₈₀	0.245	0.248	0.246	0.246	4.73	2.91	2.15	3.26	0.325	0.335	0.332	0.331
Mean	0.252	0.253	0.252		5.02	3.10	2.33		0.337	0.346	0.344	
SEm±	P: 0.004	Zn: 0.004	P × Zn: 0.009		P: 0.064	Zn: 0.064	P × Zn: 0.128		P: 0.008	Zn: 0.008	P × Zn: 0.016	
CD (P=0.05)	P: 0.013	Zn: NS	P × Zn: NS		P: 0.185	Zn: 0.185	P × Zn: NS		P: 0.022	Zn: NS	P × Zn: NS	

from root to straw the decrease being by 38.22% with Zn application @ 5 kg/ha and by 53.58% with 10 kg Zn/ha (Table 5) as compared to the control (no Zn). Such decrease may be due to higher accumulation of Zn in root upon Zn fertilization, indicating less mobility of Zn from root to straw due to inability of straw to uptake more Zn from root after attaining optimum Zn concentration in tissues.

Application of P, on the other hand, significantly decreased the transfer coefficient of Zn both from root to straw and straw to grain and the effect was more prominent with the highest level of P application, indicating the adverse effect of higher levels of P application on translocation of Zn (Gao *et al.*, 2011).

Phosphorus content in rice

Phosphorus concentration both in grain, straw and root increased significantly with increasing levels of P application, whereas the same was significantly decreased with Zn application (Table 6) and the decrease at highest level of Zn application (i.e. 10 kg/ha) being 10.59% in grain, 10.28% in straw and 17.28% in root compared to the control (no Zn). The decrease in concentration of P in grain and straw with higher levels of zinc application is attributed to the antagonistic effect between P and Zn. Excess zinc (high concentration of zinc) in plant tissue may cause a decrease in expression of P transporter genes in plant roots (Fageria *et al.*, 2011).

Phosphorus uptake by rice

Consistent with previous report (Shivay and Kumar, 2004), P uptake by grain, straw and root of rice at harvesting stage was also increased significantly (Table 7) with the application of P at different levels and the increase being 32.87% in grain, 38.84% in straw and 32.30% in root at 80 kg P/ha over the control (no P). On the contrary, Zn application did not exhibit significant effect on P uptake by grain, straw and root.

Phosphorus: Zinc ratio in rice

Application of P significantly increased the P : Zn ratio in grain, straw and root and the effect was highest in grain followed by straw and root (Table 8), indicating a higher accumulation of Zn in the root-system (Zhang *et al.*, 2012). However, this ratio was decreased significantly with the application of Zn, the decrease being 17.97% in grain, 18.26% in straw and 62.45% in root compared to the control with the application of Zn @ 10 kg/ha. Results also showed that the interaction effect between P and Zn was significant in the root. The decrease in the concentration of Zn in the straw and grain of some plants due to P fertilization has been attributed to the physiological inhibition of Zn uptake by root and translocation of Zn from root to straw (Zhang *et al.*, 2012).

Phytic acid content and phytic acid : Zn molar ratio in rice grain

Phytic acid (myo-inositol kis-hexaphosphate), the major

Table 6. Effect of phosphorus and zinc application on P content in grain, straw and root of rice

Treatment	Grain P concentration (g/kg)				Straw P concentration (g/kg)				Root P concentration (g/kg)			
	Zn ₀	Zn ₅	Zn ₁₀	Mean	Zn ₀	Zn ₅	Zn ₁₀	Mean	Zn ₀	Zn ₅	Zn ₁₀	Mean
P ₀	2.17	1.98	1.88	2.01	0.99	0.92	0.87	0.92	0.77	0.68	0.63	0.69
P ₄₀	2.32	2.15	2.05	2.17	1.03	0.97	0.94	0.98	0.80	0.69	0.64	0.71
P ₆₀	2.43	2.24	2.13	2.27	1.09	1.04	1.01	1.05	0.83	0.74	0.69	0.75
P ₈₀	2.53	2.38	2.37	2.43	1.16	1.11	1.04	1.10	0.87	0.78	0.75	0.80
Mean	2.36	2.19	2.11		1.07	1.01	0.96		0.81	0.72	0.67	
SEm±	P: 0.02	Zn: 0.02	P × Zn: 0.04		P: 0.01	Zn: 0.01	P × Zn: 0.02		P: 0.01	Zn: 0.01	P × Zn: 0.01	
CD (P=0.05)	P: 0.06	Zn: 0.07	P × Zn: NS		P: 0.04	Zn: 0.04	P × Zn: NS		P: 0.02	Zn: 0.02	P × Zn: NS	

Table 7. Effect of phosphorus and zinc application on P uptake by grain, straw and root of rice

Treatment	Grain P uptake (kg/ha)				Straw P uptake (kg/ha)				Root P uptake (kg/ha)			
	Zn ₀	Zn ₅	Zn ₁₀	Mean	Zn ₀	Zn ₅	Zn ₁₀	Mean	Zn ₀	Zn ₅	Zn ₁₀	Mean
P ₀	5.22	5.11	5.02	5.11	5.21	5.06	4.95	5.08	0.591	0.579	0.581	0.583
P ₄₀	5.71	5.65	5.58	5.65	5.67	5.57	5.51	5.58	0.626	0.606	0.601	0.611
P ₆₀	6.34	6.23	6.15	6.24	6.40	6.31	6.34	6.35	0.704	0.679	0.675	0.686
P ₈₀	6.67	6.70	7.02	6.80	7.13	7.07	6.95	7.05	0.788	0.774	0.754	0.772
Mean	5.98	5.92	5.95		6.10	6.00	5.94		0.677	0.659	0.653	
SEm±	P: 0.076	Zn: 0.066	P × Zn: 0.132		P: 0.109	Zn: 0.094	P × Zn: 0.189		P: 0.016	Zn: 0.013	P × Zn: 0.027	
CD (P=0.05)	P: 0.223	Zn: NS	P × Zn: NS		P: 0.320	Zn: NS	P × Zn: NS		P: 0.046	Zn: NS	P × Zn: NS	

anti-nutritional component in staple cereal foods and legumes, binds to dietary essential minerals (such as iron, zinc, calcium and magnesium) and makes them biologically unavailable owing to its chelating property (Roohani *et al.*, 2012). Zinc fertilization significantly reduced the phytic acid (PA) concentration in the grains and the reduction was highest (11.78% compared with the control) when Zn was applied @ 10 kg/ha. Phytic acid : zinc molar ratio (PA : Zn) in grains was also decreased with the Zn fertilization @ 5 and 10 kg/ha (Table 9) by 13.41 and 19.17%, respectively, compared with the control (i.e. no Zn). Saha *et al.* (2017) pointed out that Zn fertilization decreased phytate : Zn molar ratio of wheat grain owing to higher Zn enrichment accompanied by phytic acid reduction in the grain. In contrast, the PA content and PA : Zn molar ratio

were significantly increased by P application at various levels, the increase being 14.91 and 65.61%, respectively, over the control (i.e. no P) when P was applied @ 80 kg/ha.

Per cent use of applied Zinc by root, straw and grain and Zn-use efficiency of rice

With a vision about the recovery of applied Zn by different plant parts, viz. root, straw and grain (Table 10), for practical management or efficient utilization of applied Zn by the crop, the per cent use of applied Zn by different plant parts was determined. It was revealed that per cent utilization of applied Zn by different plant parts gradually lowered with the application of P at various levels and it varied from 0.107 to 0.136 in grain, 0.305 to 0.378 in straw and 0.630 to 0.681 in root.

Table 8. Effect of phosphorus and zinc application on P : Zn ratio in grain, straw and root of rice

Treatment	Grain P : Zn ratio				Straw P : Zn ratio				Root P : Zn ratio			
	Zn ₀	Zn ₅	Zn ₁₀	Mean	Zn ₀	Zn ₅	Zn ₁₀	Mean	Zn ₀	Zn ₅	Zn ₁₀	Mean
P ₀	78.18	67.87	62.74	69.60	27.05	23.91	21.86	24.27	15.76	8.68	6.18	10.21
P ₄₀	88.57	78.04	71.94	79.52	29.95	26.84	24.69	27.16	17.14	9.34	6.52	11.00
P ₆₀	106.0	92.48	84.86	94.44	35.98	32.23	30.04	32.75	19.87	10.83	7.47	12.73
P ₈₀	132.3	117.5	112.7	120.8	45.95	41.51	36.99	41.48	23.89	13.21	8.62	15.24
Mean	101.3	88.97	83.06		34.73	31.12	28.39		19.17	10.51	7.20	
SEm±	P: 1.39	Zn: 1.21	P × Zn: 2.42		P: 0.70	Zn: 0.61	P × Zn: 1.21		P: 0.41	Zn: 0.35	P × Zn: 0.71	
CD (P=0.05)	P: 4.09	Zn: 3.54	P × Zn: NS		P: 2.05	Zn: 1.78	P × Zn: NS		P: 1.20	Zn: 1.04	P × Zn: 2.08	

Table 9. Effect of phosphorus and zinc application on phytic acid (PA) content and PA : Zn molar ratio in rice grain

Treatment	PA content (g/kg)				PA : Zn molar ratio			
	Zn ₀	Zn ₅	Zn ₁₀	Mean	Zn ₀	Zn ₅	Zn ₁₀	Mean
P ₀	26.70	24.42	23.68	24.93	94.91	82.46	77.91	85.09
P ₄₀	28.69	26.20	25.36	26.75	108.2	94.07	88.13	96.80
P ₆₀	29.91	27.30	26.37	27.86	128.7	111.6	104.1	114.8
P ₈₀	30.81	28.11	27.03	28.65	159.1	136.9	126.7	140.9
Mean	29.03	26.51	25.61		122.7	106.3	99.20	
SEm±	P: 0.23		Zn: 0.20	P × Zn: 0.40	P: 1.65		Zn: 1.43	P × Zn: 2.85
CD (P=0.05)	P: 0.67		Zn: 0.58	P × Zn: NS	P: 4.83		Zn: 4.19	P × Zn: NS

Table 10. Effect of phosphorus application on per cent use of applied zinc by root, straw and grain and Zn use efficiency of rice

Treatment	Per cent use of applied Zn by						Zn use efficiency (%)					
	Root			Straw			Grain					
	Zn ₅	Zn ₁₀	Mean	Zn ₅	Zn ₁₀	Mean	Zn ₅	Zn ₁₀	Mean	Zn ₅	Zn ₁₀	Mean
P ₀	0.585	0.564	0.574	0.374	0.336	0.355	0.170	0.133	0.152	0.545	0.469	0.507
P ₄₀	0.565	0.556	0.561	0.362	0.335	0.349	0.157	0.130	0.144	0.519	0.466	0.492
P ₆₀	0.549	0.550	0.549	0.362	0.332	0.347	0.149	0.126	0.137	0.511	0.458	0.484
P ₈₀	0.516	0.546	0.531	0.307	0.326	0.316	0.132	0.119	0.126	0.439	0.445	0.442
Mean	0.554	0.554		0.351	0.332		0.152	0.127		0.504	0.459	
SEm±	P: 0.022	Zn: 0.016	P × Zn: 0.032	P: 0.030	Zn: 0.021	P × Zn: 0.042	P: 0.015	Zn: 0.010	P × Zn: 0.021	P: 0.031	Zn: 0.022	P × Zn: 0.044
CD (P=0.05)	P: NS	Zn: NS	P × Zn: NS	P: NS	Zn: NS	P × Zn: NS	P: NS	Zn: NS	P × Zn: NS	P: NS	Zn: NS	P × Zn: NS

Table 11. Effect of phosphorus and zinc application on acid phosphatase and alkaline phosphatase activity of post-harvest soil of rice

Treatments	Acid phosphatase activity ($\mu\text{g PNP/g soil/hr}$)				Alkaline phosphatase activity ($\mu\text{g PNP/g soil/hr}$)					
	Zn ₀	Zn ₅	Zn ₁₀	Mean	Zn ₀	Zn ₅	Zn ₁₀	Mean		
P ₀	271.3	258.9	246.1	258.8	234.2	222.0	213.2	223.1		
P ₄₀	257.6	245.6	234.1	245.8	224.2	210.5	200.9	211.8		
P ₆₀	241.7	228.5	219.3	229.9	211.6	196.1	188.1	198.6		
P ₈₀	225.0	211.4	202.4	212.9	197.8	181.8	174.9	184.8		
Mean	248.9	236.1	225.5		217.0	202.6	194.3			
SEm \pm	P: 1.19		Zn: 1.03		P: 1.14		Zn: 0.99		P \times Zn: 1.97	
CD (P=0.05)	P: 3.50		Zn: 3.03		P: 3.34		Zn: 2.89		P \times Zn: NS	

Use efficiency of soil-applied Zn in rice was very low (less than 1%), was further lowered by the application of P, which agrees with analogous findings by Debnath *et al.* (2015). Critical analysis of the results showed that, the retarding effect of P application on Zn utilization was more pronounced at lower level of applied Zn than higher level, which may be due to the fact that at higher level of Zn application, sufficient amount of Zn was left in the soil after interaction with added P to meet the requirement of the plants. The zinc-use efficiency of rice was reduced by Zn application, confirming the findings of Saha *et al.* (2015).

Acid phosphatase and alkaline phosphatase activity of post-harvest soil of rice

The results (Table 11) showed that application of P fertilizer suppressed significantly both the activity of acid and alkaline phosphatase in post-harvest rice soil and the effect was more prominent at the higher level of P application (17.72 and 17.17%, respectively, from that of no P control) (Wang *et al.*, 2008). Furthermore, Zn application also caused a significant inhibition of both acid phosphatase activity to the tune of 7.27 % and alkaline phosphatase activity to the tune of 8.54%, compared with the control (no Zn), due to inhibition of enzyme reactions by Zn either through the process of complexation of substrate or combining with the protein active group of the enzymes or by reacting with the enzyme-substrate complex (Karaca *et al.*, 2010).

The above study shows that yield of rice was not affected by higher P application rates, moreover it was increased with combined application of P and Zn. Application of P at higher rates resulted in reduction in the availability of applied Zn in soil to some extent but had a meager effect on the availability of native soil Zn. Although Zn concentration and uptake by rice, Zn-HI, relative transfer of Zn from root to grain and acid and alkaline phosphatase activity in rice soil, were significantly affected by P application rate, no such interaction effect of zinc and phosphorus was noticed upon P application up to 80 kg/ha in most of the cases. Thus, optimal P management in intensive agricultural systems is needed to ensure high yield of rice as

well as high levels of Zn in grain required for, human nutrition.

ACKNOWLEDGMENTS

We acknowledge the financial help of Ad-hoc Project, All India Coordinated Research Project on Micro and Secondary Nutrients and Pollutant Elements in Soils and Plants, Indian Council of Agricultural Research, New Delhi, Govt. of India.

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