Indian Journal of Agronomy **60** (3): 391–402 (September 2015)

Research Paper

Impact of zinc application methods on zinc concentration and zinc-use efficiency of popularly grown rice (*Oryza sativa*) cultivars

BHOLANATH SAHA[1], SUSHANTA SAHA[2], GORA CHAND HAZRA[3], SUSMIT SAHA[4], NIRMALENDU BASAK[5], ANUPAM DAS[6] AND BISWAPATI MANDAL[7]

Bidhan Chandra Krishi Viswavidyalaya, Kalyani, Nadia, West Bengal 741 235

Received : February 2015; Revised accepted : August 2015

ABSTRACT

In the present investigation, 26 rice (*Oryza sativa* L.) cultivars *viz*., some locals, aromatics, high yielding varieties (HYVs) and hybrids were evaluated for yield efficiency, Zn content in grains and also Zn recovery efficiency in a strip plot design during the rainy (*kharif*) season for the consecutive 2 years (2009 and 2010) under varied Zn application practices. Rice cultivars differed significantly in their yield and native Zn contents as well as recovery of applied Zn allocation in grains, straw and roots. Grain and straw yields as well as harvest index of different cultivars showed wide variations both with and without Zn applications. On an average, grain yields of different rice cultivars increased by 29 and 22% with soil + foliar and only soil application of Zn, respectively. HYVs showed highest yield efficiency followed by hybrid, aromatic and local cultivars, irrespective of methods of Zn fertilization. The content of native Zn in whole rice grain was the highest in aromatics (27.8 mg/kg) followed by locals (26.3 mg/kg), HYVs (23.0 mg/kg) and hybrids (22.0 mg/kg). Zinc content in whole grains increased significantly in all the cultivars with Zn-application and the magnitude of increase was higher when Zn was applied as soil + foliar application (118%) than soil application only (30%). Zinc concentration in milled grains increased to the extent of 29.5 and 119.5% upon soil application and soil + foliar application of Zn fertilizers. In rice bran and husk Zn concentration increased to the extent of 21 and 155% and 41 and 373% through soil and soil + foliar application, respectively. Zinc-use efficiency varied from 0.53 to 2.83% with a mean value of 0.90% upon soil application of 20 kg Zn as $ZnSO_4.7H_2O$ and 1.89 to 4.80% with a mean value of 2.74% upon application of 20 kg Zn as $ZnSO_4.7H_2O$ with two foliar spray @ 0.5% $ZnSO_4.7H_2O$ solution *i.e.* soil + foliar applied Zn increased the Zn-use efficiency, on an average, three fold than with only soil applied Zn. Thus, soil + foliar application of Zn offers a useful means for enriching rice grain Zn concentrations irrespective of the cultivars tested and contributed towards enhanced Zn-use efficiency by rice.

Key words : Grain yield, Milled rice, Rice bran, Rice cultivars, Soil plus foliar applied Zn, Zn content, Zn-use efficiency

In modern agriculture micronutrients are becoming deficient day by day due to intensive cultivation with high yielding varieties of crops using high analysis fertilizers, which not only reduces the crop productivity but also deteriorates the quality of produce. Micronutrient malnutrition affects more than half of the world population particularly in developing countries (Alloway, 2008) and in particular, Fe and Zn deficiency in human nutrition are widespread in developing Asian countries including India, where cereal grains are the staple food (Prasad *et al.*, 2014). Among the micronutrients, zinc deficiency is widespread throughout the world particularly in lowland rice fields causing decreased crop yields (Hazra *et al*., 1987; Mandal *et al*., 2000) and nutritional quality (Shivay *et al*., 2010; Shivay and Prasad, 2012; Impa *et al.,* 2013). Generally, the regions in the world with Zn-deficient soils are also characterized by widespread under nourishment from Zn nutrition in livestock and human. Recent estimates indicate that nearly half of the world population suffers from

[1]**Corresponding author Email**: bnsaha1@gmail.com
[1]Assistant Professor (Soil Science), College of Horticulture, Bihar Agricultural University, Noorsarai, Nalanda, Bihar 803 113; [2]Assistant Professor (Soil Science), Directorate of Research; [3,7]Professor (Soil Science), Department of Agricultural Chemistry & Soil Science, Bidhan Chandra Krishi Viswavidyalaya, Kalyani, Nadia, West Bengal 741 235; [4]Assistant Professor (Soil Science), College of Agriculture, Burdwan Campus, Bidhan Chandra Krishi Viswavidyalaya, Burdwan, West Bengal 713 101; [5]Scientist, Division of Soil and Crop Management, ICAR-Central Soil Salinity Research Institute, Karnal, Haryana 132 001; [6]Assistant Professor (Soil Science), Bihar Agricultural College, Bihar Agricultural University, Sabour, Bhagalpur, Bihar 813 210

Zn deficiency (Cakmak, 2008). Rice is the staple food for more than half of the world population and plays an important role in satisfying daily calorie intake in developing world (Maclean *et al.,* 2002), but they are inherently very low in Zn concentrations in grains, particularly when grown on Zn-deficient soils (Mandal *et al.,* 2000).

Nearly 50% of cultivated soils in India are low in plant available Zn and, these soils are under intensive cultivation of wheat and rice with no or little application of Zn fertilizers. In West Bengal, on an average, about 30% of cultivated soils are deficient in plant available Zn (Singh, 2009). Zinc deficiency is most commonly corrected by application of zinc sulphate ($ZnSO_4.7H_2O$) as of its high solubility and low cost (Mollah *et al.,* 2009; Fageria *et al.,* 2011). Two separate foliar application of 0.5% (w/v) $ZnSO_4.7H_2O$ either before or after heading stage have been found effective in doubling Zn concentration in grain of the high yielding varieties of rice (Cakmak *et al.,* 2010); while application of 5 kg Zn/ha was found sufficient for aromatic rice grown in rice-wheat cropping system under north Indian belt (Shivay *et al*., 2010). Developing rice variety with high Zn content through the process of "biofortification" aims to combine high mineral content with grain quality (Prasad *et al.*, 2012) and agronomic characteristics, such as high yield and pest and disease resistance, and to ensure acceptability by farmers and consumers (Graham *et al.,* 2001).

In view of the discussion above, providing Zn to plants (for example, by applying Zn-fertilizers to soil and/or to foliar) appears to be important to ensure success of breeding efforts for increasing Zn concentration in grains. Fertilization strategy could be a rapid solution to the problem and can be considered an important complementary approach to the on-going breeding programs. Fertilizer studies focusing specifically on increasing Zn concentration of grains (or other edible parts) are, however, very rare, although a large number of studies are available on the role of soil and foliar applied Zn fertilizers in correction of Zn deficiency and increasing plant growth and yield (Rengel *et al*., 1999 and Cakmak, 2008). Therefore, screening of elite cultivars containing higher content of this nutritionally important element and assessing their Zn use efficiencies upon different modes of Zn fertilization has become a high priority research for overcoming Zn related nutritional disorders in human, plant and animal.

MATERIALS AND METHODS

The study was conducted in *kharif* season (summer) for the consecutive two years (2009 and 2010) at the Central Research Farm of Bidhan Chandra Krishi Viswavidyalaya, Kalyani, West Bengal, India located at 22° 58.114' N latitude and 88° 29.543' E longitude. The soils of the experimental plot had clay loam texture, pH 6.6 (Page *et al*., 1982), organic carbon 8.9 g/kg (Walkley and Black, 1934), available Fe 215.8 mg/kg, available Mn 16.0 mg/kg, available Zn 0.7 mg/kg (marginally deficient in plant available Zn as critical limit of available Zn for anaerobic rice is 0.8 mg/kg) and available Cu 6.0 mg/kg (Lindsay and Norvell, 1978). Twenty six popularly grown rice cultivars including two locals, four aromatics, seventeen high yielding varieties (HYVs) and three hybrids with wide genetic variation were raised with standard management practices. The details of the rice cultivars used in the experimentation with their parentages are mentioned in Table 1. Weather conditions like rainfall, maximum and minimum temperature and relative humidity during the crop growth period (June to September) were 1265 mm, 32.0°C, 26.3°C and 97% during 2009 and 987 mm, 32.6ºC, 25.1ºC and 94% during 2010, respectively. Paddy seeds were grown in a nursery bed following standard methods of nursery raising and transplanted to the main field according to their crop growth duration. The seed bed was saturated with water for first four days and then water level was increased gradually up to 5 cm as the seedling grows. Seedlings were transplanted to the main field at an age of 25 days. Flooding method of irrigation was applied depending on rainfall pattern during the crop growth period to maintain water requirement. Three Zn treatments, viz. no Zn (Zn_0), @ 20 kg Zn/ha as zinc sulphate heptahydrate ($ZnSO_4.7H_2O$) as basal (Zn_1) and @ 20 kg Zn/ha as basal + 2 foliar sprays of Zn–one at pre-flowering and another at grain forming stage @ 0.5% $ZnSO_4.7H_2O$ were imposed. Zinc fertilizer was applied in soil at the time of land preparation through broadcast, followed by surface incorporation. Treatments were imposed in a strip plot design having three replications. As the rice cultivars varied widely in their genetic make-up, initiation of flowering was at different times in the growing season, therefore spraying was done at different days after transplanting according to the initiation of flowering. NPK fertilizers were applied as per the recommended dose in all the plots of the experimental field (80:40:40). Half of the dose of nitrogen was given at the time of transplanting and the other half at tillering stage. The entire amount of P and K were applied at the time of transplanting (through $N:P_2O_5:K_2O$:10:26:26). The brown plant hopper (*Nilaparvata lugens*) (BPH) and gundhy bug (*Leptocorisa acuta*) have been observed as major pests of rice during early crop establishing stage and milky stage, respectively. The Imidachloprid @ 100 ml/ha and Carbaryl @ 25 kg/ha were used on the crop and found to be most effective against BPH and gundhy bug infesting rice, respectively.

At maturity, the rice cultivars were harvested plot-wise and representative samples of whole grains, straw and roots were collected and subsequently processed for dry-ashing in a muffle furnace at 475°C for 4 hour and then the Zn concentration was measured by using an atomic absorption spectrophotometer (GBC *Avanta*). Harvest index (HI) of different cultivars was calculated as grain yield divided by biomass yield (grain yield + straw yield). The zinc-use efficiency (ZnUE) or apparent Zn recovery was calculated as Zn uptake in Zn treated plot subtracted from control plot per unit amount of the said nutrient applied.

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

Whole rice grains of each cultivars were then de-hulled and milled taking 100g samples each in a milling machine (SATAKE, Japan). Partitioning of whole grains produced three different components, *viz.,* husk (lemma and palea together), bran (embryo and aleurone layer) and white/milled/clean rice. Zinc concentration of the constituent parts are then analysed as mentioned previously. Analysed data of the aforesaid experimental trial were also pooled for the consecutive two years *i.e.* 2009 and 2010 are presented. Experimental design followed for statistical analysis is strip plot. All variables presented here are quantitative in nature and large in number assumed to follow normal distribution. The hypotheses under test are equality of means due to variety, Zn and their interactions.

RESULTS AND DISCUSSION

Grain and straw yields and harvest index (HI) of the rice cultivars

Grain and straw yields as well as HI varied significantly among the tested cultivars. Externally applied Zn through soil as well as soil + foliar significantly increased the grain and straw yields irrespective of the cultivars grown. Maximum grain yield was recorded with high yielding followed by hybrid, aromatic and local cultivars (Table 2). On an average, grain yield of rice cultivars varied from 1.08 to 3.53 t/ha in locals and HYVs respectively when grown under control. Highest grain yield of 6.67 t/ha as well as lowest grain yield of 1.28 t/ha was recorded in ‘Swarna’, a high yielding cultivar, and ‘Kalma 222’, a local cultivar respectively with soil + foliar application of Zn. Application of Zn as basal (@ 20 kg Zn/ha) with 2 foliar spray @ 0.5% $ZnSO_4.7H_2O$ showed a significant increase of grain yield compared to only soil application as well as no Zn treatment. Application of Zn through soil increased the grain yield to the tune of 0.67 t/ha *i.e.* 22% and as soil + foliar increased the same to 0.88 t/ha *i.e.* 29% respectively over control. Increasing grain yield by 16.5% upon application of 2.5 kg Zn/ha was reported by Bandara and Silva (2000) while 15% increase in grain yield upon application of 5 kg Zn/ha was reported by Rahman *et al.* (2008) and Shivay *et al.* (2010). A significant increase in grain yield upon Zn fertilization and its variations among the upland rice cultivars was also reported by Fageria and Baligar (2005).

Straw yield of the rice cultivars also recorded a significant increase upon Zn application, the magnitude being higher with soil + foliar application of Zn than only soil application. Highest straw yield was recorded in locals (13.56 t/ha) followed by hybrids (11.35 t/ha), aromatics (10.70 t/ha) and HYVs (8.60 t/ha) upon soil + foliar application of Zn fertilizers (Table 2). On an average, straw yield of rice varied from 4.79 to 14.51 t/ha with a mean value of 9.02 t/ha. Application of only soil applied Zn increased the straw yield to the tune of 0.97 t/ha *i.e.* 12% over no Zn treatment; and application of soil + foliar spray increased Zn to the level of 1.4 t/ha *i.e.* 17% over the control.

Results also showed that application of Zn fertilizers enhanced the transfer of photosynthates from shoot to grain *i.e.* the harvest index (HI) of rice cultivars increased upon Zn fertilizer application. The HI of the tested cultivars showed wide variations with following the trend HYV> hybrid> aromatic> local (Table 2). The lowest HI of 0.09 was recorded in “FR 43B’ and ‘Kalma 222’, local cultivars in control and highest HI of 0.51 was recorded in the cultivar ‘GB 1’, a HYV with soil + foliar application of Zn. Application of Zn both through soil and soil + foliar caused a significant increase in HI over control excepting of aromatic cultivars. On an average, about 6.5 to 7.5% increase in HI was found with application of soil and soil + foliar application of Zn over the control.

Zn in whole grains, straw and roots of the rice cultivars

Content of native Zn in rice grain was higher in aromatics (27.8 mg/kg) followed by locals (26.3 mg/kg), HYVs (23.0 mg/kg) and hybrids (22.0 mg/kg), respectively (Table 3). On an average, Zn concentration in grains of the tested cultivars varied from 17.3 to 75.3 mg/kg with a mean value of 35.6 mg/kg. Results also showed that Zn content in grain was significantly increased in all the cultivars upon Zn application over control and the magnitude of increase was higher with soil + foliar application (118%) compared to only soil application of Zn (30%). Cakmak (2008) and Pooniya and Shivay (2011) also reported ~2.5 times increase in grain Zn content of rice upon soil + foliar application of Zn. The highest grain Zn (75.3 mg/kg) was recorded in the cultivar ‘PNR 519’, a high yielding cultivar upon soil + foliar application of Zn and the lowest (17.3 mg/kg) was in ‘Khitish’, a high yielding cultivar without addition of Zn *i.e.* control. Regarding grain Zn content the different categories of the cultivars were also varied significantly and their relative efficiency in this respect was higher with hybrid followed by HYV, local and aromatic respectively.

Results further revealed that enrichment of grain Zn is not only varied among the cultivars but also the methods of Zn application. Cultivars efficient in grain Zn enrichment were ‘PHB 71’, ‘Lalat’, ‘PNR 519’, ‘PA 6444’ and ‘Triguna’ when Zn was applied as basal. However, Zn content also increased in cultivar ‘PNR 519’, ‘GB 1’, ‘Lalat, Rasi’ and ‘PHB 571’, when Zn was applied as soil + foliar. Low Zn responsive cultivars regarding their grain Zn enrichment upon Zn application were also sorted out and they were ‘Badshabhog’, ‘Gobindabhog’, ‘Gayasura’, ‘Kalma’, ‘Bhudev’ and ‘Swarna’. So, from the results it can be opined that grain Zn enrichment efficiency of the rice cultivars varied widely upon Zn applications owing to their variation in genetic make-up. This is corroborated with the view of Martinez *et al*. (2010) and Phattarakul *et al*. (2012).

Native Zn concentration in shoot of rice cultivars (Table 3) followed the trend aromatics (38.9 mg/kg) = locals (38.9 mg/kg) > HYVs (31.7 mg/kg) > hybrids (30.6 mg/kg). Zn concentration in shoot varied from 22.8 to 99.9 mg/kg with a mean value of 51.5 mg/kg. Application of only soil applied Zn increased the shoot Zn concentration to the tune of 11.4 mg/kg i.e. 34% over no Zn treatment. Whereas, application of Zn through soil + foliar spray increased Zn content to the level of 43.5 mg/kg *i.e.* 131% over no Zn treatment. Variation of Zn concentration in grains and shoots of the tested cultivars also showed a statistically significant relationship for methods of application of Zn fertilizers.

Zn concentration in roots of the twenty six cultivars varied from 41.2 to 236.2 mg/kg with a mean value of 149.4 mg/kg. Varietal differences in root Zn content followed the trend: locals (233.9 mg/kg) > aromatics (207.3 mg/kg) > hybrids (204.0 mg/kg) > HYVs (202.6 mg/kg) indicating that roots of the former cultivars could accumulate a significantly higher amount of Zn than the latter. Application of Zn through soil and soil + foliar increased the Zn concentration in roots to the extent of 2.25 and 2.5 times more respectively over control (Table 3).

Table 1. List of cultivars used for this experiment along with their IET No. and parentages

Type	IET No.	Parentage
Local		
‘FR 43B ‘	-	Indigenous improved
‘Kalma 222’	-	Indigenous improved
HYVs		
‘Sabita’	8970	Pure selection from Boyan
‘IR 36’	4555	IR 1561-228-1-2/IR 1737
‘Khitish’	4094	Bulk/CR 115
‘Satya’	7720	Telhamsa/Rasi
‘Triguna’	12875	Swarna dhan/ RP 1579-38
‘Bhudev’	14496	Pankaj/ IR 38699-493-1-2/ IR 41389-20-5
‘Swarna sub1’	7041	Basishthya/Masuri and incorporation of submergence tolerant gene
‘Samba masuri sub1’	11521	GEB 24/ TN 1/ Masuri and incorporation of submergence tolerant gene
‘Satabdi’	4786	CR 10-114/ CR 10-115
‘IR 64’	9671	IR 5657-33-2-1/ IR 2061-465-1-5-5
‘Samba masuri’	11521	GEB 24/ TN 1/ Masuri
‘Lalat’	9947	OBS-677/ IR 2071/ Bikram/ W 1263
‘Swarna’	7041	Basishthya/Masuri
‘GS 2’		Selection from Assam rice
‘GS 1’		Selection from Assam rice
‘Rasi’	1444	TN 1/ CO 29
‘PNR 519’	9944	Tainan 3/ Basmati 370//PNR 417-3
Aromatic		
‘Gobindabhog’		Selection from local scented
‘Badshabhog’		Selection from local scented
‘PNR 546’	11347	PNR 125-2/ PNR 1300-2
‘Gayasura’		Traditional
Hybrids		
‘KRH 2’	15065	IR 58025A/ KMR-3
‘PHB 71’	-	Released from Company
‘PA 6444’	6444	Released from Company

Table 2. Influence of Zn application on the grain, straw yield and HI of different rice cultivars

Type of cultivar	Name of the cultivar	Grain yield (t/ha)				Straw yield (t/ha)				HI			
		Zn_0	Zn_1	Zn_2	Mean	Zn_0	Zn_1	Zn_2	Mean	Zn_0	Zn_1	Zn_2	Mean
High yielding varieties	'Sabita'	3.56	4.19	4.28	4.01	11.79	12.55	13.17	12.50	0.233	0.251	0.246	0.243
	'IR 36'	2.62	3.42	3.65	3.23	5.35	5.52	5.79	5.55	0.329	0.382	0.387	0.366
	'Khitish'	3.40	4.14	4.19	3.91	5.22	5.71	5.79	5.58	0.395	0.420	0.420	0.412
	'Satya'	3.46	3.87	4.08	3.81	7.49	9.35	10.00	8.94	0.317	0.293	0.290	0.300
	'Triguna'	2.81	3.83	4.33	3.66	5.37	5.83	5.97	5.73	0.343	0.396	0.420	0.386
	'Bhudev'	4.40	5.08	5.44	4.98	10.85	12.90	13.72	12.49	0.289	0.283	0.284	0.285
	'Swarna sub1'	4.32	5.28	5.42	5.00	8.47	8.94	9.12	8.85	0.338	0.371	0.373	0.360
	'Samba masuri sub1'	2.78	3.93	4.25	3.65	7.81	9.04	9.51	8.79	0.263	0.303	0.309	0.291
	'Satabdi'	2.28	2.86	3.04	2.73	4.79	5.39	5.44	5.21	0.322	0.347	0.359	0.342
	'IR 64'	2.57	3.54	3.83	3.31	6.57	7.49	7.61	7.22	0.281	0.321	0.334	0.312
	'Samba masuri'	3.32	4.03	4.21	3.85	8.53	9.56	10.15	9.41	0.280	0.297	0.293	0.290
	'Lalat'	2.72	3.43	4.04	3.40	8.40	10.36	10.82	9.86	0.245	0.249	0.272	0.255
	'Swarna'	5.87	6.51	6.67	6.35	12.65	13.51	14.51	13.56	0.318	0.326	0.315	0.319
	'GB 2'	4.11	4.56	4.81	4.49	5.28	5.62	5.92	5.61	0.438	0.448	0.448	0.445
	'GB 1'	5.37	6.29	6.44	6.04	5.83	6.07	6.26	6.06	0.480	0.509	0.507	0.499
	'Rasi'	3.15	3.99	4.08	3.74	4.79	5.74	6.06	5.53	0.397	0.410	0.403	0.403
	'PNR 519'	3.28	3.85	4.10	3.75	5.43	6.24	6.33	6.00	0.377	0.382	0.393	0.384
	Mean	3.53	4.28	4.52	4.11	7.33	8.22	8.60	8.05	0.332	0.352	0.356	0.347
Hybrids	'KRH 2'	3.33	4.37	4.79	4.17	6.10	6.60	7.67	6.79	0.354	0.399	0.385	0.379
	'PHB 71'	2.43	2.90	2.97	2.77	11.01	11.79	11.96	11.59	0.181	0.198	0.199	0.193
	'PA 6444'	2.84	3.85	4.08	3.59	13.49	13.99	14.42	13.96	0.174	0.216	0.221	0.204
Mean		2.87	3.71	3.95	3.51	10.20	10.79	11.35	10.78	0.236	0.271	0.268	0.259
Local	'FR 43B'	1.14	1.58	1.68	1.47	12.28	13.67	14.24	13.39	0.085	0.104	0.107	0.099
	'Kalma 222'	1.01	1.26	1.28	1.19	10.42	12.17	12.87	11.82	0.089	0.094	0.090	0.091
	Mean	1.08	1.42	1.48	1.33	11.35	12.92	13.56	12.61	0.087	0.099	0.099	0.095
Aromatic	'Gayasur'	1.96	2.53	2.65	2.38	8.57	10.60	11.12	10.10	0.186	0.194	0.193	0.191
	'Gobindabhog'	2.26	2.61	2.74	2.54	9.87	11.15	11.58	10.87	0.187	0.190	0.191	0.189
	'Badshabhog'	2.43	2.71	2.83	2.66	11.69	12.49	12.92	12.37	0.172	0.178	0.180	0.177
	'PNR 546'	2.42	2.76	2.85	2.68	5.78	6.92	7.19	6.63	0.295	0.286	0.284	0.288
	Mean	2.27	2.65	2.77	2.57	8.98	10.29	10.70	9.99	0.210	0.212	0.212	0.211
	Overall mean	3.07	3.75	3.95	3.59	8.22	9.20	9.62	9.02	0.283	0.302	0.304	0.296

	Grain yield SEm±	Grain yield CD (P=0.05)	Straw yield SEm±	Straw yield CD (P=0.05)	HI SEm±	HI CD (P=0.05)
Variety	0.037	0.104	0.088	0.246	0.003	0.008
Zn	0.019	0.061	0.032	0.104	0.001	0.004
Variety × Zn	0.06	0.168	0.115	0.322	0.005	0.014

Zn_1, 20 kg Zn soil application; Zn_2, 20 kg Zn soil application + 2 foliar spray of Zn

Table 3. Influence of Zn application on its average concentration in whole grains, straw and roots of the tested genotypes

Type of cultivar	Name of the cultivar	Whole grain Zn (mg/kg)				Straw Zn (mg/kg)				Root Zn (mg/kg)			
		Zn_0	Zn_1	Zn_2	Mean	Zn_0	Zn_1	Zn_2	Mean	Zn_0	Zn_1	Zn_2	Mean
High yielding varieties	'Sabita'	21.9	27.9	36.1	28.6	34.9	40.2	68.4	47.8	47.8	196.2	196.7	146.9
	'IR 36'	20.6	26.5	46.1	31.1	23.1	34.9	88.6	48.9	41.2	208.3	202.6	150.7
	'Khitish'	17.3	26.9	46.9	30.4	30.4	45.7	81.8	52.6	52.6	181.9	174.3	136.2
	'Satya'	17.8	24.0	40.1	27.3	22.8	31.4	70.2	41.5	51.8	190.4	190.6	144.2
	'Triguna'	22.0	32.4	51.3	35.2	31.7	42.3	70.6	48.2	52.7	170.8	177.3	133.6
	'Bhudev'	24.8	31.8	35.9	30.8	28.4	37.1	56.3	40.6	56.4	177.2	178.0	137.2
	'Swarna sub1'	22.1	27.8	51.3	33.7	36.3	50.6	71.9	52.9	54.6	181.6	178.4	138.2
	'Samba masuri sub1'	28.8	35.1	52.7	38.9	32.7	43.6	86.9	54.4	56.6	170.3	184.0	137.0
	'Satabdi'	27.3	31.8	56.3	38.5	35.0	45.4	96.3	58.9	48.1	195.9	200.9	148.3
	'IR 64'	21.8	27.7	42.5	30.6	36.5	42.9	86.4	55.3	52.1	175.8	179.8	135.9
	'Samba masuri'	28.5	34.7	58.9	40.7	35.8	44.3	71.3	50.5	55.3	182.0	180.0	139.1
	'Lalat'	27.4	41.0	72.6	47.0	35.2	76.8	99.9	70.6	51.3	151.1	154.7	119.0
	'Swarna'	22.8	28.3	39.0	30.0	31.1	44.8	62.0	46.0	64.8	177.5	180.1	140.8
	'GB 2'	20.0	28.7	52.5	33.7	33.3	44.9	85.5	54.5	66.4	178.4	186.3	143.7
	'GB 1'	22.5	27.1	73.6	41.1	26.7	42.0	83.6	50.8	48.9	179.2	189.0	139.0
	'Rasi'	24.1	32.1	65.7	40.6	29.9	37.0	88.5	51.8	54.7	194.6	163.4	137.6
	'PNR 519'	20.7	33.7	75.3	43.2	34.4	49.9	95.8	60.1	60.8	179.9	193.5	144.7
	Mean	23.0	23.0	30.4	52.8	35.4	31.7	44.3	80.2	52.1	53.9	181.8	182.9
Hybrids	'KRH 2'	23.5	29.5	55.3	36.1	27.2	33.8	66.8	42.6	63.4	178.5	182.1	141.3
	'PHB 71'	19.8	35.3	57.1	37.4	31.7	40.2	66.4	46.1	53.3	179.9	187.4	140.2
	'PA 6444'	22.7	34.1	54.1	37.0	32.8	49.0	74.6	52.1	64.2	177.2	181.4	140.9
	Mean		22.0	33.0	55.5	36.8	30.6	41.0	69.3	46.9	60.3	178.5	183.6
Local	'FR 43B'	25.5	32.4	49.0	35.6	44.6	49.9	73.6	56.0	60.9	216.9	221.2	166.3
	'Kalma 222'	27.1	30.9	57.4	38.5	33.3	37.1	64.2	44.9	66.3	216.9	213.4	165.5
	Mean		24.9	32.1	54.0	37.0	36.2	42.7	69.0	49.3	62.5	204.1	206.1
Aromatic	'Gayasur'	25.4	30.4	43.3	33.1	44.6	56.6	82.5	61.2	74.3	206.3	209.5	163.4
	'Gobindabhog'	25.8	27.2	43.7	32.2	43.6	51.9	70.6	55.4	64.0	189.6	192.5	148.7
	'Badshabhog'	27.4	28.7	43.5	33.2	31.7	43.2	56.7	43.9	63.3	182.4	178.9	141.5
	'PNR 546'	32.7	38.2	53.0	41.3	35.6	43.4	73.8	50.9	58.9	175.1	185.8	139.9
Mean		27.8	27.8	31.1	45.9	35.0	38.9	48.8	70.9	52.9	65.1	188.4	191.7
Overall mean		23.8	23.8	30.9	52.0	35.6	33.2	44.6	76.7	51.5	57.1	185.1	187.0

	Whole grain SEm±	Whole grain CD (P=0.05)	Straw SEm±	Straw CD (P=0.05)	Root SEm±	Root CD (P=0.05)
Variety	0.5	1.41	0.9	2.5	2.9	8.1
Zn	0.16	0.53	0.4	1.3	0.8	2.7
Variety × Zn	0.89	2.49	1.3	3.5	4.6	12.9

Zn_1, 20 kg Zn soil application; Zn_2, 20 kg Zn soil application + 2 foliar spray of Zn

Partitioning of Zn in the grains (viz., husk, bran and milled rice) of rice cultivars

Rice bran consists of outer coating on brown rice mainly consists of embryo and aleurone layers where mineral nutrients *viz.,* Zn and Fe are localized. Zinc and iron are seldom capable to enrich seed endosperm due to presence of ferritin protein moieties in the outer layers like embryo and endosperm (Stein *et al.,* 2009). Results showed that on an average, Zn concentration in bran of rice cultivars varied from 26.7 to 111.4 mg/kg with a mean value of 54.4 mg/kg (Table 4). Such concentration of Zn in bran of rice grains was higher in aromatics (40.8 mg/kg) followed by locals (38.1 mg/kg), HYVs (33.0 mg/kg) and hybrids (30.3 mg/kg). Results showed that application of Zn in soil increased the Zn concentration in bran to the level of 7.2 mg/kg (21%) over the control; whereas, soil + foliar applied Zn increased its magnitude to the tune of 53.2 mg/kg (155%) than the control. The results, therefore, revealed that leaving bran from the rice grains *i.e.* for polished rice/ white rice caused a huge loss of Zn from rice grains. It may be opined that consumption of white rice would not alleviate Zn malnutrition (Chen *et al*., 1998).

Zn concentration in milled rice grains (white rice) varied significantly not only among the rice cultivars but also within the different categories of the cultivars (Table 4). On an average, Zn concentration in milled rice grains of the tested cultivars varied from 15.3 to 61.2 mg/kg with a mean value of 29.9 mg/kg. Such concentration was higher with aromatics (22.0 mg/kg) followed by locals (21.9 mg/kg), HYVs (19.5 mg/kg) and hybrids (18.6 mg/kg). Results also showed that Zn application caused a significant increase in its amount over the control, irrespective of the cultivars and the magnitude of increase was higher with soil + foliar application of Zn (120.1%) than with only soil application (29.8%). Results further showed that Zn content in milled rice among the different categories upon Zn application was higher with hybrid followed by local, HYV and aromatic (Table 4). Results, therefore, indicate that soil + foliar application of Zn would be effective to increase the Zn content in milled rice.

Application of Zn through soil as well as soil + foliar spray showed a significant enhancement of Zn concentration in rice bran, rice husk (lemma and palea together) as well as in milled rice (white rice or cleaned rice obtained after removal of the bran layer). But such increase was lower in the case of milled rice as compared to rice bran or rice husk indicating an accumulation of Zn in the outer layers of rice grain.

Zn uptake by rice grains, straw and roots

Results of uptake of Zn by grains, straw and roots of the tested rice cultivars showed almost a similar trend of results as that of its concentration in same plant parts. On an average, 60 and 190% increase in whole grain Zn uptake was recorded upon soil application and soil + foliar application of Zn. Such enhancement in straw and roots of the tested cultivars were 49 and 157% and 262 and 270%, respectively upon soil application and soil + foliar application of Zn (Table 5).

Zn-use efficiency (ZnUE)

Results revealed that ZnUE varied from 0.53 to 2.83% with a mean value of 0.90% upon soil application of 20 kg Zn and 1.89 to 4.80% with a mean value of 2.74% upon application of 20 kg Zn with two foliar spray of 0.5% $ZnSO_4.7H_2O$ solution (calculated amount of Zn applied was 942 g/ha through foliar spray with basal application of 20 kg Zn) (Table 6). Cakmak (2008) also reported low use efficiency of Zn (1.0–2.0%) in rice. The ZnUE of the tested cultivars varied widely among themselves as well as within the different categories of the cultivars. Results further showed that ZnUE was higher with hybrid followed by HYV, aromatic and local upon basal application of Zn; while soil + foliar application, the said order was hybrid > HYV > local > aromatic (Fig. 1). On an average, soil + foliar applied Zn increased the ZnUE three folds than only soil applied Zn. So, from the results it can be opined that use efficiency of soil applied Zn in rice is very low (less than 1%) but its magnitude increased enormously (about three fold) when soil + foliar application is made due to modification in re-translocation process of Zn *via* phloem. Results also revealed that the higher Zn-use efficient cultivars upon soil application of Zn were: ‘Lalat’, ‘PA 6444’, ‘Swarna’, ‘Gayasur’, ‘Bhudev’ and ‘Samba masuri sub1’, whereas, upon soil+foliar application of Zn they were: ‘Lalat’, ‘PA 6444’, ‘GB 1’, ‘Samba

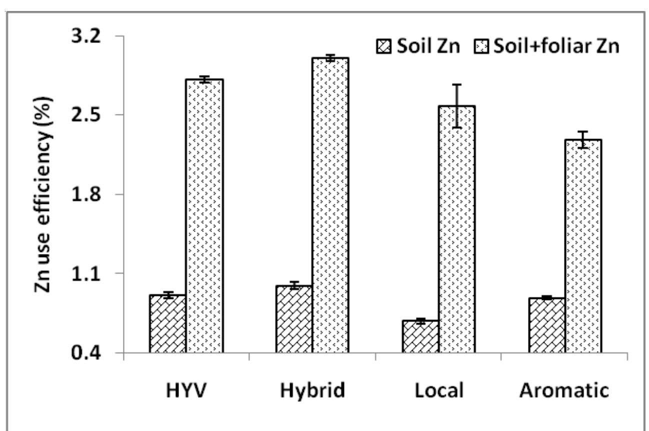

Fig. 1. Zinc-use efficiency of the rice cultivars upon different methods of Zn application.

Table 4. Partitioning of Zn in rice husk, rice bran and milled rice of the tested cultivars

Type of cultivar	Name of the cultivar	Rice bran Zn (mg/kg)				Rice husk Zn (mg/kg)				Milled rice Zn (mg/kg)			
		Zn_0	Zn_1	Zn_2	Mean	Zn_0	Zn_1	Zn_2	Mean	Zn_0	Zn_1	Zn_2	Mean
High yielding varieties	'Sabita'	33.9	40.0	71.3	48.4	14.9	25.4	79.4	39.9	19.1	22.2	29.9	23.7
	'IR 36'	34.6	41.2	83.8	53.2	15.8	24.7	81.3	40.6	18.6	22.5	39.8	27.0
	'Khitish'	35.7	43.7	83.7	54.4	15.6	23.1	65.4	34.7	15.3	21.4	37.9	24.8
	'Satya'	36.6	43.6	70.4	50.2	15.9	25.4	72.3	37.9	17.1	22.2	34.7	24.7
	'Triguna'	35.0	41.6	81.7	52.8	16.4	24.3	81.5	40.7	19.2	24.4	43.4	29.0
	'Bhudev'	30.8	35.1	66.7	44.2	15.9	22.1	75.7	37.9	19.6	26.0	30.1	25.2
	'Swarna sub1'	33.1	40.1	80.4	51.2	16.3	25.3	63.3	35.0	17.0	24.9	43.7	28.5
	'Samba masuri sub1'	31.7	38.5	100.7	57.0	15.0	21.4	65.5	34.0	22.2	27.8	45.0	31.7
	'Satabdi'	34.0	40.7	104.8	59.9	15.6	24.3	64.3	34.7	20.4	26.7	51.1	32.7
	'IR 64'	36.7	43.2	79.9	53.3	14.7	23.2	71.3	36.4	16.8	24.2	35.9	25.6
	'Samba masuri'	33.9	39.4	91.5	54.9	15.4	27.5	72.7	38.5	23.2	31.6	52.7	35.9
	'Lalat'	34.3	41.8	111.4	62.5	16.5	26.4	70.2	37.7	23.9	34.6	55.6	38.0
	'Swarna'	32.3	39.5	70.1	47.3	15.4	25.6	65.5	35.5	22.3	19.2	32.4	24.7
	'GB 2'	31.8	39.4	87.7	53.0	15.8	22.6	70.4	36.3	15.8	19.5	41.4	25.6
	'GB 1'	31.5	39.5	108.4	59.8	16.6	23.1	82.9	40.9	20.1	21.4	61.2	34.2
	'Rasi'	27.9	35.1	96.4	53.1	14.7	22.0	71.1	35.9	22.2	29.9	54.9	35.7
	'PNR 519'	26.7	33.8	109.6	56.7	15.8	23.5	78.3	39.2	18.6	28.9	53.7	33.7
	Mean	33.0	39.8	88.1	53.6	15.7	24.1	72.4	37.4	19.5	25.1	43.7	29.5
Hybrids	'KRH 2'	29.3	38.1	92.1	53.2	17.1	23.1	83.3	41.2	19.8	25.6	53.2	32.8
	'PHB 71'	30.0	37.5	93.1	53.5	18.1	21.6	75.7	38.4	16.1	31.7	42.0	29.9
	'PA 6444'	31.5	43.2	93.7	56.1	17.1	22.3	79.5	39.6	19.9	30.7	43.7	31.4
	Mean		39.6	93.0	54.3	17.4	22.3	79.5	39.7	18.6	29.3	46.3	31.4
Local	'FR 43B'	39.3	44.7	84.3	56.1	14.7	22.4	78.7	38.6	20.0	26.7	37.4	28.0
	'Kalma 222'	36.8	45.3	91.9	58.0	15.6	22.6	74.1	37.4	23.8	25.7	50.3	33.2
	Mean		45.0	88.1	57.1	15.2	22.5	76.4	38.0	21.9	26.2	43.8	30.6
Aromatic	'Gayasur'	39.8	47.0	77.4	54.7	15.3	22.4	77.3	38.3	21.1	25.4	42.6	29.7
	'Gobindabhog'	45.1	51.5	79.0	58.5	18.4	20.4	75.2	38.0	22.2	22.5	42.6	29.1
	'Badshabhog'	45.0	54.6	78.0	59.2	15.4	21.6	76.4	37.8	20.3	25.2	43.9	29.8
	'PNR 546'	33.4	40.0	86.6	53.3	14.4	23.4	72.9	36.9	24.4	32.4	42.8	33.2
	Mean	40.8	48.3	80.3	56.5	15.9	21.9	75.4	37.8	22.0	26.4	43.0	30.4
	Overall mean	35.5	43.2	87.4	55.4	16.0	22.7	75.9	38.2	20.0	25.9	43.9	29.9

	Rice bran SEm±	Rice bran CD (P=0.05)	Rice husk SEm±	Rice husk CD (P=0.05)	Milled rice SEm±	Milled rice CD (P=0.05)
Variety	0.30	0.90	0.100	0.290	0.12	0.34
Zn	0.10	0.40	0.032	0.140	0.04	0.13
Variety × Zn	0.60	1.60	0.230	0.520	0.22	0.60

Zn_1, 20 kg zn soil application; Zn_2, 20 kg zn soil application + 2 foliar spray of zn

Table 5. Influence of Zn application on its uptake by whole grains, straw and roots of the tested cultivars

Type of cultivar	Name of the cultivar	Zn uptake in grain (g/ha)				Zn uptake in straw (g/ha)				Zn uptake in root (g/ha)			
		Zn_0	Zn_1	Zn_2	Mean	Zn_0	Zn_1	Zn_2	Mean	Zn_0	Zn_1	Zn_2	Mean
High yielding varieties	'Sabita'	78.0	117.2	154.6	116.6	412.1	505.3	899.3	605.6	40.5	181.2	177.9	133.2
	'IR 36'	54.2	90.5	168.5	104.4	123.4	192.5	512.0	275.9	29.9	162.1	173.0	121.7
	'Khitish'	59.0	111.6	197.4	122.7	158.6	261.1	474.4	298.0	64.2	236.8	225.5	175.5
	'Satya'	61.5	92.9	164.1	106.1	170.4	293.6	701.4	388.5	41.7	171.9	175.8	129.8
	'Triguna'	61.7	124.3	222.3	136.1	170.6	246.7	421.8	279.7	43.9	149.0	156.6	116.5
	'Bhudev'	109.3	161.4	195.5	155.4	307.9	478.6	772.0	519.5	83.8	294.4	278.4	218.9
	'Swarna sub1'	95.6	146.4	277.8	173.3	307.8	453.2	656.2	472.4	41.3	136.5	144.6	107.5
	'Samba masuri sub1'	79.7	137.4	224.2	147.1	255.1	393.7	826.4	491.7	31.6	109.0	120.4	87.0
	'Satabdi'	62.1	90.9	171.4	108.1	167.9	244.3	523.2	311.8	39.3	178.9	197.4	138.5
	'IR 64'	56.2	98.2	165.5	106.6	239.9	321.3	657.6	406.3	42.1	167.0	166.8	125.3
	'Samba masuri'	94.5	139.5	247.4	160.5	305.7	423.3	724.1	484.4	43.3	168.6	162.0	124.6
	'Lalat'	74.4	141.4	292.7	169.5	296.2	795.7	1082.2	724.7	63.2	212.4	222.2	165.9
	'Swarna'	134.0	184.5	259.7	192.7	393.3	604.5	900.4	632.7	44.4	142.6	149.4	112.1
	'GB 2'	82.0	130.5	252.0	154.8	175.7	252.2	505.7	311.2	60.2	185.0	212.3	152.5
	'GB 1'	120.7	170.4	474.5	255.2	155.8	255.3	524.2	311.7	37.7	143.3	159.3	113.4
	'Rasi'	76.1	128.1	268.8	157.7	143.2	211.9	535.1	296.8	69.1	265.2	228.9	187.7
	'PNR 519'	68.0	130.1	308.5	168.8	186.8	311.0	605.6	367.8	60.9	211.3	228.3	166.9
	Mean	80.4	129.1	237.9	149.2	233.5	367.3	666.0	422.3	49.2	183.2	187.0	139.8
Hybrids	'KRH 2'	78.3	129.0	264.7	157.3	165.9	223.2	511.5	300.2	58.1	191.2	195.4	148.2
	'PHB 71'	47.9	102.5	169.6	106.7	349.2	474.4	793.9	539.2	47.3	175.5	189.3	137.3
	'PA 6444'	64.4	131.2	220.7	138.8	442.7	684.7	1075.2	734.2	59.1	181.9	190.6	143.9
	Mean		120.9	218.3	134.3	319.3	460.8	793.6	524.5	54.8	182.9	191.8	143.1
Local	'FR 43B'	29.1	51.2	82.6	54.3	547.6	682.5	1048.1	759.4	43.2	180.6	185.1	136.3
	'Kalma 222'	27.5	39.1	73.4	46.7	345.8	449.6	826.8	540.8	65.3	240.5	229.2	178.4
	Mean		45.2	78.0	50.5	446.7	566.1	937.4	650.1	54.3	210.6	207.2	157.3
Aromatic	'Gayasur'	49.9	76.8	135.2	87.3	382.3	601.9	915.8	633.3	68.4	223.4	241.8	177.9
	'Gobindabhog'	58.4	71.1	137.5	89.0	431.2	578.8	818.0	609.3	55.5	200.4	209.0	155.0
	'Badshabhog'	66.5	77.8	133.9	92.7	370.5	539.2	732.5	547.4	64.3	205.9	195.0	155.1
	'PNR 546'	79.1	105.7	151.0	111.9	205.8	300.0	530.6	345.4	55.0	182.4	192.4	143.2
	Mean	63.5	82.8	139.4	95.2	347.5	505.0	749.2	533.9	60.8	203.0	209.6	157.8
	Overall mean	71.8	114.6	208.2	131.6	277.4	414.6	714.4	468.8	52.0	188.3	192.6	144.3
			SEm±	CD (P=0.05)			SEm±	CD (P=0.05)			SEm±	CD (P=0.05)	
	Variety		2.3	6.6			10.1	28.4			4.9	13.8	
	Zn		1.2	3.9			3.8	12.5			1.1	3.5	
	Variety × Zn		4.4	12.3			13.1	36.5			7.9	22.0	

Zn_1, 20 kg Zn soil application; Zn_2, 20 kg Zn soil application + 2 foliar spray of Zn

Table 6. Percent use of applied Zn by root, shoot and grains upon application of soil Zn, soil + foliar Zn as well as only foliar applied Zn and Zn use efficiency of the tested rice cultivars

Types of cultivar	Name of the cultivars	Percent use of applied Zn by							Zn-use efficiency (%)	
		Root	Shoot			Grain				
		Soil Zn	Soil Zn	Soil + foliar Zn	Foliar Zn	Soil Zn	Soil + foliar Zn	Foliar Zn	Soil Zn	Soil + foliar Zn
High yielding varieties	'Sabita'	0.70	0.47	2.33	41.82	0.20	0.37	3.97	0.66	2.69
	'IR 36'	0.66	0.35	1.86	33.90	0.18	0.55	8.27	0.53	2.40
	'Khitish'	0.86	0.51	1.51	22.63	0.26	0.66	9.10	0.78	2.17
	'Satya'	0.65	0.62	2.54	43.28	0.16	0.49	7.56	0.77	3.03
	'Triguna'	0.53	0.38	1.20	18.58	0.31	0.77	10.41	0.69	1.97
	'Bhudev'	1.05	0.85	2.22	31.13	0.26	0.41	3.61	1.11	2.63
	'Swarna sub1'	0.48	0.73	1.66	21.54	0.25	0.87	13.95	0.98	2.53
	'Samba masuri sub1'	0.39	0.69	2.73	45.92	0.29	0.69	9.21	0.98	3.42
	'Satabdi'	0.70	0.38	1.70	29.59	0.14	0.52	8.54	0.53	2.22
	'IR 64'	0.62	0.41	1.99	35.69	0.21	0.52	7.15	0.62	2.52
	'Samba masuri'	0.63	0.59	2.00	31.93	0.23	0.73	11.45	0.81	2.73
	'Lalat'	0.75	2.50	3.75	30.41	0.33	1.04	16.06	2.83	4.80
	'Swarna'	0.49	1.06	2.42	31.40	0.25	0.60	7.98	1.31	3.02
	'GB 2'	0.62	0.38	1.58	26.91	0.24	0.81	12.90	0.63	2.39
	'GB 1'	0.53	0.50	1.76	28.54	0.25	1.69	32.27	0.75	3.45
	'Rasi'	0.98	0.34	1.87	34.30	0.26	0.92	14.93	0.60	2.79
	'PNR 519'	0.75	0.62	2.00	31.26	0.31	1.15	18.93	0.93	3.15
	Mean	0.67	0.67	2.07	31.70	0.24	0.75	11.55	0.91	2.82
Hybrids	'KRH 2'	0.67	0.29	1.65	30.60	0.25	0.89	14.40	0.54	2.54
	'PHB 71'	0.64	0.63	2.12	33.91	0.27	0.58	7.12	0.90	2.70
	'PA 6444'	0.61	1.21	3.02	41.44	0.33	0.75	9.50	1.54	3.77
	Mean		0.71	2.26	35.32	0.28	0.74	10.34	0.99	3.00
Local	'FR 43B'	0.69	0.67	2.39	38.79	0.11	0.26	3.33	0.79	2.65
	'Kalma 222'	0.88	0.52	2.30	40.03	0.06	0.22	3.63	0.58	2.52
	Mean		0.60	2.35	39.41	0.09	0.24	3.48	0.69	2.59
Aromatic	'Gayasur'	0.78	1.10	2.55	33.31	0.13	0.41	6.19	1.23	2.95
	'Gobindabhog'	0.72	0.74	1.85	25.38	0.06	0.38	7.05	0.80	2.22
	'Badshabhog'	0.71	0.84	1.73	20.51	0.06	0.32	5.95	0.90	2.05
	'PNR 546'	0.64	0.47	1.55	24.47	0.13	0.34	4.81	0.60	1.89
	Mean	0.71	0.79	1.92	25.92	0.10	0.36	6.00	0.88	2.28
Overall Mean	0.68	0.69	2.09	31.82	0.21	0.65	9.93	0.90	2.74	
	Variety	Variety	Zn	Variety × Zn	Variety	Zn	Variety × Zn	Variety	Zn	Variety × Zn
SEm±	0.121	0.361	1.13	3.33	0.068	0.96	2.82	0.070	0.025	0.069
CD (P=0.05)	0.239	0.712	2.23	6.52	0.135	1.89	5.56	0.195	0.097	0.194

Zn_1, 20 kg Zn soil application; Zn_2, 20 kg Zn soil application + 2 foliar spray of Zn

masuri sub1', 'PNR 519' and 'Satya'. Mortvedt (1991 and 1994) reported that crop recovery of applied micronutrients is relatively low (5% to 10%) compared to macronutrients.

Percent use of applied Zn by root, shoot and grains upon application of Zn through varied method

Utilization of applied micronutrients are generally very low usually less than 2.0% upon conventional methods of application commonly followed by the farmers in our country. In the present study an attempt has been made to get an insight view about Zn recovery by different plant parts *viz*., root, shoot and grains for practical management or efficient utilization of applied Zn by the crop. Results revealed that root uptake of soil applied Zn varied from 0.39 to 1.05% with a mean value of 0.68%, while shoot uptake and grain uptake varied from 0.29 to 2.50% and 0.06 to 0.33% with mean values of 0.69 and 0.21%, respectively of the basally applied 20 kg Zn/ha (Table 6); whereas, in case of soil + foliar application, the per cent utilization of applied Zn was greater than only soil application. In case of soil + foliar application, Zn utilization by the shoot and grains varied from 1.20 to 3.75 and 0.22 to 1.69 with mean values of 2.09 and 0.65%, respectively. Results further revealed that foliar application of Zn @ 0.5% $ZnSO_4.7H_2O$ twice (~ 942 g Zn) with basal application of 20 kg Zn/ha increased the per cent use of applied Zn to the tune of 2-fold (204%) in both grains and straw than only basal application of Zn fertilizers; where results showed that foliar application of Zn only effected to increase the per cent use of applied Zn by grains and straw to the levels of 46 times than soil application of Zn. So, from the results it can be opined that foliar application could be a useful strategy to increase the use efficiency of applied Zn.

Zinc malnutrition in humans is a serious problem and enrichment of rice with Zn can solve this to a greater extent. Growing evidence is now available indicating that aromatic and local rice cultivars are inherently rich in grain Zn. Zn fertilizer strategies can provide an immediate and effective option to increase grain Zn concentration and productivity of rice, particularly in areas deficient in plant available Zn. Such bio-fortified Zn tends to enrich the outer layer of seed (embryo and aleurone) to a greater extent than the endosperm. Recovery of applied Zn could also be enhanced through use of soil + foliar as well as foliar methods of application of Zn fertilizers.

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