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Effect of Zinc Application on Growth, Yield, Zinc uptake and Zinc Use Indices of Rice

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Abstract

A field experiment was conducted at the agriculture farm, Palli Siksha Bhavana, Visva-Bharati, Birbhum, West Bengal, India during *kharif* (rainy) seasons (June–September) of 2016 and 2017 to study effect of zinc application on growth, yield and nutrient uptake of rice. The experiment was laid out in split plot design replicated thrice, consisting two main plot treatments i.e. crop establishment methods (CEMs) and seven sub-plot treatments (levels of zinc and methods of application). Two CEMs were direct seeded rice (DSR) and transplanted puddled rice (TPR) and seven levels of zinc and methods of application were namely control (Zn_0), Seed coating of Zn @ 1250 mg kg^{-1} (Zn_1), Seed coating of Zn @ 2500 mg kg^{-1} (Zn_2), Seed coating of Zn @ 3750 mg kg^{-1} (Zn_3), two foliar sprays @ 1050 mg kg^{-1} (Zn_4), three foliar spray @ 1050 mg kg^{-1} (Zn_5), 2500 mg kg^{-1} seed coating+2-foliar spray @ 1050 mg kg^{-1} (Zn_6). In respect of yield attribute and yield, Zn_6 resulted significantly highest number of Panicle m^{-2} as well as number of filled grains panicle^{-1}. Zn_3 though recorded 5.7% more grain yield than Zn_6 but later Zn_6 resulted highest zinc concentration and uptake. Zn_1 recorded highest zinc use indices. Zn_1 resulted much highest Zn use efficiency than foliar application and combined application of seed coating and foliar spray. Correlation between Zn levels and Zn concentration in both grain and straw of rice was highly positive; very highly positive correlation was recorded with the Zn levels and Zn uptake by both grain and straw.

Keywords: Biofortification, correlation, productivity, rice, use efficiency, zinc utilization

1. Introduction

The human body contains 2–3 g zinc, and nearly 90% is found in muscle and bone (Wastney et al., 1986). Zn plays an important role in production of protein and thus helps in wound healing, blood formation and growth and maintenance of tissue (Bell and Dell, 2008). Zn malnutrition and deficiency leads to diarrhoea in infants, dwarfism in adolescents (Cakmak et al., 1999; Fisher et al., 2009).

Zinc is also one of the most important micronutrients for many crop plants such as rice, maize and wheat, or soybeans, which all are worldwide, cultivated (Preetha et al., 2014). Zn malnutrition is more prevalent in Asian countries, where cereals are staple food (Cakmak, 2008 and Prasad, 2009). Cereals not only contain lesser amounts of Zn but also contain phytates, which reduce the bioavailability of Zn (Welch and Graham, 2004). crop establishment Asian, especially Indian soils are low in available Zn (Prasad, 2006; Singh, 2011; Kuzhivilayil et al., 2019) and this leads to production of low Zn containing rice.

Rice (*Oryza sativa* L.) is one of the most important staple food crops in the world especially in South East Asia. About 90% of rice is grown and consumed in Asia, where about 57.8 of the world's total. In India, rice has occupied highest area (46.37 million ha) with 195.42 mt production (Anonymous, 2022). Rice fulfils about 21% of the global energy and protein requirements of the human population and feeds more than half of the world population (McLean et al., 2002; Farooq et al., 2018). In general, the efficiency of Zn absorption from a diet range from 15–35%, depending upon the amounts consumed (decreases with an increase in amounts consumed) and the presence of dietary phytate (Hambidge et al., 2010).

The two main approaches for grain biofortification are breeding (Phattarakul et al., 2012; Johnson-Beebout et al., 2016) and micronutrient application. The later is a cost-effective approach for enhancing Zn concentration in grains (Farooq et al., 2018), also termed as agronomic biofortification resulted in higher Zn concentration in grains and yield (Prasad, 2009). Different methods of Zn application may have different outcomes in different rice production systems (Rehman et al., 2012). In conventional flooding method, rice yields increased more with soil application of Zn than with a foliar spray (Ram et al., 2015; Ghoneim, 2016). In contrast, foliar spray improved grain Zn concentrations than soil application in addition to improved grain yield under dry-seeded aerobic rice (Abilay and De Datta, 1978). For seed priming, seeds are soaked in aerated micronutrient solution followed by re-drying to the original seed weight and for seed coating, the target material adheres to the seed surface as an outer covering (Farooq et al., 2012; Rehman et al., 2016).

Several authors reported the importance of soil, foliage and seed treatments of Zn application in rice (e.g. Slaton et al., 2001; Khan et al., 2003; Phattarakul et al., 2012; Imran et al., 2015). However, the information on the influence of various levels of Zn and methods of its application under different crop establishment methods might give valid information for the researchers. Thus, the study was aimed to determine the right level and methods of application of Zn under direct seeded rice and transplanted puddled rice systems.

2. Materials and Methods

2.1. Description of the study area

A field experiment was conducted to study effect of zinc application on growth of rice during wet seasons (June–September) of 2016 and 2017 in red and lateritic soil of West Bengal, India ($23^0$39′ N latitude and $87^0$42′ E longitude with an average altitude of 58.90 m above mean sea level. The climate of the study area falls under sub-humid, semi-arid region. Average temperature during both 2016 and 2017 crop growing seasons were almost same (26° C to 33.7° C and 26.2° C to 33.8° C, respectively) however, average rainfall (167.8 mm) of the first year was little higher than second year (143.3 mm). The soil of the experimental field was well drained sandy loam in texture. The soil of the experimental field had 105.29 mg kg^{-1} alkaline permanganate oxidizable nitrogen (N) (Subbiah and Asija, 1956), 12.73 mg kg^{-1} available phosphorus (P) (Olsen et al., 1954), 66.39 mg kg^{-1} 1 N ammonium acetate exchangeable potassium (K) (Hanway and Heidel, 1952) and 0.39% organic carbon (C) (Walkley and Black, 1934). The pH of the soil was 6.2 (1:2.5 soil: water ratio). Diethylene tri-amine penta acetic acid (DTPA) extractable Zn (Lindsay and Norvell, 1978) in soil was 0.50 to 0.55 mg kg^{-1} of soil, respectively. The critical level of DTPA extractable Zn for rice grown on red soils varies from 0.60 to 1.00 mg kg^{-1} soil (Takkar et al., 1997). Hence, it can be said that it was a Zn deficient soil.

2.2. Experimental treatments and design

The experiment was laid out in split plot design which consisting of two main plot treatments and seven sub-plot treatments replicated thrice. Crop establishment methods were considered as main plot treatment and there were two crop establishment methods i.e. direct seeded rice (DSR) and transplanted puddled rice (TPR). Whereas, levels of Zn and methods of application was laid out in subplots and seven subplot treatments were control (Zn_0), Seed coating of Zn @ 1250 mg kg^{-1} (Zn_1), Seed coating of Zn @ 2500 mg kg^{-1} (Zn_2), Seed coating of Zn @ 3750 mg kg^{-1} (Zn_3), two foliar sprays @ 1050 mg kg^{-1} (Zn_4), three foliar spray @ 1050 mg kg^{-1} (Zn_5), 2500 mg kg^{-1} seed coating+2-foliar spray @ 1050 mg kg^{-1} (Zn_6). Popular rice variety, MTU-1010 was line sown at 5 cm soil depth under DSR, whereas 21 days rice seedlings were transplanted under TPR uniform spacing of 25×15 cm^2.

2.3. Application of treatments and fertilizers

Coating of rice seeds with $ZnSO_4.7H_2O$ was done before land preparation started. Gum acacia was used as an adhesive material for coating of $ZnSO_4.7H_2O$. For direct sowing of rice, 60 kg ha^{-1} seed rate was used. The 40 g gum acacia per kg of seed was added to ensure adequate adhesiveness in DSR. For seed coating @ 1250 mg kg^{-1}, 360 g ha^{-1} $ZnSO_4.7H_2O$ was used which contains 75.6 g Zn (21%). Seed coating of Zn @ 2500 mg kg^{-1} root dipping of rice seedlings was done instead of seed coating in case of transplanted rice. The roots of the seedlings were washed properly after uprooting from the nursery bed to clean mud. Utmost care was taken to avoid any damage caused inadvertently. Then seedlings were kept on the net for an hour for draining the water followed by dipping of seedlings root in a tray solution of $ZnSO_4.7H_2O$. Gum acacia @ 50 g l^{-1} was added to the solution adequate for 2000 seedlings for three hours. In case of foliar spray of rice, 2.5 kg $ZnSO_4.7H_2O$ was used per 500 litres of water for a hectare land. Likewise, 5 kg and 7.5 kg of $ZnSO_4.7H_2O$ were used for two- and three-times sprays per hectare, respectively.

Recommended dose (100:60:40 kg ha^{-1}) of mineral fertilizers viz., nitrogen, phosphorus (P_2O_5) and potassium (K_2O) were applied from Urea, Single Super Phosphate (SSP) and Muriate of Potash (MOP). One-third quantity of nitrogen and full quantity of phosphorus and potassium were applied as basal. For DSR, rest of nitrogen was top dressed in equal splits at 21 DAS and 50 DAS, while for transplanted rice, 21 days after transplanting and rest at 50 DAS.

2.4. Recording of growth, yield attributes and yields of rice

Ten hills were randomly selected in each plot for measuring plant height and fertile tillers $hill^{-1}$ 10 at 30 DAS, 60 DAS, 90 DAS and at harvest and the average values were computed. Then total plant dry weight (g $plant^{-1}$) were found out of sum of dry weight of different plant parts and dry matter accumulation in g m^{-2} was worked out based on plant density in different plots. Representative green leaves were taken randomly from each plot during destructive sampling at 30, 60, and 90 DAS under study and their areas were recorded by leaf area meter. The leaves were then dried in a hot air oven at 80°C for 48 hours still constant weights were obtained and dry weights of leaves were taken with an electrical balance. The area/weight relationship was used to determine leaf area indices as described by Kemp (1960). Since, LAI is area of leaf surface per unit land surface (Watson, 1952), it was obtained by multiplying the area/weight ratio with the dry weight of green leaves obtained per unit of land area. Crop growth rate during 30 to 60, 60 to 90 DAS and 90 DAS to harvest were determined with the help of following formula; CGR= $(W_2 - W_1)/(t_2 - t_1)$ Where, w_2 and w_1 are the final and initial total dry weights of all plant parts per unit land area (m^2) at the time t_2 and t_1, respectively and the unit was g m^{-2} day^{-1}. At harvest, grain and straw yield was recorded for each plot and finally expressed in kg ha^{-1}.

2.5. Plant tissue analysis

Plant samples (grain and straw) collected at maturity during both 2016 and 2017 were dried at 105°C for about 30 min for electro-thermal de-enzyme and then dried at 65°C until constant weight. The zinc content of grain and stalk of the crop were determined following the Atomic Absorption Spectrophotometer (AAS-4129), nitrogen, phosphorous and potassium uptake from the extract obtained through digestion with di-acid mixture (Prasad et al., 2006). The concentration was expressed in parts per million or mg kg^{-1}.

2.6. Zinc use indices

Partial factor productivity (PFP), agronomic efficiency (AE), recovery efficiency or apparent Zn recovery (RE), and physiological efficiency (PE) of applied Zn were computed using the following expressions as suggested by Baligar et al. (2001), Fageria and Baligar (2003), Dobermann (2005) and Shahane et al. (2019):

$PFP = Y_{Zn} / Zn_a$

$AE = (Y_{Zn} - Y_C) / Zn_a$

$RE = [(U_{Zn} - U_C) / Zn_a] \times 100$

$PE = (Y_{Zn} - Y_C) / (U_{Zn} - U_C)$

where, Y_{Zn} and U_{Zn} refer to the grain yield (kg ha^{-1}) and total Zn uptake (kg ha^{-1}), respectively, of rice in Zn applied plots; Y_C and U_C refer to the grain yield (kg ha^{-1}) and total Zn uptake (kg ha^{-1}), respectively, of rice in control (no Zn) plots; Zn_a refers to the Zn applied (kg ha^{-1}).

2.7. Data analysis

The experimental data were analysed following the standard statistical method (Panse and Sukhatme, 1985; Gomez and Gomez, 1984) and the data of both the years i.e. 2016 and 2017 were pooled. Least significant difference (LSD) values (p=0.05) were used to determine the significance of difference between treatment means.

3. Results and Discussion

3.1. Yield attributes and yield

The investigation of the data revealed that the CEMs did not show any significant influence on the various yield attributes (Table 1) of rice i.e. number of panicle per square metre, number of filled grain per panicle and 1000-seed weight of rice, while in respect to Zn levels and methods of application, the treatments showed significant effect on the yield parameters and yield of rice. Between the CEMs, TPR resulted in higher yield attributes than DSR.

The treatment with Zn_3 resulted leading number (233.75) of number of panicle m^{-2} which was significantly higher than the treatments Zn_1, Zn_4 and Zn_5 and Zn_0. However, this treatment Zn_3 was statistically at par with Zn_6 and Zn_2. In comparison to seed coating, Zn_3 was found statistically significant with Zn_1 and at par with Zn_2. Similarly, in case of foliar spray also, the treatment Zn_5 was observed statistically non-significant to Zn_4. No significant interaction was found between CEMs and Zn levels and methods of application.

The treatment maximum number (96.25) of filled grains $panicle^{-1}$ of rice which showed significant difference with the treatments, Zn_4 and Zn_0. However, this treatment Zn_6 was statistically at par with Zn_1, Zn_2, Zn_3 and Zn_5. In comparison to seed coating, Zn_3 was found statistically at par with Zn_2 and Zn_1. However, in case of foliar spray also, the treatment with Zn_5 was observed statistically non-significant to Zn_4. No significant interaction was found between CEMs and Zn levels and methods of application.

The treatment Zn_2 resulted highest (23.85 g) test weight followed by Zn_6 and Zn_3. These treatments proved non-significant with each other. In comparison to seed coating, Zn_2 was found statistically at par with Zn_3 and Zn_1. However, in case of foliar spray also, the treatment Zn_5 was observed statistically non-significant to Zn_4. No significant interaction was found between CEMs and Zn levels and methods of application.

The perusal of the data revealed that the CEMs did not have significant influence on grain yield of rice. Between the CEMs, TPR resulted in higher grain yield than DSR. Whereas, in respect to Zn levels and methods of application, the treatments had significant influence on grain yield. Zn_3 recorded highest grain yield which was though statistically at par but 5.7% higher than Zn_6; proved significant with 10.2% and 13.4% more grain yield over Zn_2 and Zn_1. In comparison to seed coated treatments, Zn_3 resulted into significantly higher grain yield than other seed coated treatments i.e. Zn_2 and Zn_1 while in comparison to foliar application, Zn_5 resulted in higher grain yield, but no significant variation was observed between the two foliar applied treatments i.e. Zn_4 and Zn_5. No significant interaction was found between CEMs and Zn levels and methods of application.

The perusal of the data revealed that the CEMs did not influence significantly the straw yield of rice, but in respect to Zn levels and methods of application, the treatments had significant influence on rice straw yield. The highest rice straw yield was recorded with application of Zn_3 followed by Zn_6 and Zn_2. In comparison to seed coated treatments, Zn_3 resulted in the significantly higher straw yield than other seed coated treatments i.e. Zn_2 and Zn_1 while in comparison to foliar application, Zn_5 resulted in the highest rice straw yield, but no significant variation was observed between the two foliar applied treatments i.e. Zn_4 and Zn_5. No significant

Table 1: Effect of crop establishment methods and zinc levels and their methods of application on yield attributes and yield of rice

Treatment	No. of Panicle m^{-2}	No. of filled grains $panicle^{-1}$	1000-seed weight (g)	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Harvest index (%)
Crop establishment methods						
Direct seeded rice (DSR)	206.03	91.16	22.52	3346.7	4247.6	44.0
Transplanted puddled rice (TPR)	213.03	93.91	23.52	3406.7	4249.0	44.4
SEm±	7.13	2.08	0.83	79.84	144.21	1.36
CD (p=0.05)	NS	NS	NS	NS	NS	NS
CV	16.03	10.10	16.62	11.4	15.9	14.2
Zinc levels and methods of application						
Control (Zn_0)	182.60	87.35	22.25	3024.1	3846.1	43.8
Seed coating of Zn @ 1250 mg kg^{-1} (Zn_1)	207.80	91.55	22.75	3405.0	4243.8	44.6
Seed coating of Zn @ 2500 mg kg^{-1} (Zn_2)	223.70	92.70	23.85	3469.0	4339.9	44.3
Seed coating of Zn @ 3750 mg kg^{-1} (Zn_3)	233.75	96.25	23.65	3827.1	4792.3	44.4
2-foliar sprays of Zn @ 1050 mg kg^{-1} (Zn_4)	190.60	87.90	22.40	3100.5	3851.7	44.6
3-foliar sprays of Zn @ 1050 mg kg^{-1} (Zn_5)	200.45	93.20	22.50	3190.4	4124.5	43.7
2500 mg kg^{-1} seed coating+2-foliar sprays of Zn @ 1050 mg kg^{-1} (Zn_6)	227.80	98.80	23.75	3620.6	4540.0	44.3
SEm±	7.71	2.58	0.88	109.36	148.80	1.44
CD (p=0.05)	22.49	7.54	NS	319.16	434.27	NS
CV	9.26	6.69	9.36	8.3	8.8	8.0
Interaction						
Crop establishment methods within Zn levels and methods of application						
SEm±	15.41	4.85	1.78	196.96	304.65	2.91
CD (p=0.05)	NS	NS	NS	NS	NS	NS
Zn levels and methods of application within crop establishment methods						
SEm±	10.90	3.65	1.24	154.65	210.44	2.03
CD (p=0.05)	NS	NS	NS	NS	NS	NS

Note: Seed rate of 60 kg ha^{-1} for DSR and 40 kg ha^{-1} for TPR were applied; Foliar spray of 1050 mg kg^{-1} @ 500 litres solution ha^{-1}

interaction was found between CEMs and Zn levels and methods of application.

The perusal of the data revealed that various yield attributes of rice viz. panicle per square metre, filled grains $panicle^{-1}$, 1000-seed weight etc and grain and straw yield has been markedly influenced by various levels of Zn and methods of application (Amanullah et al., 2020; Munir et al., 2020; Rashid et al., 2019; Yadav et al., 2018; Kumar et al., 2017; Shivay et al., 2019). The critical perusal of the data revealed that the highest number of panicle m^{-2}, grain as well as straw yields was recorded in seed coating of Zn followed by combined application of seed coating and foliar application. In this context, Farooq et al. (2018) reported that seed coating produced the highest grain and biological yield over soil and foliar application alone. Because, fertilization by Zn containing fertilizer through soil application or seed coating provide availability of rhizospheric Zn (Kabir et al., 2014). Besides, soil application of Zn improved the early seedling growth of rice by modulating the agronomic, water related and biochemical attributes (Zaman et al., 2020).

3.2. Grain and straw zinc concentration

The perusal of the data revealed that the CEMs did not have significant influence on grain zinc concentration of rice (Table 2). Among the CEMs, TPR resulted in higher grain Zn concentration than DSR. However, in respect to Zn levels and methods of application the treatments had significant influence on grain zinc concentration. The highest grain zinc concentration was recorded in Zn_5 followed by Zn_6 and Zn_4. In comparison to seed coated treatments, Zn_3 resulted in the highest grain Zn concentration while in comparison to foliar

Table 2: Effect of crop establishment methods and zinc levels and their methods of application on concentration and uptake of Zn by rice

Treatment	Zn Concentration (mg kg^{-1})		Zn uptake (g ha^{-1})	
	Grain Zn Concentration	Straw Zn Concentration	Grain Uptake	Straw uptake
Crop establishment methods				
Direct seeded rice (DSR)	38.01	70.22	127.66	299.30
Transplanted puddled rice (TPR)	39.11	71.57	133.69	306.82
SEm±	1.28	2.64	6.10	13.60
CD (p=0.05)	NS	NS	NS	NS
CV	12.16	13.99	18.02	17.47
Zinc levels and methods of application				
Control (Zn_0)	25.05	45.23	75.78	175.46
Seed coating of Zn @ 1250 mg kg^{-1} (Zn_1)	33.00	64.18	112.38	272.46
Seed coating of Zn @ 2500 mg kg^{-1} (Zn_2)	35.75	67.68	124.06	295.97
Seed coating of Zn @ 3750 mg kg^{-1} (Zn_3)	38.10	71.48	145.85	342.90
2-foliar sprays of Zn @ 1050 mg kg^{-1} (Zn_4)	43.75	80.08	135.66	309.12
3-foliar sprays of Zn @ 1050 mg kg^{-1} (Zn_5)	47.60	85.78	151.88	352.94
2500 mg kg^{-1} seed coating + 2-foliar sprays of Zn @ 1050 mg kg^{-1} (Zn_6)	46.70	81.88	169.10	372.57
SEm±	2.03	3.42	5.08	14.59
CD (p=0.05)	5.94	9.97	14.82	42.59
CV	10.35	9.68	8.02	10.02
Interaction				
Crop establishment methods within Zn levels and methods of application				
SEm±	3.48	6.29	11.76	29.29
CD (p=0.05)	NS	NS	NS	NS
Zn levels and methods of application within crop establishment methods				
SEm±	2.88	4.83	7.18	20.64
CD (p=0.05)	NS	NS	NS	NS

Note: Seed rate 60 kg ha^{-1} for direct seeded; Foliar spray of 1050 mg kg^{-1} @ 500 litres solution ha^{-1}

application; Zn_5 resulted in the highest grain Zn concentration. No significant variation was observed among the seed coated treatments. Similarly, both the foliar applied treatments i.e. Zn_4 and Zn_5 proved non-significant to each other. No significant interaction was found between CEMs and Zn levels and methods of application.

The perusal of the data revealed that CEMs did not have significant influence on straw zinc concentration of rice. Between the CEMs, TPR resulted in higher straw Zn concentration than DSR. However, with respect to Zn levels and methods of application the treatments had significant influence on straw zinc concentration. The highest straw zinc concentration was recorded in Zn_5 followed by Zn_6 and Zn_4. In comparison to seed coated treatments, Zn_3 resulted in the highest straw Zn concentration while in comparison to foliar application; Zn_5 resulted in the higher straw Zn concentration. No significant variation was observed among the seed coated treatments. Similarly, both the foliar applied treatments i.e. Zn_4 and Zn_5 proved non-significant to each other. No significant interaction was found between CEMs and Zn levels and methods of application.

Grain Zn concentration and straw Zn concentration has been markedly influenced by various levels of Zn and methods of application (Shivay et al., 2015; Hajiboland and Salehi, 2006, Phuphong et al., 2020). As per the results obtained, grain and straw Zn concentration was recorded highest in Zn_5. Interestingly, straw Zn concentration was recorded almost twice of grain Zn concentration (Shivay and Prasad, 2012). In the field study, foliar applied treatments recorded the higher grain and straw Zn concentration than the combined application of both foliar and seed coating (Zn_6); and seed coated treatments. In this regard, Prom-u-thai et al. (2020) reported that irrespective of the rice cultivars used and the diverse soil conditions existing in five major rice-producing countries, the foliar application of the micronutrient solution was highly effective in increasing grain Zn. This was previously cited by Zhang et al. (2012); Shivay and Prasad (2012); Shivay et al. (2015). However, Farooq et al. (2018) reported that seed coating consistently gave the smallest increase in grain Zn concentration while foliar Zn application consistently gave the highest or equal to the highest grain Zn concentration. Foliar Zn spray improved Zn concentration of the new growth formed after foliar spraying which shows that Zn is phloem is mobile and moved from treated leaves into youngest new leaves (Phuphong et al., 2020). More distinct increases in grain Zn by foliar Zn application were achieved when Zn was applied after flowering time, e.g., at early milk plus dough stages (Zhang et al., 2012).

3.3. Grain and straw zinc uptake

The perusal of the data revealed that the CEMs did not influence significantly the grain zinc uptake of rice (Table 2). Between the CEMs, TPR resulted in the higher grain Zn uptake than DSR. Application of different levels and methods of zinc had significant influence on grain zinc uptake. The highest grain zinc uptake was recorded with Zn_6 followed by Zn_5 and Zn_3. In comparison to seed coated treatments, Zn_3 resulted in the highest grain Zn uptake while in comparison to foliar application; Zn_5 resulted in the highest grain Zn uptake. No significant variation was observed among the seed coated treatments as well as foliar applied treatments i.e. Zn_4 and Zn_5. No significant interaction was found between CEMs and Zn levels and methods of application.

The perusal of the data revealed that the CEMs did not influence significantly the rice straw zinc uptake (Table 2). Between the CEMs, TPR resulted in the higher straw Zn uptake than DSR. Application of levels and methods of Zn application had significant influence on rice straw zinc uptake. The highest rice straw zinc uptake was recorded with Zn_6 followed by Zn_5 and Zn_3. In comparison to seed coated treatments, Zn_3 resulted in the highest rice straw Zn uptake which was significantly higher than other two seed coated treatments i.e. Zn_2 and Zn_1. Similarly, in comparison to foliar application, Zn_5 resulted in the highest straw Zn uptake and this treatment was significantly varied with other foliar applied treatment i.e. Zn_4. No significant interaction was found between CEMs and Zn levels and methods of application.

Thus, the current research showed that application of zinc through seed coating was found effective not only in enhancing yield of rice, but its accumulation in the plant was quite low. This method however, found more efficient as measured with different indices as compared to foliar spray alone. The foliar application proved to have little influence on yield but had more zinc accumulation both in grain and straw. Overall, Zn_6 proved best in influencing both grain yield and zinc concentration in both grain and straw.

There was significant influence of Zn levels and methods of application on Zn uptake by rice. The perusal of the data revealed that the highest grain as well as straw Zn uptake was recorded in Zn_6 i.e. combined application of both foliar and seed coating followed by Zn_5 i.e. foliar application and Zn_3 (seed coating). In this context, Shivay et al. (2015) reported that soil+foliar application of zinc sulphate resulted in the highest grain and straw uptake of rice followed by soil application. In the present study, likewise Zn concentration, straw Zn uptake was recorded almost twice of grain Zn uptake. In another study, Shivay and Prasad (2012) reported that foliar spray of $ZnSO_4.7H_2O$ recorded the highest Zn concentration in rice grain and straw and also resulted in the highest Zn uptake by rice under low available Zn concentration (0.36 mg kg^{-1} soil). Further, they also mentioned that, Zn concentration in rice straw was nearly twice that in rice grain. In this regard, Ghasal et al. (2018) reported that application of 1.25 kg Zn/ha (Zn-EDTA) + 1050 mg kg^{-1} foliar spray at maximum tillering and panicle initiation and 2.5 kg ha^{-1} $ZnSO_4.7H_2O$ (ZnSHH)+ 1050 mg kg^{-1} foliar spray at maximum tillering and panicle initiation resulted in higher Zn uptake than other treatments. The combined application of seed coating and foliar spray had positive effect on plants which ultimately led to the productivity. This might be due to effects of seed zinc (Zn) coating on seedling vigour and viability in rice (Prom-u-thai et al., 2012) and further the remobilization of Zn from vegetative parts via phloem to developing grain after foliar spraying (Khampuang et al., 2020).

3.4. Zinc use indices

Zn use-efficiency by rice was quantified in terms of partial factor productivity (PFP), agronomic efficiency (AE), apparent Zn recovery or recovery efficiency (RE), and physiological efficiency (PE). The data on the effect of different CEMs and Zn levels and their application methods on Zn use efficiency in rice are depicted on Table 3.

3.4.1. Agronomic efficiency (AE)

The perusal of the data revealed that the CEMs did not show any significant influence on AE of zinc in rice. While, Zn levels and methods of application treatments had significant influence on AE in rice. A widely varied range was seen among the treatments regarding AE of Zn by rice. The highest AE was obtained from Zn_1 which was significantly higher than other treatments. A decreasing trend was observed in AE with the increase in applied Zn. On the other hand, seed coated treatments showed higher AE than foliar applied treatments as well as combined treatment (Zn_6).

3.4.2. Partial factor productivity (PFP)

The inspection of the data revealed that the CEMs did not show any significant influence on PFP of zinc in rice. While, with respect to Zn levels and methods of application the treatments showed significant influence on PFP of zinc in rice. A widely varied range was seen among the treatments

Table 3: Effect of crop establishment methods and zinc levels and their methods of application on Zn use indices of rice

Treatment	Agronomic efficiency (kg grain increase kg^{-1} Zn applied)	Partial factor productivity (kg grain yield kg^{-1} Zn)	Apparent Zn recovery (%)	Physiological efficiency (kg grain increase kg^{-1} Zn uptake)
Crop establishment methods				
Direct seeded rice (DSR)	1742.44	13149.88	64.09	1724.31
Transplanted puddled rice (TPR)	1742.44	13378.48	64.99	1700.65
SEm±	2.41	80.90	0.43	19.47
CD (*p*=0.05)	NS	NS	NS	NS
CV	10.47	18.13	12.08	13.67
Zinc levels and methods of application				
Control (Zn_0)	0.00	0.00	0.00	0.00
Seed coating of Zn @ 1250 mg kg^{-1} (Zn_1)	5038.80	45039.46	176.71	2852.34
Seed coating of Zn @ 2500 mg kg^{-1} (Zn_2)	2942.59	22942.92	111.63	2643.06
Seed coating of Zn @ 3750 mg kg^{-1} (Zn_3)	3540.67	16874.23	104.72	3384.20
2-foliar sprays of Zn @ 1050 mg kg^{-1} (Zn_4)	72.81	2952.86	18.43	395.85
3-foliar sprays of Zn @ 1050 mg kg^{-1} (Zn_5)	105.60	2025.63	16.10	656.03
2500 mg kg^{-1} seed coating + 2-foliar sprays of Zn @ 1050 mg kg^{-1} (Zn_6)	496.64	3014.17	24.18	2055.88
SEm±	4.20	98.06	0.60	23.52
CD (*p*=0.05)	12.24	286.20	1.74	68.65
CV	9.73	11.75	9.04	8.83
Interaction				
Crop establishment methods within Zn levels and methods of application				
SEm±	6.99	185.75	1.07	44.62
CD (*p*=0.05)	NS	NS	NS	NS
Zn levels and methods of application within crop establishment methods				
SEm±	5.93	138.68	0.85	33.27
CD (*p*=0.05)	NS	NS	NS	NS

Note: Seed rate 60 kg ha^{-1} for direct seeded; Foliar spray of 1050 mg kg^{-1} @ 500 litres solution ha^{-1}

regarding PFP of Zn by rice. The highest PFP was obtained from Zn_1 which was significantly higher than other treatments. A decreasing trend was observed in PFP with the increase in applied Zn. Besides regarding PFP, seed coated treatments showed higher results than both foliar and combined treatment (Zn_6).

3.4.3. Apparent Zn recovery (RE)

The skim of the data revealed that the CEMs did not show any significant influence on RE of zinc in rice. However, with respect to Zn levels and methods of application the treatments showed significant influence on RE of zinc in rice. A widely varied range was seen among the treatments regarding RE of Zn by rice. The highest RE was obtained from Zn_1 which was significantly higher than other treatments. A decreasing trend was observed in RE with the increase in applied Zn. Besides, seed coated treatments showed higher RE than foliar applied treatments as well as combined treatment (Zn_6).

3.4.4. Physiological efficiency (PE)

The perusal of the data revealed that the CEMs did not have significant influence on PE of zinc in rice. However, with respect to Zn levels and methods of application the treatments showed significant influence on PE of zinc in rice. The highest PE was observed with the treatment, Zn_3. In this case also, seed coated treatments showed higher PE than foliar applied treatments as well as combined treatment (Zn_6).

Overall seed coating treatments showed significantly higher zinc use efficiency in respect of AE, PFP, RE and PE. The ranges of AE (5038.8-72.8 kg grain increase kg^{-1} Zn applied), PFP (45039-2025 kg grain yield kg^{-1} Zn), RE (176.7%-16.1%) and PE (3384.2-395.9 kg grain increase kg^{-1} Zn uptake) were widely varied. In this context Farooq et al. (2018) reported that seed coating produced by far the highest agronomic efficiency and apparent recovery, mainly due to the low amount of Zn applied. The agronomic, physiological and agro-physiological apparent recovery and utilization efficiencies was highest at lower level of zinc application and decreased with increase in the Zn doses (Muthukumararaja and Sriramachandrasekharan, 2012). The main cause for low RE for Zn is due to its rapid adsorption over soil organic matter and clay minerals (Hazra and Mandal, 1995) and it's subsequent slow desorption (Mandal et al., 2000).

3.5. Correlation studies

Correlation between Zn levels and Zn concentration in both grain and straw of rice was highly positive with R^2 values of 0.6371 and 0.6643 (Figure 1 and 2). On the other hand, very highly positive correlation was recorded with the Zn levels and Zn uptake by both grain and straw (Figure 3 and 4). Interestingly, the correlation analysis revealed medium strength between grain and straw yield with grain Zn uptake of rice (Figure 5 and 6). The comparison between Zn levels with N, P and K uptakes revealed R^2 value as 0.4995 (Figure 7) in case of N uptake. This indicated medium correlation existed between nitrogen uptake and zinc levels. The strength of correlation was even litter lower (R^2=0.4709) in case of Zn levels and P uptakes (Figure 8). However, Zn levels and K uptake was proved high with R^2=0.5299 (Figure 9).

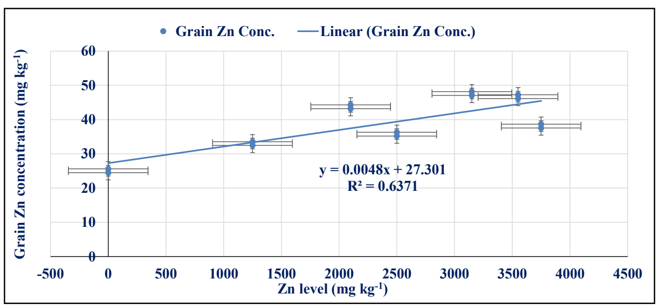

Figure 1: Correlation between Zn level and Zn concentration in grain

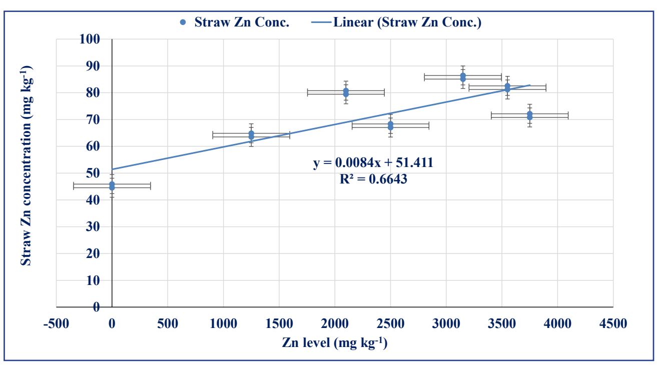

Figure 2: Correlation between Zn level and Zn concentration in straw

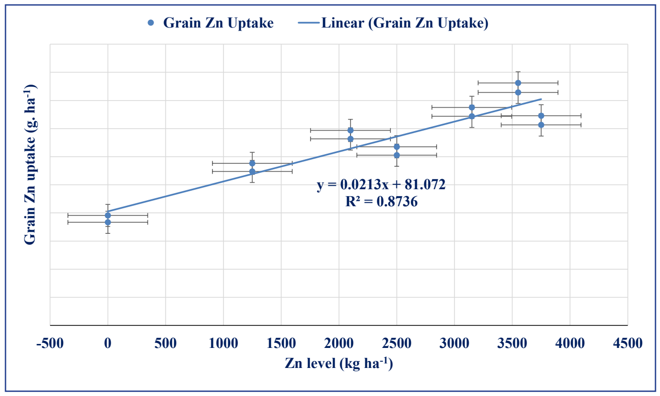

Figure 3: Correlation between Zn level and Zn uptake in grain

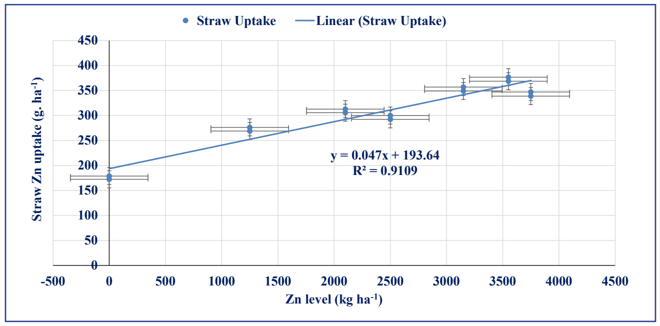

Figure 4: Correlation between Zn level and Zn uptake in straw

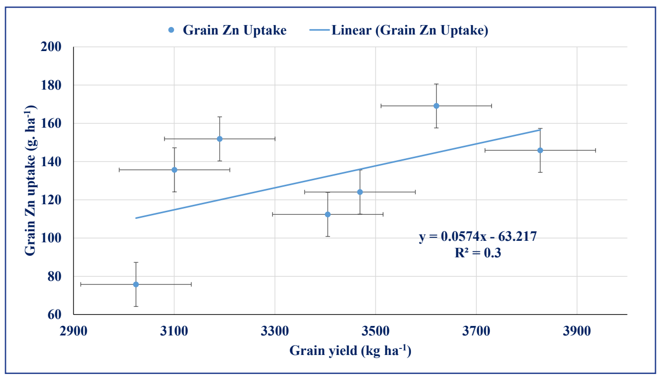

Figure 5: Correlation between grain yield and Zn uptake by grain

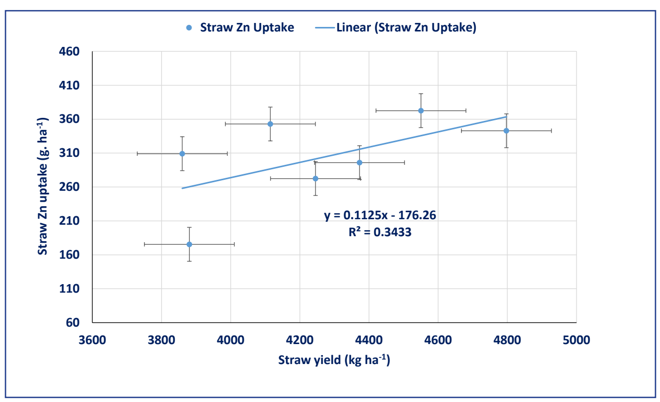

Figure 6: Correlation between straw yield and Zn uptake by straw

Correlation between Zn levels and grain and straw Zn concentration of rice was positive. Stronger correlation was found between Zn levels and grain Zn concentration of rice. Correlation between Zn levels and grain and straw Zn uptake of rice was positive. So, stronger correlation was found between Zn levels and grain Zn uptake of rice. Correlation between grain yield and grain Zn uptake of rice was positive. However, stronger correlation was found between straw yield and straw Zn uptake. In this regard, Shahane et al. (2019) reported that positive correlation between milled rice yield and Zn concentration showed the importance of Zn nutrition in improving rice yield. Yadav et al. (2020) found that correlation analysis showed positive correlation between Zn uptake and grain yield of wheat. Phattarakul et al. (2012) reported that the correlation between grain yield and the effectiveness of foliar Zn application on grain Zn was condition dependent, and was positive and significant at certain conditions.

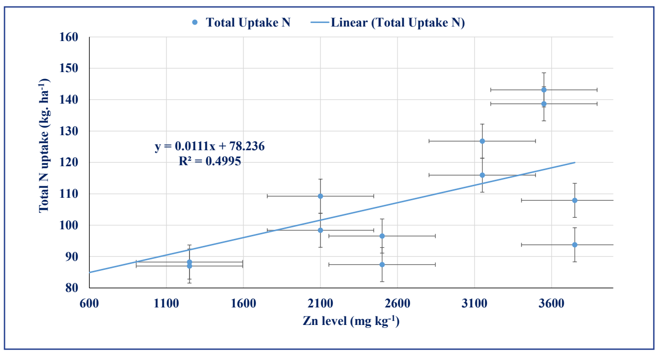

Figure 7: Correlation between Zn level and N uptake

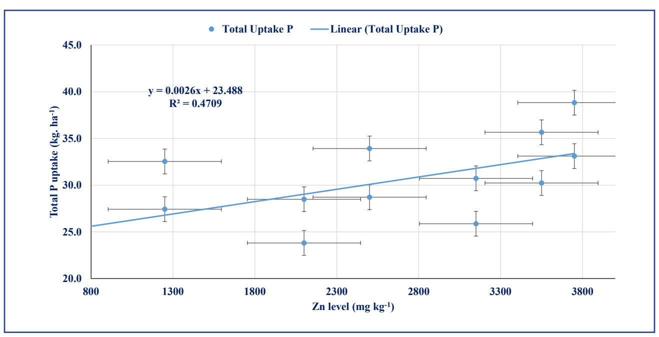

Figure 8: Correlation between Zn level and P uptake

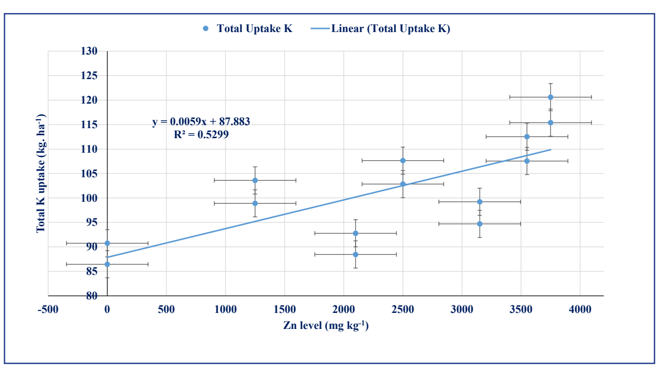

Figure 9: Correlation between Zn level and K uptake

4. Conclusion

Both the CEMs did not show any significant influence on growth, yield and Zn uptake by rice. However, in respect of different zinc levels and methods of application, all of these attributes showed significant difference. Zn_6 resulted significantly highest yield attributes and yield and Zn uptake but remained statistically at par with Zn_5 in most of the cases. Zn_1 recorded highest zinc use indices.

5. References

Abilay, W.P., De Datta, S.K., 1978. Management practices for correcting Zn deficiency in transplanted and direct seeded wet land rice. Philippine Journal of Crop Science 3, 191–194.

Amanullah, Inamullah, Alkahtani, J., Elshikh, M.S., Alwahibi, M.S., Muhammad, A., Ahmad, M., Khalid, S., 2020. Phosphorus and zinc fertilization influence crop growth rates and total biomass of coarse vs. fine types rice cultivars. Agronomy 10(9), 1356.

Anonymous, 2022. Food and agriculture data. The Food and Agriculture Organization of the United Nations, Rome. Available at https://www.fao.org/faostat/en/#data/QCL.

Baligar, V., Fageria, N., He, Z., 2001. Nutrient use efficiency in plants. Communications in Soil Science and Plant Analysis 32, 921–950.

Bell, R.W., Dell, B., 2008. Micronutrients for sustainable food, feed, fibre and bioenergy production. International Fertilizer Industry Association (IFA).

Cakmak, I., 2008. Enrichment of cereal grains with zinc: Agronomic or genetic biofortification? Plant and Soil 302, 1–17.

Cakmak, I., Kalayci, M., Ekiz, H., Braun, H.J., Yilmaz, A., 1999. Zinc deficiency an actual problem in plant and human nutrition in Turkey. A NATO-Science for Stability Project. Field Crops Research 60, 175–188.

Dobermann, A.R., 2005. Nitrogen use efficiency-state of the art. Agronomy-Faculty Publications, 316.

Fageria, N.K., Baligar V.C., 2001. Lowland rice response to nitrogen fertilization. Communications in Soil Science and Plant Analysis 32(9-10), 1405–1429. doi:10.1081/CSS100104202.

Farooq, M., Ullah, A., Rehman, A., Nawaz, A., Nadeem, A., Wakeel, A., Nadeem, F., Siddique, K.H.M., 2018. Application of zinc improves the productivity and biofortification of fine grain aromatic rice grown in dry seeded and puddled transplanted production systems. Field Crops Research 216, 53–62.

Farooq, M., Wahid, A., Siddique, K.H.M., 2012. Micronutrient application through seed treatments-a review. Journal of Soil Science and Plant Nutrition 12, 125–142.

Fisher, W., Ezzati, M., Black, R.E., 2009. Global and regional child mortality and burden of disease attributable to zinc deficiency. European Journal of Clinical Nutrition

63, 591–597.
Ghasal, P.C., Shivay, Y.S., Pooniya, V., Choudhary, M., Verma, R.K., 2018. Zinc partitioning in basmati rice varieties as influenced by Zn fertilization. Crop Journal 6(2), 136–147.
Ghoneim, A.M., 2016. Effect of different methods of Zn application on rice growth, yield and nutrient dynamics in plant and soil. Journal of Agriculture and Ecology Research International 6, 1–9.
Hajiboland, R., Salehi, S.Y., 2006. Characterization of Zn efficiency in Iranian rice genotypes i. Uptake efficiency. General and Applied Plant Physiology 32(3–4), 191–206.
Hambidge, K.M., Miller, L.V., Westcott, J.E., Shang, X., Krebs, N.F., 2010. Zn bioavaiability and homeostasis. The American Journal of Clinical Nutrition 91, 1478S–1483S.
Hanway, J.J., Heidal, H., 1952. Soil analysis methods as used in Iowa State College Soil Testing Laboratory. Iowa State College of Agriculture Bulletin 57, 1–31.
Hazra, G.C., Mandal, B., 1995. Zinc adsorption in soils in relation to soil properties. Indian Journal of Agricultural Sciences 65, 659–664.
Imran, M., Kanwal, S., Hussain, S., Aziz, T., Maqsood, M.A., 2015. Efficacy of zinc application methods for concentration and estimated bioavailability of zinc in grains of rice grown on a calcareous soil. Pakistan Journal of Agricultural Sciences 52, 169–175.
Johnson-Beebout, S.E., Goloran, J.B., Rubianes, F.H.C., Jacob, J.D.C., Castillo, O.B., 2016. Zn uptake behavior of rice genotypes and its implication on grain Zn biofortification. Scientific Reports 6, 38301.
Kabir, A.H., Swaraz, A.M., Stangoulis, J., 2014. Zinc deficiency resistance and biofortification in plant. Journal of Plant Nutrition 177, 311–319.
Kemp, C.D., 1960. Methods of estimating the leaf area of grasses from linear measurements. Annals of Botany 24(4), 491–499.
Khampuang, K., Lordkaew, S., Dell, B., Prom-u-thai, C., 2020. Foliar zinc application improved grain zinc accumulation and bioavailable zinc in unpolished and polished rice. Plant Production Science. doi:10.1080/134394 3X.2020.1797512.
Khan, M.U., Qasim, M., Subhan, M., Jamil, M., Ahmad, R.D., 2003. Response of rice to different methods of Zn application in calcareous soils. Pakistan Journal of Engineering and Applied Sciences 3, 524–529.
Kumar, A., Sen, A., Upadhyay, P.K., Singh, R.K., 2017. Effect of zinc, iron and manganese levels on quality, micro and macro nutrients content of rice and their relationship with yield. Communications in Soil Science and Plant Analysis 48(13), 1539–1551.
Kuzhivilayil, S.J., Anju, P.S., Suja, G., Mathew, J., Shivay, Y.S., 2019. Zinc nutrition in tropical tuber crops: A review. Indian Journal of Agronomy 64(1), 1–10.
Lindsay, W.L., Norvell, W.A., 1978. Development of DTPA soil test for zinc, iron, manganese and copper. Soil Science Society of America Journal 42, 421–428. http://dx.doi.org/10.2136/sssaj1978.03615995004200030009x.
Mandal, B., Hazra, G.C., Mandal, L.N., 2000. Soil management influences on zinc desorption for rice and maize nutrition. Soil Science Society of America Journal 64, 1699 –1705.
McLean, J.L., Dawe, D.C., Hardy, B., Hettel, C.P., 2002. Rice Almanac, third ed. CABI Publishing, Wallingford, UK, p. 2533.
Munir, M., Khan, A., Khan, S.M., Khan, S.A., Saeed, M., Bari, A., 2020. Phenology and yield of coarse and fine rice under varying levels of zinc and farmyard manure. Pakistan Journal of Botany 52(2), 557–564.
Muthukumararaja, T.M., Sriramachandrasekharan, M.V., 2012. Effect of zinc on yield, zinc nutrition and zinc use efficiency of lowland rice. Journal of Agricultural Technology 8(2), 551–561.
Olsen, S.R., 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate (No. 939). US Department of Agriculture.
Panse, V.G., Sukhatme, P.V., 1985. Statistical method of Agricultural workers. ICAR, New Delhi, 152–159.
Phattarakul, N., Rerkasem, B., Li, L.J., Wu, L.H., Zou, C.Q., Ram, H., Sohu, V.S., Kang, B.S., Surek, H., Kalayci, M., Yazici, A., Zhang, F.S., Cakmak, I., 2012. Biofortification of rice grain with zinc through zinc fertilization in different countries. Plant and Soil 361, 131–141.
Phuphong, P., Cakmak, I., Yazici, A., Rerkasem, B., Prom-u-Thai, C., 2020. Shoot and root growth of rice seedlings as affected by soil and foliar zinc applications. Journal of Plant Nutrition 43(9), 1259–1267.
Prasad, R., 2006. Zinc in soils and in plant, human and animal nutrition. Indian Journal of Fertilizers 2, 103–119.
Prasad, R., 2009. Zinc malnutrition and its alleviation through zinc fortified cereal grains. In: Proceedings of the Indian National Science Academy 75, 89–91.
Preetha, P.S., Stalin, P., 2014. Response of maize to soil applied zinc fertilizer under varying available zinc status of soil. Indian Journal of Science and Technology 7(7), 939–944.
Prom-u-thai, C., Rashid, A., Ram, H., Zou, C.Q., Guilherme, L.R.G., Corguinha, A.P.B., Guo, S.W., Kaur, C., Naeem, A., Yamuangmorn, S., Ashraf, M.Y., Sohu, V.S., Zhang, Y.Q., Martins, F.A.D., Jumrus, S., Tutus, Y., Yazici, M.A., Cakmak, I., 2020. Simultaneous biofortification of rice with zinc, iodine, iron and selenium through foliar treatment of a micronutrient cocktail in five countries. Frontiers in Plant Science 11. doi: 10.3389/fpls.2020.589835.
Prom-u-thai, C., Rerkasem, B., Yazici, A., Cakmak, I., 2012. Zinc priming promotes seed germination and seedling vigor of rice. Journal of Plant Nutrition and Soil Science 175(3), 482–488.
Ram, H., Sohu, V.S., Cakmak, I., Singh, K., Buttar, G.S., Sodhi, G.P.S., Gill, H.S., Bhagat, I., Singh, P., Dhaliwal, S.S., Mavi,

G.S., 2015. Agronomic fortification of rice and wheat grains with zinc for nutritional security. Current Science 109, 1171–1176.

Rashid, A., Ram, H., Zou, C.Q., Rerkasem, B.A., Duarte, A.P., Simunji, S., Yazici, A., Guo, S., Rizwan, M., Bai, R.S., Wang, Z., Malik, S.S., Phattarakul, N., de Freitas, R.S., Lungu, O., Barros, V.L.N.P., Cakmak, I., 2019. Effect of zinc-biofortified seeds on grain yield of wheat, rice, and common bean grown in six countries. Journal of Plant Nutrition and Soil Science 182(5), 791–804.

Rehman, A., Farooq, M., Nawaz, A., Ahmad, R., 2016. Improving the performance of short-duration basmati rice in water-saving production systems by boron nutrition. Annals of Applied Biology 168, 19–28.

Rehman, H., Aziz, T., Farooq, M., Wakeel, A., Rengel, Z., 2012. Zinc nutrition in rice production systems. Plant and Soil 361, 203–226.

Shahane, A.A., Shivay, Y.S., Kumar, D., Prasanna, R., 2019. Zinc nutrition of rice as influenced by crop establishment methods, rates of nitrogen and phosphorus fertilization and inoculation with microbial consortia. Journal of Plant Nutrition 42(16), 1967–1981. https://doi.org/10.1080/01904167.2019.1636066.

Shivay, Y.S., Prasad, R., 2012. Zinc-coated urea improves productivity and quality of basmati rice (*Oryza sativa* L.) under zinc stress condition. Journal of Plant Nutrition 35, 928–951. doi:10.1080/01904167.2012.663444.

Shivay, Y.S., Prasad, R., Singh, R.K., Pal, M., 2015. Relative efficiency of zinc-coated urea and soil and foliar application of zinc sulphate on yield, nitrogen, phosphorus, potassium, zinc and iron biofortification in grains and uptake by basmati rice (*Oryza sativa* L.). Journal of Agricultural Science 7(2). doi: 10.5539/jas.v7n2p161.

Shivay, Y.S., Pooniya, V., Pal, M., Ghasal, P.C., Bana, R., Jat, S.L., 2019. Coated urea materials for improving yields, profitability, and nutrient use efficiencies of aromatic rice. Global Challenges 3(12).

Singh, M.V., 2011. Assessing extent of zinc deficiency for soil factors affecting and nutritional scarcity in humans and animals. Indian Journal of Fertiliser 7(10), 36–43.

Slaton, N.A., Wilson Jr., C.E., Ntamatungiro, S., Norman, R.J., Boothe, D.L., 2001. Evaluation of zinc seed treatments for rice. Agronomy Journal 93, 152–157.

Subbiah, B., Asija, G.L., 1956. Alkaline permanganate method of available nitrogen determination. Current Science 25, 259–260.

Takkar, P.N., Singh, M.V., Ganeshmurthy, A.N., 1997. Micronutrients and trace elements. In: Kanwar, J.S., Katyal, J.C. (Eds.), Plant nutrient needs, efficiency and policy issues, 2000-2025. National Academy of Agricultural Sciences, New York, P. 238–264.

Walkley, A., Black, I. A., 1934. An examination of the degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Science 34, 29–38.

Wastney, M.E., Aamodt, R.L., Rumble, W.F., Henkin, R.I., 1986. Kinetic analysis of zinc metabolism and its regulation in normal humans. The American Journal of Physiology 251, R398–R408.

Watson, D.T., 1952. The physiological basis of variation in yield. Advances in Agronomy 4, 101–145.

Welch, R.M., Graham, R. D., 2004. Breeding for micronutrients in staple food crops from a human nutrition perspective. Journal of Experimental Botany 55, 353–364.

Yadav, D., Shivay, Y.S., Singh, Y.V., Sharma, V.K., Bhatia, A., 2018. Yield attributes, yields and nutrient uptake of Basmati rice (*Oryza sativa*) as influenced by in-situ and ex-situ green manuring crops and zinc fertilization. Indian Journal of Agricultural Sciences 88(5), 671–678.

Yadav, D., Shivay, Y.S., Singh, Y.V., Sharma, V.K., Bhatia, A., 2020. Enhancing nutrient translocation, yields and water productivity of wheat under rice–wheat cropping system through zinc nutrition and residual effect of green manuring. Journal of Plant Nutrition 43(4), 1–12.

Zaman, Q.U., Aslam, Z., Rashid, M., Aslam, A., Ehsan, N., Riaz, U., Abbas, R.N., Iqbal, A., Naeem, M.S., Bashir, S., Saqib, Z.A., Yaseen, M., 2020. Zinc nutrition application augments morpho-physiological attributes, productivity, and grain zinc bioavailability of Paddy Rice. Journal of Applied Botany and Food Quality 93, 11–19.

Zhang, Y.Q., Sun, Y.X., Ye, Y.L., Karim, M.R., Xue, Y.F., Yan, P., Meng, Q.F., Cui, Z.L., Cakmak, I., Zhang, F.S., 2012. Zinc biofortification of wheat through fertilizer applications in different locations of China. Field Crops Research 125, 1–7.

