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RESEARCH

Interaction Effects of Phosphorus and Zinc Application on Their Availability and Growth of Rice (*Oryza sativa*) in an Alfisol of Sri Lanka

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ABSTRACT

This study investigated the interactive effects of phosphorus (P) and zinc (Zn) application on P and Zn availability, and growth of rice (*Oryza sativa*) in an Alfisol. In a laboratory incubation experiment, soil samples were supersaturated with treatment solutions with all possible combinations of four P levels (0, 6, 12, and 24 mg kg^{-1} equivalent to 0, 10, 20, and 40 kg ha^{-1}, respectively) and three Zn levels (0, 1.2, and 2.4 mg kg^{-1} equivalent to 0, 2, and 4 kg ha^{-1}, respectively), and then allowed to air-dry. Available P and Zn contents in soil increased as the application rates were increased but P×Zn rate interaction effect was not significant. In a pot experiment, rice (*var* Bg 358) was grown for 10 weeks with all possible combinations of three P levels (0, 5.5, and 16.5 mg kg^{-1}) and three Zn levels (0, 1, and 2 mg kg^{-1}). Initial soil P was higher than the critical level (12 mg kg^{-1}), but available Zn was below the critical level (1.5 mg kg^{-1}). The main effect of P rate did not significantly affect the number of tillers and shoot dry matter content while Zn application decreased them. Root dry matter, and root and shoot P concentrations were significantly ($P<0.05$) influenced by P×Zn rate interaction effect. While, plant P uptake was significantly decreased due to P and Zn application, plant Zn uptake was not affected. Therefore, for a better growth of rice plant, the soils with high available P and low Zn contents should be carefully fertilized with P and Zn fertilizers.

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INTRODUCTION

Dry zone accounts for more than 65% of Sri Lanka's yearly rice output and most of these lands have been used for rice cultivation for thousands of years. With conventional rice farming, mostly with only synthetic fertilizers, we produce about 4 - 6 t ha^{-1} of rice annually from Dry zone paddy growing areas (Kadupitiya et al., 2022). This value is greatly below the potential yield (9 t ha^{-1}) of commonly grown rice varieties in Sri Lanka (Nissanka and Bandara, 2004). Application of nitrogen (N), phosphorus (P) and potassium (K) fertilizer, increases their availability in paddy soils, but Dry zone soils of Sri Lanka have relatively low levels of plant available zinc (Zn) in them (Bandara, 2007). The distribution patterns of plant available Zn contents reported by Nayanaka *et al.* (2010) indicates that 80% of the land area of Dry zone had Zn levels less than 1 mg kg^{-1}. Optimum range of Zn for high growth of paddy under flooded conditions is 2 - 4 mg kg^{-1} (Dobermann and Fairhurst, 2000; Portch and Hunter, 2002). Yet only less than 8% of the farmers apply Zn into their paddy lands (Kadupitiya et al., 2022).

Zinc deficiency is an important abiotic factor limiting rice productivity worldwide. Low Zn availability increases time taken for crop maturity, reduces the final yield, and severe cases may cause death of the rice plant (Mustafa et al., 2011). Moreover, 10-60% yield losses can be caused by low availability of Zn in soil (Coffin and Slaton, 2020). Therefore, maintaining sufficient concentration of all essential elements in soil is vital to achieve potential productivity.

Phosphorus is a plant nutrient that is required for root growth, tillering, early flowering, and ripening of the rice plant (Choudhury et al., 2007). Low availability of P retard crop growth and yield (Syers et al., 2011). As large amount of P exists in insoluble forms in soil, the available forms to plant uptake is often limited. Plants can uptake only the inorganic form of primary and secondary orthophosphate ions in the solution, which are $H_2PO_4^-$ and HPO_4^{-2} (Amarawansha et al., 2009). In addition to the application of P fertilizers, availability of P in soil could be altered by application of Zn containing fertilizers to paddy fields (Paulsson et al., 2002).

Zinc act as an essential component of numerous enzymes, and regulates several biochemical processes in rice plant required for growth and development (Kumaragamage and Indraratne, 2011). The form of Zn exists in soil solution play an important role in determining its availability to plants. In soil, plant-available forms of Zn exist as the free ions of Zn^{2+}, $ZnOH^+$, soluble organic complexes, and labile Zn (Kiekens, 1995), while the Zn associated with primary and secondary minerals is relatively unavailable for plant uptake. According to Wijebandara *et al.* (2011), only about 5% of total Zn in soil or less is available to plants at any given time.

Zn deficiency in paddy soil is due to low native soil Zn availability, and chemical or biological interaction of Zn with some other elements. Phosphorus is the most important element, influencing mobility and bioavailability of Zn in soil (Pérez-Novo et al., 2011). It can be a synergistic or antagonistic interaction (Aboyeji et al., 2020). A better combination of P-Zn application could significantly increase the biomass and yield of rice. Bandara *et al.* (2006) has reported that application of P and Zn (35 kg ha^{-1} and 2 kg ha^{-1}, respectively) has increased the yield based on their study conducted in Elayapaththuwa soil series at Mahailuppllama. Moreover, high dose phosphate additions can alter the equilibrium of Zn in soil, leading to a redistribution of Zn in their different fractions (Mandal and Mandal, 1990). If excess P binds a large quantity of Zn, which could otherwise have been available for plant uptake, the result can be a P-induced Zn deficiency (Alwahibi et al., 2020; Hafeez et al., 2013). Moreover, $Zn_3(PO_4)_2$ can be precipitated within the roots restricting the translocation of Zn to the upper part of the rice plant (Pongrac et al., 2019). The final outcome of this phenomena is the reduction of growth of the rice plant.

Although, previous studies have examined the relationship between Zn and P on growth of rice plants, there has been little research on their interaction under Sri Lankan conditions. Therefore, this study aims to investigate the impact of P and Zn application on their availability and growth of rice plants in an Alfisol in the Dry zone of Sri Lanka.

METHODOLOGY

Soil sampling and characterization

A bulk surface (0 – 15 cm) soil sample of about 200 kg was collected from several randomly selected locations in a 100 × 100 m^2 area of a paddy cultivating field in Anuradhapura (8° 17' 12.4764" N; 80° 33' 13.2012" E). After removing visible plant residues, about 2 kg of soil was air-dried and then sieved using 2-mm sieve for a laboratory incubation study. The rest were stored as field fresh samples to be used in a pot experiment. Available P, K and Zn in air-died soils were extracted using Mehlich-3 (M3) solution. Available P (M3-P) was determined based on ascorbic acid method (Murphy and Riely, 1962). Available Zn (M3-Zn) was measured using atomic absorption spectrometry and available K was measured using flame photometry (Sims, 1989). Soil pH and electrical conductivity (EC) were determined with 1:5 (water) suspension using a pH meter and a EC meter, respectively.

Soil incubation study

Four levels of P: 0, 6, 12, and 24 mg of P kg^{-1} as K_2HPO_4 (equivalent to 0, 10, 20, and 40 kg of P ha^{-1}, respectively) and three levels of Zn: 0, 1.2, and 2.4 mg of Zn kg^{-1} as $ZnSO_4$ (equivalent to 0, 2, and 4 kg of Zn ha^{-1}, respectively) were applied to 3 g of air-dried and 2-mm sieved soils contained in 10 ml plastic bottles. Required quantities of P and Zn for each of the 12 treatments were dissolved in 3 mL of distilled water separately prior to their application into soil. Then supersaturated soils were allowed to air dry for 3 days for fixation (Portch and Hunter, 2002). Available P and Zn in the air-dried soils were extracted and analyzed using the same procedures as initial soil analysis using three replicates per treatment.

Pot experiment

The pot experiment was conducted in the same paddy field from where the soil samples were collected. This paddy field was located in the Anuradhapura district in the Dry zone of Sri Lanka. Dry zone is having a mean annual rainfall of <1750 mm with a distinct dry season from May to September and a mean annual temperature of 27.3 °C with maximum temperatures ranging from 26.2 °C to 33.9 °C. Plastic pots were filled with 5.5 kg of field fresh soil (moisture content 19% w/w), and puddled well after adding nine treatments, comprising three levels of P (0, 5.5, and 16.5 mg kg^{-1} - equivalent to 0, 11, and 33 kg ha^{-1}, respectively) and three levels of Zn (0, 1, and 2 mg kg^{-1} - equivalent to 0, 2, and 4 kg ha^{-1}, respectively), with the commercially available fertilizers of Triple Super Phosphate and Zinc Sulphate as the source of P and Zn, respectively. Recommended rates of P (11 kg ha^{-1}) and Zn (2 kg ha^{-1}) for rice cultivations in Sri Lanka were equivalent to 5.5 mg kg^{-1} and 1 mg kg^{-1}, respectively. Four pre-germinated rice seeds (*var* Bg 358) were planted in puddled soils. Nitrogen and K were applied as urea and muriate of potash (MOP), at rates recommended (225 kg of urea and 60 kg of MOP ha^{-1}) by the Department of Agriculture, Sri Lanka for field plants. The experiment was laid-out in Randomized Complete Block Design (RCBD) with three replications per treatment and all the pots were arranged in natural light. Number of tillers per plant was recorded during crop growth and plants were carefully uprooted at the panicle initiation (10 weeks after seeding) and subjected to further analysis.

Roots of the uprooted plants were washed several times with running tap water. Shoots were also washed with tap water to decontaminate any dust particles. Root and shoot were separated and oven dried at 70 °C to a constant weight. Oven dried plant materials were cut into small pieces, ground and passed through 1 mm sieve prior to analysis. Plant samples (0.25g) were microwave digested (ETHOS EASY MAXI-44) with HNO_3 (Calderon et al., 2014). The concentrations of P and Zn in digestion solution were determined by ascorbic acid method (Murphy and Riely, 1962) and Atomic Absorption Spectrometry (Sims, 1989), respectively. Nutrient (P and Zn) contents in plant parts were calculated by multiplying dry mass with P and Zn concentrations (%).

Statistical Analysis

After the exploratory data analysis, data were subjected to a two-way analysis of variance (ANOVA) using SPSS software to determine the main and interaction effects of P and Zn application rates on measured soil and plant parameters. Post-Hoc test was performed using Duncan Multiple Range Test at 5% probability level.

RESULTS AND DISCUSSION

Basic soil characteristics

The experimental soil was moderately alkaline and had a low EC value (Table 1). The available P content in the soil was higher than the critical level (12 mg kg^{-1}) while, available Zn was below the critical level (1.5 mg kg^{-1}) proposed by others for lowland rice (Dobermann and Fairhurst, 2000; Portch and Hunter, 2002). The soil had a loamy sand texture and an organic carbon content of 0.95%.

Statistical significance of P and Zn interaction on soil and plant parameters

ANOVA conducted for measured soil parameters of the incubation study, the application of P has significantly affected ($P<0.05$) M3-P content, while the application of Zn significantly affected ($P<0.05$) M3-Zn contents in soil (Table 2). However, the application of P had no significant effect ($P>0.05$) on Zn availability, and vice versa.

ANOVA conducted on the plant parameters after treating soils with different rates of P and Zn, revealed that P × Zn interaction effect was significant on root dry matter content, root and shoot P concentrations, and total P uptake by the rice plants (Table 2). Application of P has significantly affected shoot dry matter content while, application of Zn has significantly influenced tillering, shoot dry matter accumulation, and total Zn uptake by plants. Total P uptake, root and shoot P concentrations were significantly affected by main effects of P and Zn application. Mean values of the measured parameters under different P × Zn levels are given in the Supplementary Table 1.

Effect of P and Zn application on their availabilities in soil

Mehlich-3 extractable P contents in soil increased significantly ($p<0.001$) as P application increased from 0 to 24 mg kg^{-1} irrespective of Zn application (Figure 1a). Similarly, the M3-Zn content also increased significantly ($p<0.05$) with Zn rate irrespective of P application (Figure 1b). However, this contradicts with the observations made by Mandal and Haldar (1980) in lowland rice fields in west Bengal, India. They observed that application of Zn had significantly decreased Bray-2 extractable P content, and application of P decreased DTPA extractable Zn contents in soils with very high clay content (32-43%) and low available P contents of 6.1 - 8.4 mg kg^{-1} but with a similar soil pH to that in the present study. While this disparity could be in part due to differences in soil properties of the two studies. Agbenin (1998) found that formation of Zn-phosphate complexes and precipitation could happen at sufficiently large concentrations of P applications, limiting Zn solubility and availability. Even at 2.4 mg kg^{-1} Zn application in our study, the M3-Zn content remained less than the critical level in our soil of high available P content.

Table 1. pH, electrical conductivity (EC), Mehlich-3 (M3) extractable plant nutrient contents of soil used for the experiment.

Property	M3-P (mg kg^{-1})	M3-Zn (mg kg^{-1})	M3-K (mg kg^{-1})	pH (1:5 water)	EC (1:5 water) (dS m^{-1})
Value	19.9	1.02	61.5	8.03	0.09

Table 2. ANOVA of the Mehlich-3 extractable P and Zn contents of the soil, plant growth parameters, concentration and uptake of P and Zn.

Source	Parameter §‡										
	M3-P	M3-Zn	TIL	SDM	RDM	RPC	SPC	RZnC	SZnC	TPU	TZnU
P	***	ns	ns	†	ns	**	*	ns	ns	*	ns
Zn	ns	*	*	*	ns	*	**	ns	ns	**	†
P × Zn	ns	ns	ns	ns	*	**	**	ns	ns	†	ns

§ M3-P - Mehlich-3 extractable P in soil, M3-Zn - Mehlich-3 extractable Zn in soil, TIL - Tiller Count, SDM - Shoot dry matter, RDM - Root dry matter, RPC - Root P Concentration, SPC - Shoot P Concentration, RZnC - Root Zn Concentration, SZnC - Shoot Zn Concentration, TPU - Total P uptake, TZnU - Total Zn uptake. ‡ †, *, **, and *** indicate the significance at p≤ 0.1, 0.05, 0.01, and 0.001

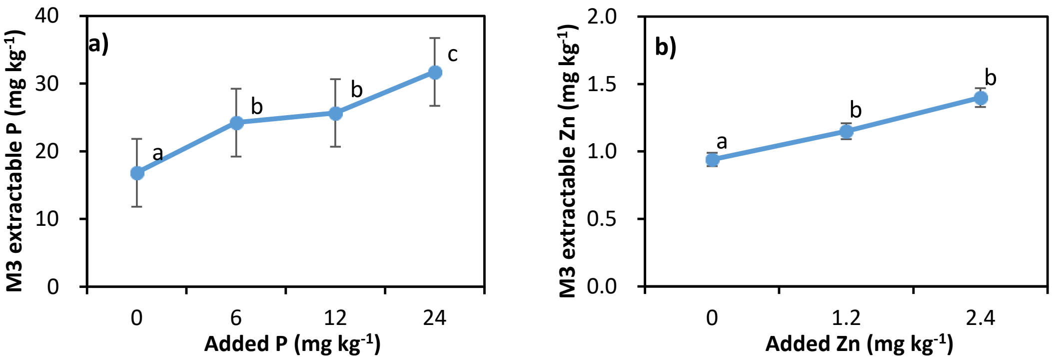

Figure 1. Mehlich-3 (M3) extractable a) P and b) Zn contents in soil as affected by P and Zn application. The vertical bars at each data point denotes the standard error (n=3). Same letters within each graph are not significantly different at P<0.05.

Effect of P and Zn application on their concentrations in rice plant

Shoot and root P concentrations were significantly influenced (P<0.01) by P level × Zn level interaction effect. The highest P concentrations in both shoots and roots were observed in the control treatment; *i.e.* without P and Zn application (Figure 2a and 2b). In soils with no Zn application, P concentrations in shoots and roots decreased continuously as rate of P application increased. This could be either due to the dilution effect or less absorption of P. When the crop shows fast growth, nutrients present in biomass will be diluted, due to the inverse relationship between improvements in the dry matter content and the amount of nutrients (Davis, 2009). The interaction between P content in soils and Zn availability to plants is highly complex. Generally, with high soil P content or supply of P fertilizers, plant uptake of Zn decreases more or less sharply and often beyond a level which can be attributed to dilution effects (Marschner, 1993). But, analysis of dry matter data (Supplementary Table 1) does not support the idea of dilution effect on shoot P concentration. Therefore, further studies are required to determine the reason for reduction of P absorption with P application in soils with high available P contents.

In soils that received Zn, P concentrations in both above and below ground dry matter decreased significantly with increasing P application but except for 16.5 mg kg^{-1} P application with 2 mg kg^{-1} Zn in shoots and with 1 mg kg^{-1} of Zn in roots. In these two situations, P concentrations in plant has increased significantly compared to plants with recommended level of P application. Khan *et al.* (2014) reported that the gene, encoding P exporter from root to shoot was significantly restricted under high Zn supply reducing P concentration of the shoots of the rice plant. Ding *et al.* (2021) also observed similar results under high Zn supply. In low availability of one nutrient, insoluble $Zn_3(PO_4)_2$ precipitation may form due to negative interaction between P and Zn (Saha et al., 2022; Saboor et al., 2021; Hayes et al., 2019). The formation of Zn-P complex might reduce the availability of P for the plant uptake (Gupta and Deb, 1984), reducing root P concentration, even under P supply conditions. In support of this argument, we observed that in the absence of P application, root P concentration was decreased significantly, when the rate of Zn application increased from 0 to 2 mg kg^{-1}. Haldar and Mandal (1981) stated that, applying Zn also similarly could lower the concentration of P.

Both shoot and root Zn concentrations were not significantly influenced (p>0.05) by P level × Zn level interaction or main effects (Table 2). Available Zn in experimental soil did not go beyond the critical level even under increasing of Zn level (Figure 1b). That might be the reason for these observations. Precipitation of $Zn_3(PO_4)_2$ may occur in roots and restrict the translocation of P from roots to shoots (Pongrac et al., 2019). As a result, shoot Zn concentration could not have been significantly affected by the P application.

Effect of P and Zn application on growth parameters

The number of tillers was not significantly affected by the increasing P level but it decreased significantly with increasing Zn application (P<0.05), irrespective of quantities of P applied (Figure 3a). In rice life cycle, tillering stage is the most sensitive growth stage for nutrients (Somaweera et al., 2017), and tillering is accelerated with the application of P fertilizers (Kekulandara et al., 2017; Sirisena and Suriyagoda, 2018). But, increasing rate of P application will not increase growth parameters of the rice plant in soils rich in P (Rehim, 2014), which is also same for this study. Yoshida and Hayakawa (1970) observed that when the plant has >0.2% P concentration in leaves, tillering is not affected. We observed average P concentration of 0.12 – 0.16 % in the shoot dry matter (Fig 3b) suggesting that P concentration in leaf bladed could have been >0.2%. However, application of Zn could reduce P translocation from roots to shoots (Pongrac et al., 2019), and the P concentration in leaves could have been limiting the tillering with Zn application.

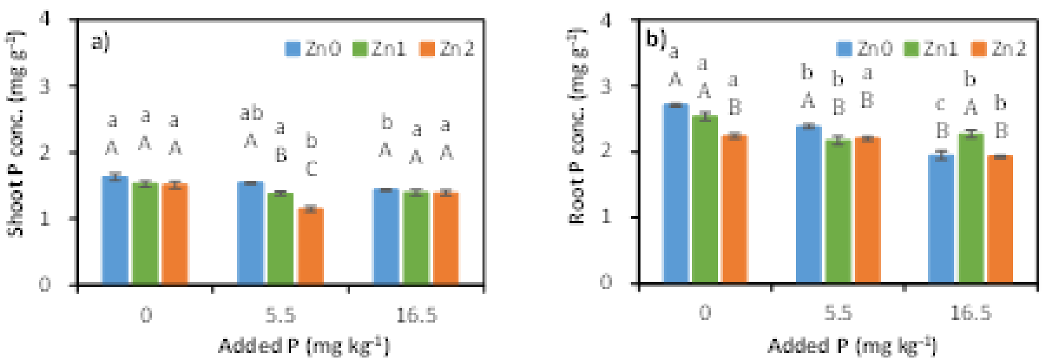

Figure 2. Phosphorus concentrations in a) shoot and b) root of the rice plant as affected by P and Zn application (Zn0 - Control Zn treatment, Zn1 - Recommended dose of Zn, Zn2 - Double the recommended dose). Bars with same uppercase letters within a given P level and lowercase letters within same Zn level are not significantly different (P<0.05). The vertical line on each bar represent the standard error (n=3).

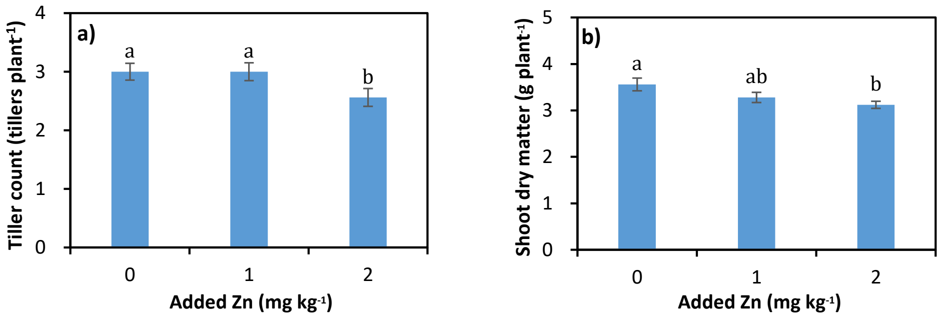

Figure 3. Production of a) tillers and b) shoot dry matter by the rice plant as affected by the rate of Zn application. Bars with same letters are not significantly different (P<0.05). The vertical line on each bar represents the standard error (n=3).

There was only marginal impact on shoot dry matter production with the increasing of P level (P<0.1). Increasing P in soils that has adequate P concentrations for the growth of rice plants will not result any increase in dry matter production, as observed by Fageria and Filho (2007). However, Bandara *et al.* (2006) observed a significantly low plant growth at higher P application rates. It can be either due to toxicity of P (Loneragan et al., 1979) or antagonistic interaction with other nutrients. Antagonism may occur with zinc (Zn), iron (Fe), aluminum (Al), or calcium (Ca). Antagonistic P-Zn interactions may occur when soils receive high P application rates or those that are very low in plant available Zn (Norvell et al., 1987; Salimpour et al., 2010). As the soil we used was low in available Zn, negative P-Zn interaction may occur reducing Zn availability to plants. Similar results have been reported by Bandara *et al.* (2006) in their studies. In addition, P readily reacts with Ca and Mg, then reduce solubility and availability to crops, in alkaline soils. Phosphorus reacts with Fe and Al when their availabilities are high in soils. The reaction of these cations with P in soil solution results in precipitation of compounds reducing their availability to the rice plant (Withana and Kumaragamage, 1993; Johan et al., 2021). Hence lower the accumulated P in shoots.

Shoot dry matter production was significantly decreased with Zn application, irrespective of P application (Figure 3b). Phosphorus and Zn are two essential nutrients the rice plant requires for its normal growth. These two are mutually antagonistic and can cause growth reduction in rice due to either P or Zn deficiency (Salimpour et al., 2010) and often occurs when one nutrient is available in small amounts (Amin et al., 2014). Precipitation of $Zn_3(PO_4)_2$ may occur within the roots and restrict the translocation of Zn from roots to shoots and upper parts (Pongrac et al., 2019). Hence application of Zn to this Zn deficient soil could have reduced nutrients (P, Zn or both) required for its physiological functions within the plant and finally affecting dry matter accumulation. We observed that, shoot P uptake : root P uptake ratio decrease with increasing Zn application at all levels of P applications (Supplementary Table 1) supporting the argument of reducing P translocation from root to shoot and distribution of P into new leaves by down-regulating P transporter genes in shoot (Ding et al., 2021).

Root dry matter production was significantly influenced (p<0.05) by P level × Zn level interaction effect (Table 2). In the absence of Zn application, root dry matter production was not significantly (p>0.05) influenced by the P application (Figure 4). Zinc act as an essential nutrient in growth of the rice plant, and component of numerous enzymes and regulates several biochemical processes within the rice plant (Rehman et al., 2012) without involving in root growth. Hence, root growth had probably not been affected even when the Zn availability is low in soil. When Zn was applied at lower rates (1 mg kg^{-1}), root dry matter content was significantly reduced with P application (Figure 4). When Zn was applied at higher rates (2 mg kg^{-1}), root dry matter content was significantly reduced with P application at recommended dose (Figure 4) but increased again with P application beyond the recommended dose. The experimental soil was Zn deficient even with the application of 2.4 kg of Zn ha^{-1} (Figure 1b). Under low Zn availability, P application might induce negative P-Zn interaction in soil (Boawn and Brown, 1968). Hence, reduce root dry matter content due to low availability of nutrients in soil with the formation of insoluble P-Zn complexes. P-Zn antagonistic interaction may occur when soils receive high P application rates or those that are very low in plant-available Zn (Bandara et al., 2004).

Effect of P and Zn application on P and Zn uptake by the rice plant

Total P uptake was significantly decreased as rate of P ($P<0.05$) and Zn ($P<0.01$) applications increase (Figure 5a and 5b). Growth of the rice plant could be significantly inhibited at increased P treatment rates (Cakmak and Marchsner, 1986) either due to P toxicity (Loneragan et al., 1979) or antagonistic interaction with Zn, Fe, Al, or Ca. This negative interaction occurs under low availability of soil nutrients (Saha et al., 2022). The reactions of these cations with P in soil solution results in precipitation of compounds, reducing P availability to the rice plant for uptake (Johan et al., 2021). The decrease of P uptake with the increasing of Zn application could be due to higher Zn supply, restricting the gene encoding P exporter from root to shoot (Khan et al., 2014). Moreover, plant Zn uptake was not significantly influenced ($P>0.05$) by increasing of P or Zn levels. This may be due to available Zn in experimental soil did not exceed the critical level, even with the increase of Zn application to soil (Figure 1b).

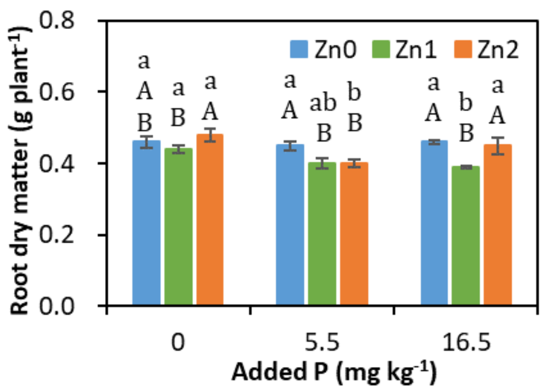

Figure 4. Root dry matter production of the rice plant as affected by P and Zn application. (Zn0 - Control Zn treatment, Zn1 - Recommended dose of Zn, Zn2 - Double the recommended dose) Bars with same uppercase letters within a given P level and lowercase letters within same Zn level are not significantly different (p<0.05). Vertical line on each bar represents the standard error (n=3).

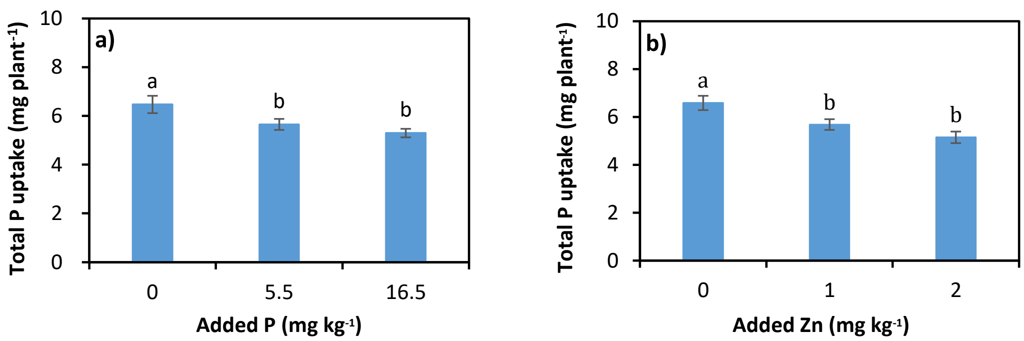

Figure 5. Total P uptake of the rice plant as affected by a) P and b) Zn application. Bars with same letters are not significantly different (p<0.05). Vertical line on each bar represents the standard error (n=3).

CONCLUSION

The growth and nutritional status of the rice plants grown under pot culture using a soil with a high available P and low Zn contents have significantly been affected by the rates of P and Zn application. While P and Zn application has increased their availability in this soil, that did not transform to improve the P and Zn nutritional status of the plant or growth of the rice plants. In fact, application of P and Zn to this high P soil decreased P uptake, and dry matter accumulation in shoots. This was attributed by poor P translocation from roots to shoots due to high Zn application or P interactions with other nutrients in soil. Application of Zn even at double the recommended rates cannot increase the Zn availability beyond the critical levels in this high P soil. Therefore, soils with high available P contents should be carefully fertilized with P and Zn fertilizers to achieve better growth of rice plants cultivated under flooded conditions. Moreover, field experiments should be conducted in the future under different soil environments to study the impact of P and Zn interaction effects on yield parameters and quality.

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Supplementary Table 1. Mean plant growth and nutritional parameters measured at booting stage (70 days after seeding) of rice plants at different P (0, 5.5, 16.5, mg kg^{-1}) and Zn (0, 1, 2, mg kg^{-1}) levels. Same uppercase letters within a given P level and lowercase letters within same Zn level are not significantly different ($p<0.05$).

P treatment	Tiller Count (tillers/plant)			Shoot Dry Matter (g/plant)			Root Dry Matter (g/plant)		
	Zn0	**Zn1**	**Zn2**	**Zn0**	**Zn1**	**Zn2**	**Zn0**	**Zn1**	**Zn2**
P0	3.0aA	2.9aA	3.0aA	3.66abA	3.50aA	3.06aA	0.46aAB	0.44aB	0.48aA
P5.5	3.1aA	2.8aA	2.5aA	3.89aA	3.15aB	3.24aAB	0.45aA	0.40abB	0.40bB
P16.5	2.9aA	2.9aA	2.4aA	3.12bA	3.20aA	3.06aA	0.46aA	0.39bB	0.45aA

P treatment	Root P Concentration (mg/g)			Shoot P Concentration (mg/g)			Root Zn Concentration (mg/g)		
	Zn0	**Zn1**	**Zn2**	**Zn0**	**Zn1**	**Zn2**	**Zn0**	**Zn1**	**Zn2**
P0	2.71aA	2.54aA	2.24aB	1.63aA	1.53aA	1.51aA	0.040aA	0.038aA	0.047aA
P5.5	2.39bA	2.17bB	2.19aB	1.54abA	1.38aB	1.15bC	0.050aA	0.040aA	0.052aA
P16.5	1.95cB	2.27bA	1.93bB	1.44bA	1.40aA	1.39aA	0.043aA	0.049aA	0.047aA

P treatment	Shoot Zn Concentration (mg/g)			Total P Uptake (mg/plant)			Total Zn Uptake (mg/plant)		
	Zn0	**Zn1**	**Zn2**	**Zn0**	**Zn1**	**Zn2**	**Zn0**	**Zn1**	**Zn2**
P0	0.024aA	0.025aA	0.027aA	7.25aA	6.46aAB	5.71aB	107.68aA	104.79aA	106.26aA
P5.5	0.026aA	0.022aA	0.024aA	7.11aA	5.23aB	4.60aB	123.95aA	83.94aA	98.66aA
P16.5	0.025aA	0.022aA	0.025aA	5.39abA	5.35aA	5.15aA	98.18aA	88.92aA	97.74aA