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Zinc partitioning in basmati rice varieties as influenced by Zn fertilization☆

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Zinc (Zn) ferti-fortification using different sources and methods in Zn deficient soils is being advocated to increase Zn concentration in rice kernel as an alternative to pursuing greater Zn-use efficiency (ZnUE). A two-year field study was conducted to assess the effect of Zn application on Zn content and uptake at several growth stages and in several parts of the rice kernel: hull, bran, and the white rice kernel. Variety 'PB 1509' with 1.25 kg Zn ha^{-1} as Zn-EDTA + 0.5% foliar spray (FS) at maximum tillering (MT) and panicle initiation (PI) stages registered the highest Zn content in hull, bran, and white rice kernel. Among parts of the rice kernel, Zn concentration decreased in the order hull > bran > white rice kernel, indicating that brown rice kernels are much denser in Zn content than polished rice. Considering the higher Zn accumulation in the bran, brown rice consumption, especially in Asia and Africa, could be recommended to overcome Zn malnutrition. The variety 'PB 1401' showed the highest Zn uptake in rice straw, while 'PB 1509' showed the highest Zn uptake in hull and white rice kernel. Application of 1.25 kg Zn ha^{-1} (Zn-EDTA) + 0.5% FS at MT and PI and 2.5 kg Zn ha^{-1} $ZnSO_4{\cdot}7H_2O$ (ZnSHH) + 0.5% FS at MT and PI resulted in higher Zn uptake than other treatments. On average, about one third of total Zn uptake remained in the white rice kernel, with the remaining two thirds accumulating in both hull and bran of brown rice. Zn-EDTA along with 0.5% FS, despite the application of a lower quantity of Zn leading to the highest Zn mobilization efficiency index (ZnMEI) and Zn-induced nitrogen recovery efficiency (ZniNRE), produced the highest kernel yield. However, of the two Zn sources, Zn-EDTA contributed more to the increase in ZnUE than did ZnSHH.

1. Introduction

Rice (*Oryza sativa* L.), a vital food crop in South and Southeast Asia, is grown under various agro-ecological conditions on an area of 43.86 Mha in India and makes large energy and protein contributions to human diet [1,2]. Basmati rice is a specialty rice in the Indo-Gangetic Plains of South Asia prized for its desirable cooking quality [3] and produced only in India and

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Pakistan. When cereals are cultivated on Zn-deficient soils, they have low Zn content and consequently bioavailability [4,5]. Zn inadequacy accounts for about 4% of global morbidity and mortality among children under five years of age [6]. Accordingly, biofortification plays a vital role in development of micronutrient-enriched varieties, especially for Zn and Fe, as these nutrients are required for better human health. Rice varieties show large variation in grain Zn content (15.0–58.0 mg kg^{-1}) [3]. Higher grain Zn concentrations lead to reduced yield, indicating an inverse trend between grain yield and Zn content [2,7,8]. Thus, improving Zn concentration in cereals without incurring a yield penalty is an important concern for genetic biofortification, but requires an extended period of breeding. In view of the large demand for basmati rice, efforts have been made to develop varieties having high yield potential with good cooking quality and increased Zn content by researchers of the Indian Agricultural Research Institute (IARI), New Delhi, India. Tested varieties in this experiment are fetching premier prices in domestic and exotic markets, potentially leading to higher profitability. Agronomic ferti-fortification is an alternative and faster way to increase productivity with Zn-enriched grain in multiple rice varieties [9].

Globally, about 50% of cultivated soils under cereal–cereal rotations have low Zn content [2]. Plant response to Zn deficiency involves decreased membrane integrity, susceptibility to heat stress, and decreased synthesis of carbohydrates, cytochromes, nucleotides, auxin, and chlorophyll. Further, Zn-containing enzymes are inhibited, including alcohol dehydrogenase, carbonic anhydrase, Cu–Zn-superoxide dismutase, alkaline phosphatase, phospholipase, carboxypeptidase, and RNA polymerase [10]. Zn binds with more than 500 different proteins. Zn chelates (EDTA) used for foliar fertilization and soil application (Zn sulphate heptahydrate) increased Zn concentration in plant parts such as hull, bran, white rice kernel, and straw [11]. Foliar fertilization contributes more than soil application to increasing Zn concentration in rice, as assessed by immediate crop response to applied nutrients. Different varieties of rice showed wide variation in grain and straw yield both with and without Zn application. On average, grain yields of different rice varieties increased by 29% and 22% with soil plus foliar and only soil application of Zn, respectively [12]. This study also provided information on Zn content in different parts of the rice kernel; however, most of the available data on Zn enrichment in rice refers to unhusked rice.

Ferti-fortification is an economically viable approach that may result in higher Zn concentration as well as higher productivity. The tested basmati rice varieties are in a very high demand for their good cooking quality characteristics and aroma. However, no precise information is available on the Zn fertilization response of these high yielding basmati rice varieties. Our efforts were therefore directed toward evaluating the effect of two Zn fertilization sources, chelated Zn (Zn-EDTA) and $ZnSO_4 \cdot 7H_2O$ (ZnSHH) along with foliar fertilization on Zn concentration, uptake, ZnUE, mobilization, and yield of different parts of basmati rice.

2. Materials and methods

2.1. *Experimental location and climate and soil characteristics*

Field experiments were performed during the kharif (July–October) seasons of 2013 and 2014 at ICAR-Indian Agricultural Research Institute (IARI), New Delhi, India (28°38′N and 77°10′E, 228.6 m above mean sea level). The climate is semi-arid with hot, dry summers and cold winters. Its mean annual rainfall is 650 mm. The experimental soil was a sandy clay loam with 50.2% sand, 23.2% silt, and 26.6% clay. A uniformity trial using wheat crop without any treatment was conducted during the winter season of 2012–2013 to know soil physicochemical properties of experimental area for formation of uniform blocks. The soil (0–30 cm layer) had pH 7.8 (1:2.5, soil and water ratio), oxidizable soil organic carbon (SOC) [13] 0.51%, alkaline $KMnO_4$-oxidizable N 252.8 kg ha^{-1} [14], 0.5 mol L^{-1} $NaHCO_3$-extractable P 13.1 kg ha^{-1} [15] and 1 mol L^{-1} NH_4OAc-extractable K 291.2 kg ha^{-1} [16]. The soil had 0.63 mg kg^{-1} DTPA-extractable Zn [17].

2.2. *Layout and treatments*

The experiment employed a split-plot design with three replications. Six scented rice varieties: 'Pusa basmati 1401', 'Pusa basmati 1460', 'Pusa basmati 1509', 'Pusa Rice Hybrid 10', 'Pusa basmati 1121', and 'Pusa sugandha 5', were assigned to main plots. Five Zn fertilization treatments were applied: control (Zn_0), soil application of Zn at 5 kg ha^{-1} as $ZnSO_4 \cdot 7H_2O$ (Zn_1), soil application of Zn at 2.5 kg ha^{-1} as $ZnSO_4 \cdot 7H_2O$ + 0.5% foliar spray of $ZnSO_4 \cdot 7H_2O$ (ZnSHH) at maximum tillering (MT) and panicle initiation (PI) stages (Zn_2), soil application of Zn at 2.5 kg ha^{-1} as Zn-EDTA (Zn_3), soil application of Zn at 1.25 kg ha^{-1} as Zn-EDTA + 0.5% foliar spray of Zn-EDTA at MT and PI stages (Zn_4), respectively. Foliar application provided Zn at 1.05 kg ha^{-1}. The field was ploughed twice and then puddled and levelled. At the time of final field preparation, P at 25.8 kg ha^{-1} and K at 49.8 kg ha^{-1} were mixed into the soil. Nitrogen at 120 kg ha^{-1} was applied in three splits: one third of the N at the time of puddling and the remaining two thirds at 22 and 45 days after transplanting (DAT). Transplanting of 25 day-old seedlings at 20 cm × 10 cm spacing was performed in the first two weeks of July. Standard practices were followed for the cultivation of rice and it was harvested in the second half of October in both study years.

2.3. Chemical analysis of plant samples

Plant samples were collected at several growth stages and sun-dried. Sun-dried samples were then dried at 60 ± 2 °C in a hot-air oven for 6 h and ground. Samples of 0.5 g dry matter were taken at several growth stages of rice, straw, and several parts of the rice kernel for chemical analysis. Zn content in dry matter was determined by a di-acid digestion method using atomic absorption spectrophotometry [18]. Zn uptake was computed by multiplying respective Zn concentrations by the mass of plant dry matter and expressed in g ha^{-1}. For nitrogen analysis, plant samples of 0.5 g were digested in 10 mL of analytical-grade concentrated H_2SO_4 with a pinch of digestion mixture ($CuSO_4$ + K_2SO_4 + Se powder + Hg oxide). Samples were analyzed in a Kjeldahl apparatus and expressed as N percentage.

2.4. Zinc use indices

Estimated values of agronomic efficiency (AE), partial factor productivity (PFP), recovery efficiency (RE), physiological efficiency (PE), and Zn harvest index (ZnHI) of applied Zn were calculated following equations proposed by Fageria and Baligar

Table 1 – Zn concentration at different crop growth stages and in rice straw as influenced by variety and Zn fertilization strategy.

Variety	2013						2014					
	Zn_0	Zn_1	Zn_2	Zn_3	Zn_4	Mean	Zn_0	Zn_1	Zn_2	Zn_3	Zn_4	Mean
Zn concentration at 30 days after transplanting (mg kg^{-1} dry matter)												
PB 1401	10.70	11.37	11.48	12.27	11.29	11.42 d	11.24	11.39	11.50	12.26	11.27	11.53 d
PB 1460	15.39	14.44	14.56	15.51	15.54	15.09 b	14.32	15.59	15.46	15.27	15.12	15.15 b
PRH 10	12.52	12.23	13.57	13.03	12.13	12.70 c	12.63	12.63	12.64	12.83	12.51	12.65 c
PB 1121	12.33	13.06	12.50	12.35	12.08	12.46 c	12.14	13.68	12.05	12.38	12.32	12.51 c
PB 1509	12.39	13.01	11.89	13.54	12.00	12.57 c	11.89	12.72	12.97	12.59	12.92	12.62 c
PS 5	16.99	17.75	16.72	16.60	18.06	17.22 a	17.42	16.52	16.18	17.56	17.08	16.95 a
Mean	13.39	13.64	13.45	13.88	13.52		13.28	13.76	13.47	13.82	13.54	
$LSD_{0.05}$	Variety = 0.60						Variety = 0.55					
Zn concentration at 60 days after transplanting (mg kg^{-1} dry matter)												
PB 1401	13.83	13.93	15.72	15.54	16.26	15.05 e	15.59	15.74	16.17	16.36	16.15	16.00 e
PB 1460	18.60	17.90	17.56	17.27	17.47	17.76 d	17.81	18.21	17.90	17.90	18.25	18.01 d
PRH 10	22.87	22.80	22.88	23.65	24.93	23.43 b	22.96	23.19	24.18	23.46	24.22	23.60 b
PB 1121	18.64	19.81	20.05	19.05	19.94	19.50 c	19.36	20.62	20.86	19.81	19.84	20.10 c
PB 1509	23.55	24.49	24.18	24.24	24.34	24.16 ab	23.50	25.07	24.37	25.10	24.92	24.59 a
PS 5	23.61	24.23	25.34	24.96	23.99	24.43 a	24.42	24.39	25.06	25.02	25.83	24.94 a
Mean	20.19 b	20.53 ab	21.00 ab	20.79 ab	21.16 a		20.61 b	21.20 ab	21.42 a	21.28 a	21.53 a	
$LSD_{0.05}$	Variety = 0.81; Zn fertilization = 0.80						Variety = 0.76; Zn fertilization = 0.62					
Zn concentration at 90 days after transplanting (mg kg^{-1} dry matter)												
PB 1401	50.15	50.65	51.19	50.85	53.08	51.18 c	50.78	50.65	51.31	50.36	51.55	50.93 b
PB 1460	42.37	42.14	41.80	42.37	42.71	42.28 d	43.30	44.21	45.49	44.75	46.20	44.79 c
PRH 10	53.00	52.92	53.20	52.79	54.64	53.31 b	52.54	51.84	50.86	51.26	51.95	51.69 b
PB 1121	36.74	39.82	39.08	40.51	38.10	38.85 e	40.11	41.02	40.26	40.96	42.70	41.01 d
PB 1509	41.55	41.99	44.65	42.76	42.15	42.62 d	43.26	45.16	45.92	46.17	45.65	45.23 c
PS 5	64.28	64.29	65.49	64.03	66.17	64.85 a	58.27	59.66	61.69	61.25	59.57	60.09 a
Mean	48.02 b	48.63 ab	49.24 ab	48.88 ab	49.48 a		48.04 b	48.76 ab	49.26 a	49.13 a	49.61 a	
$LSD_{0.05}$	Variety = 1.38; Zn fertilization = 1.20						Variety = 1.46; Zn fertilization = 0.99					
Zn concentration in straw at harvest (mg kg^{-1} dry matter)												
PB 1401	38.85	37.53	42.80	40.66	44.14	40.79 b	37.03	37.68	42.24	38.77	45.56	40.26 b
PB 1460	35.33	37.05	36.21	38.56	37.66	36.96 c	33.86	38.42	35.69	37.81	37.41	36.64 c
PRH 10	38.54	39.73	44.71	38.57	42.87	40.88 b	38.02	40.50	44.36	40.95	42.95	41.36 ab
PB 1121	31.61	34.69	36.47	34.09	34.59	34.29 d	29.08	33.36	34.02	31.25	32.56	32.05 d
PB 1509	33.71	35.07	34.96	37.41	35.80	35.39 d	34.98	37.31	36.10	38.15	37.36	36.78 c
PS 5	44.21	45.42	43.38	45.94	45.02	44.79 a	43.02	43.87	42.05	44.22	44.12	43.45 a
Mean	37.04 b	38.25 ab	39.75 a	39.20 a	40.01 a		36.00 b	38.52 a	39.08 a	38.52 a	39.99 a	
$LSD_{0.05}$	Variety = 1.53; Zn fertilization = 2.09						Variety = 2.36; Zn fertilization = 2.24					

Main effects sharing the same case letter, for a parameter during an experimental year, do not differ significantly (P = 0.05) by the LSD test. Likewise, the figures of main effects without lettering do not differ significantly (P = 0.05) by the LSD test.

Zn_0, control (no zinc); Zn_1, soil application of Zn at 5 kg ha^{-1} as $ZnSO_4 \cdot 7H_2O$ (ZnSHH); Zn_2, soil application of Zn at 2.5 kg ha^{-1} as ZnSHH + 0.5% foliar spray of ZnSHH at maximum tillering (MT) and panicle initiation (PI) stages; Zn_3, soil application of Zn at 2.5 kg ha^{-1} as Zn-EDTA; Zn_4, soil application of Zn at 1.25 kg ha^{-1} as Zn-EDTA + 0.5% foliar spray of Zn-EDTA at MT and PI stage.

Degree of freedom for replication = 2; Variety = 5; Error I = 10; Zn fertilization = 4; Variety × Zn fertilization = 20; Error II = 48; Total = 89.

[19] and Prasad and Shivay [20].

$$\text{PFP} = \text{Y}_\text{t}/\text{Zn}_\text{a}$$

$$\text{AE} = (\text{Y}_\text{t}–\text{Y}_\text{Ac})/\text{Zn}_\text{a}$$

$$\text{RE} = [(\text{U}_\text{Zn}–\text{U}_\text{Ac})/\text{Zn}_\text{a}] \times 100$$

$$\text{PE} = (\text{Y}_\text{t}–\text{Y}_\text{Ac})/(\text{U}_\text{Zn}–\text{U}_\text{Ac})$$

$$\text{ZnHI} = \text{GU}_\text{Zn}/\text{U}_\text{Zn}$$

where, Y_t and U_{Zn} refer to the grain yield (kg ha^{-1}) and total Zn uptake (g ha^{-1}), respectively of rice varieties in Zn-treated plots; Y_{AC} and U_{AC} refer to the grain yield (kg ha^{-1}) and total Zn uptake (g ha^{-1}), respectively of scented rice varieties in control (Zn_0) plots; Zn_a refers to the Zn application (kg ha^{-1}); and GU_{Zn} refers to Zn uptake (g ha^{-1}) in grain.

Zn mobilization efficiency index (ZnMEI) was computed by the following equation [21]:

$$\text{ZnMEI} = \frac{\text{Zn concentration in white rice kernel } \left(\text{mg kg}^{-1}\right)}{\text{Zn concentration in rice straw } \left(\text{mg kg}^{-1}\right)}$$

Zn-induced nitrogen recovery efficiency (ZniNRE) was calculated by the following equation [20]:

$$\text{ZniNRE} = \frac{\left[\text{N uptake } \left(\text{kg ha}^{-1}\right) \text{ in Zn treatment} - \text{N uptake } \left(\text{kg ha}^{-1}\right) \text{ in control } (\text{Zn}_0)\right]}{\text{N applied } \left(\text{kg ha}^{-1}\right)}$$

Table 2 – Zn concentration in different parts of the rice kernel as influenced by variety and Zn fertilization strategy.

Variety	2013						2014					
	Zn_0	Zn_1	Zn_2	Zn_3	Zn_4	Mean	Zn_0	Zn_1	Zn_2	Zn_3	Zn_4	Mean
Zn concentration in hull (mg kg^{-1} dry matter)												
PB 1401	53.96	56.06	55.83	55.42	55.36	55.33 b	55.07	54.52	54.31	55.23	55.78	54.98 b
PB 1460	40.54	41.23	42.29	42.78	44.30	42.23 d	42.18	45.80	45.57	44.90	45.21	44.73 d
PRH 10	39.11	42.11	41.75	40.58	42.59	41.23 d	41.49	42.91	43.61	42.72	45.29	43.20 d
PB 1121	37.59	39.84	39.45	37.57	42.68	39.43 e	38.80	41.77	41.78	40.25	42.27	40.97 e
PB 1509	73.23	75.21	76.47	75.81	77.42	75.63 a	70.24	73.84	75.54	75.91	73.99	73.90 a
PS 5	42.94	43.18	44.00	46.74	46.27	44.63 c	46.43	45.88	46.54	48.04	48.60	47.10 c
Mean	47.90 c	49.61 b	49.97 b	49.82 b	51.44 a		49.04 b	50.79 a	51.23 a	51.18a	51.86 a	
$LSD_{0.05}$	Variety = 0.98; Zn fertilization = 0.95						Variety = 1.54; Zn fertilization = 1.08					
Zn concentration in bran (mg kg^{-1} dry matter)												
PB 1401	33.99	34.76	35.12	35.16	35.47	34.90 cd	36.97	36.20	37.07	36.61	37.04	36.78 c
PB 1460	29.44	32.20	32.56	31.46	32.83	31.70 e	30.85	32.15	33.16	33.11	34.16	32.69 d
PRH 10	31.91	36.16	35.17	33.52	34.72	34.30 d	33.17	34.96	38.36	35.56	35.87	35.58 c
PB 1121	34.68	35.03	35.82	37.35	37.61	36.10 c	36.18	38.23	36.48	37.22	37.98	37.22 c
PB 1509	49.09	50.60	50.47	50.88	49.95	50.20 a	45.28	48.18	49.41	50.21	50.60	48.74 a
PS 5	37.83	37.24	39.55	39.41	39.96	38.80 b	37.62	40.42	39.01	40.55	40.43	39.61 b
Mean	36.16 b	37.66 a	38.11 a	37.97 a	38.43 a		36.68 c	38.36 b	38.92 ab	38.88 ab	39.35 a	
$LSD_{0.05}$	Variety = 1.24; Zn fertilization = 0.85						Variety = 1.65; Zn fertilization = 0.89					
Zn concentration in white rice kernel (mg kg^{-1} dry matter)												
PB 1401	7.53	8.81	9.39	9.60	10.40	9.15 d	8.06	9.30	9.27	9.82	10.22	9.34 d
PB 1460	10.47	11.44	11.60	11.78	12.75	11.61 c	10.19	12.05	11.83	11.65	12.60	11.67 c
PRH 10	7.69	8.82	8.88	8.76	10.57	8.94 d	7.64	8.54	9.74	9.20	10.51	9.13 d
PB 1121	10.65	11.82	11.82	11.07	12.88	11.65 c	10.58	11.76	12.74	12.24	11.77	11.82 bc
PB 1509	12.43	13.75	14.13	14.01	15.42	13.95 a	12.40	13.49	15.15	14.14	14.61	13.96 a
PS 5	10.90	12.05	12.29	12.43	13.07	12.15 b	11.04	13.01	11.92	12.74	12.98	12.34 b
Mean	9.94 c	11.12 b	11.35 b	11.28 b	12.52 a		9.99 c	11.36 b	11.77 b	11.63 b	12.12 a	
$LSD_{0.05}$	Variety = 0.26; Zn fertilization = 0.29						Variety = 0.64; Zn fertilization = 0.42					

Main effects sharing the same case letter, for a parameter during an experimental year, do not differ significantly ($P = 0.05$) by the LSD test. Likewise, the figures of main effects without lettering do not differ significantly ($P = 0.05$) by the LSD test.

Zn_0, control (no zinc); Zn_1, soil application of Zn at 5 kg ha^{-1} as $ZnSO_4 \cdot 7H_2O$ (ZnSHH); Zn_2, soil application of Zn at 2.5 kg ha^{-1} as ZnSHH + 0.5% foliar spray of ZnSHH at maximum tillering (MT) and panicle initiation (PI) stages; Zn_3, soil application of Zn at 2.5 kg ha^{-1} as Zn-EDTA; Zn_4, soil application of Zn at 1.25 kg ha^{-1} as Zn-EDTA + 0.5% foliar spray of Zn-EDTA at MT and PI stage.

Degree of freedom for replication = 2; Variety = 5; Error I = 10; Zn fertilization = 4; Variety × Zn fertilization = 20; Error II = 48; Total = 89.

2.5. Hull, bran, and kernel yields

To evaluate milling parameters, 100 g of well sun-dried paddy samples were taken from each treatment. Rough rice samples were dehulled in a mini Satake rice mill (Satake, Tokyo, Japan) and weights of brown rice and hulls were recorded separately. The hulled brown rice was passed through a Satake rice whitening and caking machine for 2 min and the weights of polished rice and bran were recorded separately.

2.6. Statistical analysis

The data obtained from the two years were investigated statistically with the help of analysis of variance (ANOVA) using the *F*-test following Gomez and Gomez [22]. LSD values at $P = 0.05$ were used to determine the significance of differences between treatment means and identify interactions.

Table 3 – Effect of rice variety and Zn fertilization strategy on Zn uptake by plant parts of rice.

Variety	2013						2014					
	Zn_0	Zn_1	Zn_2	Zn_3	Zn_4	Mean	Zn_0	Zn_1	Zn_2	Zn_3	Zn_4	Mean
Zn uptake in straw (g ha^{-1})												
PB 1401	315.0	380.6	378.42	415.3	440.6	386.0 a	295.4	379.6	427.2	354.7	401.8	371.7 a
PB 1460	246.9	305.3	330.82	283.7	288.2	291.0 bc	218.1	317.3	366.1	278.3	333.4	302.6 b
PRH 10	263.7	296.8	320.67	309.4	413.7	320.8 b	254.1	309.1	331.7	304.3	354.2	310.7 b
PB 1121	221.8	304.6	304.53	265.7	271.1	273.6 cd	181.5	211.3	245.5	238.0	221.1	219.5 c
PB 1509	225.6	263.5	261.06	275.7	227.2	250.6 d	196.3	223.1	206.5	259.7	215.1	220.1 c
PS 5	276.2	294.8	289.90	356.7	353.7	314.3 bc	229.1	273.5	250.7	279.0	294.0	265. bc
Mean	258.2 b	307.6 a	314.23 a	317.8 a	332.4 a		229.1 b	285.7 a	304.6 a	285.7 a	303.3 a	
$LSD_{0.05}$	Variety = 41.85; Zn fertilization = 27.8						Variety = 45.31; Zn fertilization = 27.4					
Zn uptake in hull (g ha^{-1})												
PB 1401	58.14	70.36	65.88	67.88	73.41	67.13 b	47.91	54.50	48.67	51.88	56.76	51.94 b
PB 1460	27.50	29.20	34.88	35.36	36.83	32.75 d	25.50	32.95	32.66	31.66	33.48	31.25 d
PRH 10	45.70	47.83	45.67	44.52	46.55	46.05 c	42.61	41.53	44.68	44.35	47.68	44.17 c
PB 1121	40.55	46.79	47.15	41.83	51.39	45.54 c	34.54	39.62	41.85	41.94	45.15	40.62 c
PB 1509	75.20	77.35	87.22	76.98	82.35	79.82 a	65.16	72.51	85.34	77.77	77.22	75.60 a
PS 5	43.33	43.71	45.78	44.60	46.79	44.84 c	49.73	48.18	50.87	48.55	45.17	48.50 bc
Mean	48.40 b	52.54 ab	54.43 ab	51.86 b	56.22 a		44.24 b	48.21 a	50.68 a	49.36 a	50.91 a	
$LSD_{0.05}$	Variety = 6.93; Zn fertilization = 4.05						Variety = 4.55; Zn fertilization = 3.90					
Zn uptake in bran (g ha^{-1})												
PB 1401	16.27	18.24	17.50	16.81	16.01	16.97 cd	24.08	25.37	19.06	19.12	22.57	22.04 b
PB 1460	10.51	11.51	11.57	11.84	15.52	12.19 d	15.00	12.95	15.40	16.05	14.27	14.73 c
PRH 10	24.44	34.26	40.06	40.74	39.81	35.86 a	32.53	33.69	44.51	31.23	27.35	33.86 a
PB 1121	20.33	19.46	22.62	19.22	22.60	20.85 c	31.71	29.66	28.69	29.44	28.19	29.54 a
PB 1509	33.22	27.50	30.93	29.77	30.12	30.31 b	40.36	28.26	30.30	29.38	33.81	32.42 a
PS 5	33.77	32.09	31.71	29.67	29.45	31.34 ab	13.47	19.22	19.77	23.48	27.53	20.70 b
Mean	23.09	23.84	25.73	24.67	25.59		26.19	24.86	26.29	24.78	25.62	
$LSD_{0.05}$	Variety = 4.87						Variety = 5.22					
Zn uptake in white rice kernel (g ha^{-1})												
PB 1401	14.95	18.70	22.32	21.16	26.53	20.73 d	18.19	25.19	24.74	25.05	30.77	24.79 c
PB 1460	15.88	18.97	23.57	19.51	25.23	20.63 d	16.26	23.62	24.00	22.22	27.13	22.65 c
PRH 10	27.14	33.18	31.79	34.65	39.56	33.26 b	24.27	27.71	34.59	33.27	40.48	32.06 b
PB 1121	21.98	28.86	28.58	27.68	33.50	28.12 c	25.68	30.41	36.00	36.43	36.46	33.00 b
PB 1509	33.24	39.68	45.54	43.40	46.25	41.63 a	32.94	40.29	50.42	43.34	44.39	42.28 a
PS 5	30.25	38.09	39.52	37.70	43.61	37.84 ab	32.77	42.63	40.74	41.77	39.31	39.45 a
Mean	23.91 c	29.58 b	31.89 ab	30.69 b	35.78 a		25.02 c	31.64 b	35.08 ab	33.68 b	36.42 a	
$LSD_{0.05}$	Variety = 4.54; Zn fertilization = 2.00						Variety = 4.78; Zn fertilization = 2.45					

Main effects sharing the same case letter, for a parameter during an experimental year, do not differ significantly ($P = 0.05$) by the LSD test. Likewise, the figures of main effects without lettering do not differ significantly ($P = 0.05$) by the LSD test.

Zn_0, control (no zinc); Zn_1, soil application of Zn at 5 kg ha^{-1} as $ZnSO_4{\cdot}7H_2O$ (ZnSHH); Zn_2, soil application of Zn at 2.5 kg ha^{-1} as ZnSHH + 0.5% foliar spray of ZnSHH at maximum tillering (MT) and panicle initiation (PI) stages; Zn_3, soil application of Zn at 2.5 kg ha^{-1} as Zn-EDTA; Zn_4, soil application of Zn at 1.25 kg ha^{-1} as Zn-EDTA + 0.5% foliar spray of Zn-EDTA at MT and PI stage.

Degrees of freedom for replication = 2; Variety = 5; Error I = 10; Zn fertilization = 4; Variety × Zn fertilization = 20; Error II = 48; Total = 89.

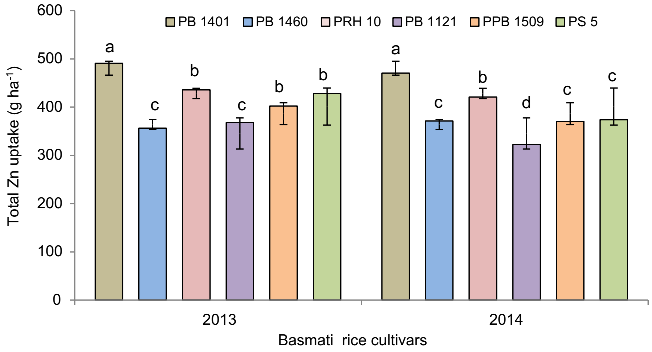

Fig. 1 – Total (straw + hull + bran + white rice kernel) Zn uptake in scented rice varieties. The vertical bars represent standard error of mean. Different small letters on the bars indicate significant differences between varieties at the 0.05 probability level according to Duncan's multiple range test.

3. Results

3.1. *Zn concentration and uptake*

The highest Zn concentrations in straw were found in 'PS 5', 'PRH 10', and 'PB 1401' (Table 1). In general, Zn concentration was lower during initial crop growth stages and subsequently increased. Of the six rice varieties studied, 'PS 5' showed the highest Zn concentration at 30, 60, and 90 days after transplanting (DAT) compared to the others. On average, at 60 DAT all rice varieties showed ~54% higher Zn concentration than at 30 DAT, and at 90 DAT showed 132% higher Zn content than at 60 DAT. Among the kernel parts, the hull showed the highest Zn concentration followed by bran and white rice kernel (Table 2). In both years, 'PB 1509' showed the highest Zn concentration in the hull (75.63 and 73.90 mg kg^{-1}), bran (50.20 and 48.74 mg kg^{-1}) and rice kernel (13.95 and 13.96 mg kg^{-1}), as reflected in maximum Zn mobilization efficiency (0.40 and 0.38). 'PB 1121', 'PB 1460', and 'PRH 10' showed moderate Zn content in hull, bran, and white rice kernel. These varieties also showed lower ZnHI and ZnMEI, leading to the lowest Zn concentrations. However, irrespective of source, Zn applications did not increase Zn concentration in rice plants at 30 DAT. On average, Zn_4 treatment resulted in significantly higher Zn concentrations at 60 and 90 DAT, followed by Zn_2. Zn fertilization effects were clearly visible when plots supplied with treatments Zn_4 and Zn_2 showed highest Zn concentrations in straw, hull, rice bran, and white rice kernel (Table 2). On an average, hulls had 50.4% Zn concentration and bran 38.1%, while white rice kernel had only 11.5% of the total Zn concentration in rice seed. Zn concentration decreased in the order hull > bran > white rice kernel (Table 2).

Among the varieties, 'PB 1401' produced maximum straw yield (9.36 Mg ha^{-1}; data not shown), leading to the highest Zn uptake (386.0 and 371.7 g ha^{-1}) followed by 'PRH 10' (Table 3). For Zn uptake in hull and rice kernel, 'PB 1509' showed the highest values. However, 'PB 1509' remained statistically similar to 'PS 5' with respect to Zn uptake in the white rice kernel, owing to a higher Zn concentration in 'PB 1509'. Similarly, 'PRH 10' proved superior with respect to Zn uptake in rice bran and found similar to 'PS 5' during the first year and 'PB 1509' during the second year of the study. The highest

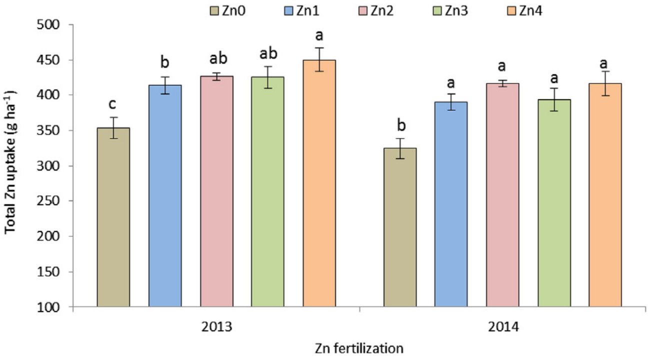

Fig. 2 – Total (straw + hull + bran + white rice kernel) Zn uptake in scented rice as influenced by Zn fertilization treatment. The vertical bars represent standard error of mean. Different small letters on the bars indicate significant differences between treatments at the 0.05 probability level according to Duncan's multiple range test. Zn_0, control (no zinc); Zn_1, soil application of Zn at 5 kg ha^{-1} as $ZnSO_4{\cdot}7H_2O$ (ZnSHH); Zn_2, soil application of Zn at 2.5 kg ha^{-1} as ZnSHH + 0.5% foliar spray of ZnSHH at maximum tillering (MT) and panicle initiation (PI) stages; Zn_3, soil application of Zn at 2.5 kg ha^{-1} as Zn-EDTA; Zn_4, soil application of Zn at 1.25 kg ha^{-1} as Zn-EDTA + 0.5% foliar spray of Zn-EDTA at MT and PI stages.

total Zn uptake (straw + hull + bran + kernel) was recorded in ‘PB 1401’ (490.8 and 470.5 g ha^{-1}) significantly higher than that of the rest of the varieties (Fig. 1). Zn fertilization significantly increased Zn uptake over control in different parts of rice seed viz. hull, bran, white rice kernel and also straw. Zn-fertilized plots remained on par with respect to Zn uptake in rice straw and showed significantly more Zn uptake in rice straw than the control. Among these, Zn_4 yielded the highest values (332.4 and 303.2 g ha^{-1}) followed by Zn_2 (314.2 and 304.6 g ha^{-1}). Zn uptake in hull, bran, and white rice kernel was highest in the plots supplied with Zn_4 and this treatment remained on par with Zn_2 except for Zn uptake in rice kernel during 2013. Total Zn uptake by rice (grain + straw) was greatest under Zn_4 treatment, significantly greater than in Zn_1 and control plots in the first year, whereas in the second year, uptake was significantly superior only to the control plot (Fig. 2). When the Zn uptake in different parts of the kernel was determined, the maximum proportion of Zn remained in the hull: 64% in ‘PB 1401’, 53% in ‘PB 1509’, 50% in ‘PB 1460’, 48% ‘PB 1121’, and 40% in ‘PRH 10’. However, of the total uptake of Zn in grain, only 33% accumulated in the rice kernel in ‘PS 5’, 31% in ‘PB 1460’, 30% in ‘PB 1121’, 29% in ‘PRH 10’, 27% in ‘PB 1509’, and 20% in ‘PB 1401’ (Fig. 3). Thus, ‘PB 1509’ seems to be the variety that was most efficient with respect to Zn accumulation in the rice kernel. Only about one third of total Zn was found in the white rice kernel, and the remaining two thirds accumulated in the hull and bran of brown rice.

3.2. Zinc use efficiency

Variety ‘PB 1401’ showed the highest agronomic efficiency (AE) (197.9 and 195.2 kg grain increased per kg Zn applied), significantly superior to the rest of the varieties except for ‘PB 1121’ during the second year (Table 4). Irrespective of Zn

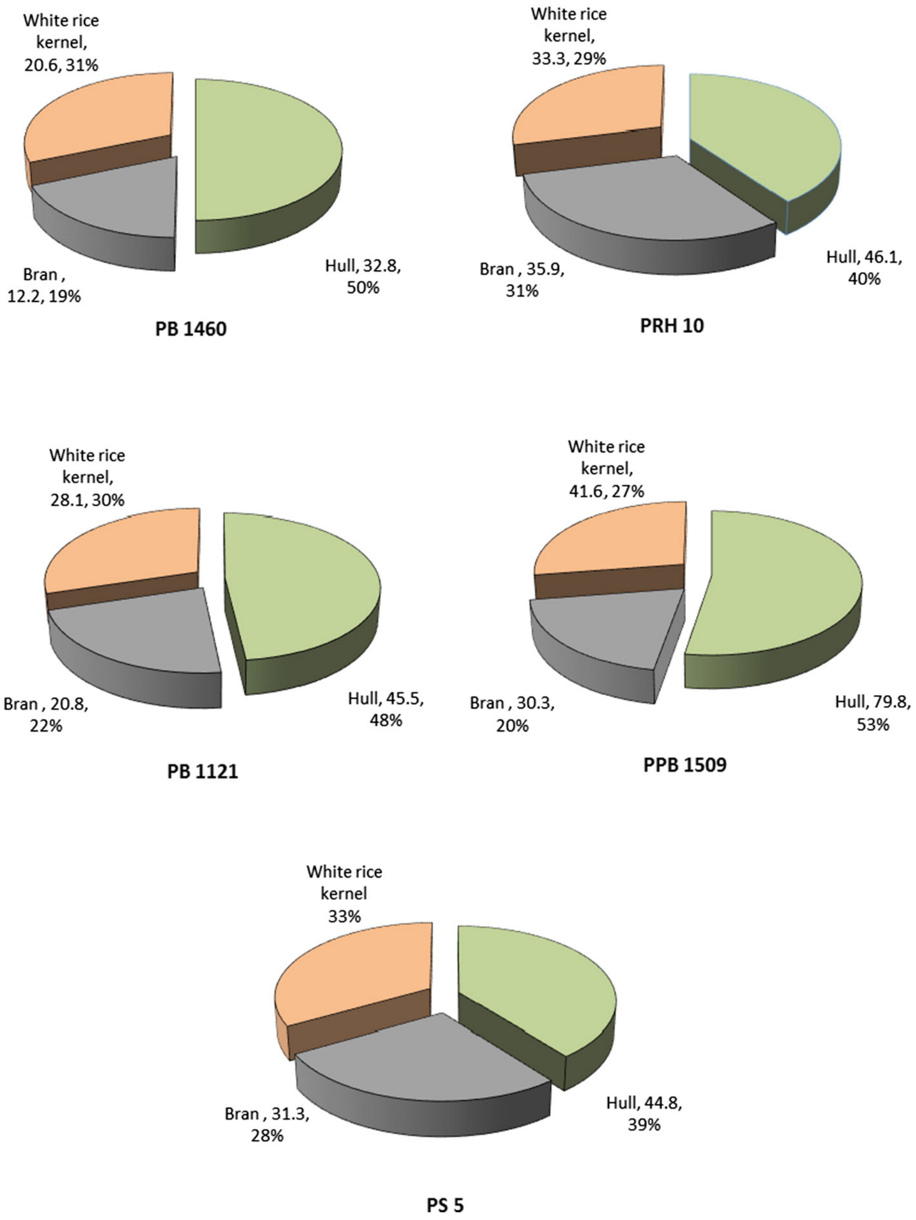

Fig. 3 – Zn uptake in different parts of rice kernel of *basmati* rice varieties (average over two years).

Table 4 – Zn use efficiencies of scented rice as influenced by rice variety and Zn fertilization strategy.

Variety	2013						2014					
	Zn_0	Zn_1	Zn_2	Zn_3	Zn_4	Mean	Zn_0	Zn_1	Zn_2	Zn_3	Zn_4	Mean
Agronomic efficiency (kg grain increased kg^{-1} Zn applied)												
PB 1401	–	73.3	144.6	146.7	427.0	197.9 a	–	127.3	86.4	98.7	468.5	195.2 a
PB 1460	–	34.0	187.8	125.3	398.2	186.3 b	–	82.0	152.1	160.0	345.9	185.0 b
PRH 10	–	68.0	93.9	313.3	261.3	184.1 b	–	6.0	171.8	152.0	270.3	150.0 c
PB 1121	–	84.7	141.8	154.7	362.2	185.8 b	–	22.0	115.5	244.0	383.8	191.3 ab
PB 1509	–	16.7	170.9	129.3	156.8	118.4 c	–	18.0	169.0	80.0	151.4	104.6 d
PS 5	–	71.3	108.0	29.3	219.8	107.1 d	–	78.0	171.8	192.0	135.1	144.2 c
Mean	–	58.0 d	141.2 c	149.8 b	304.2 a		–	55.6	144.4	154.4	292.5	
$LSD_{0.05}$	Variety = 7.66; Zn fertilization = 3.60						Variety = 8.93; Zn fertilization = 3.53					
Recovery efficiency (%)												
PB 1401	–	1.67	2.25	4.67	8.23	4.20 a	–	1.98	3.78	2.61	6.83	3.80 b
PB 1460	–	1.28	2.82	1.98	3.51	2.40 d	–	2.24	4.60	2.93	7.21	4.25 a
PRH 10	–	1.02	2.18	2.73	9.66	3.90 b	–	1.17	2.87	2.38	6.28	3.18 c
PB 1121	–	1.90	2.77	1.99	3.99	2.66 c	–	0.75	2.21	2.89	3.10	2.24 e
PB 1509	–	0.82	1.62	2.34	1.01	1.45 e	–	0.59	1.06	3.01	1.93	1.65 f
PS 5	–	0.50	0.66	3.41	4.87	2.36 d	–	1.17	1.04	2.71	4.38	2.32 d
Mean	–	1.20 d	2.05 c	2.86 b	5.21 a			1.32 d	2.59 c	2.76 b	4.96 a	
$LSD_{0.05}$	Variety = 0.06; Zn fertilization = 0.04						Variety = 0.06; Zn fertilization = 0.04					
Physiological efficiency (kg grain increased kg^{-1} Zn uptake)												
PB 1401	–	4390.6	6439.0	3141.7	5189.6	4790.2 c	–	6421.5	2288.6	3803.7	6860.5	4843.56 c
PB 1460	–	2645.4	6662.9	6312.3	11,337.4	6739.5 b	–	3663.5	3308.9	5458.6	4797.8	4307.20 d
PRH 10	–	6674.5	4319.1	11,469.5	2704.5	6291.9 b	–	499.1	5988.4	6370.6	4306.0	4291.02 d
PB 1121	–	4452.2	5125.1	7758.7	9072.9	6602.2 b	–	2927.9	5222.0	8428.4	12,373.9	7238.03 b
PB 1509	–	2045.3	10,553.4	5519.2	15,962.6	8520.1 a	–	3036.5	15,914.1	2654.8	7813.6	7354.75 b
PS 5	–	14,158.5	16,379.2	861.4	4516.1	8978.8 a	–	6666.9	16,481.5	7086.9	3089.4	8331.20 a
Mean	–	5727.7 b	8246.449 a	5843.8 b	8130.5 a		–	3869.2 d	8200.6 a	5633.8 c	6540.2 b	
$LSD_{0.05}$	Variety = 671.3; Zn fertilization = 464.0						Variety = 429.2; Zn fertilization = 203.8					
Partial factor productivity (kg grain kg^{-1} Zn)												
PB 1401	–	782.0	1142.7	1564.0	2342.3	1457.8 d	–	882.0	1149.3	1608.0	2506.3	1536.4 c
PB 1460	–	544.7	907.0	1146.7	1778.4	1094.2 e	–	618.0	906.1	1232.0	1794.6	1137.7 d
PRH 10	–	1166.7	1641.3	2510.7	3230.6	2137.3 a	–	1035.3	1622.5	2210.7	3055.9	1981.1 a
PB 1121	–	832.7	1195.3	1650.7	2383.8	1515.6 cd	–	862.7	1297.7	1925.3	2652.3	1684.5 bc
PB 1509	–	892.7	1404.7	1881.3	2524.3	1675.8 bc	–	912.0	1429.1	1869.3	2567.6	1694.5 bc
PS 5	–	1006.7	1425.4	1900.0	2747.8	1769.9 b	–	959.3	1413.2	1957.3	2520.7	1712.6 b
Mean	–	870.9 d	1286.1 c	1775.6 b	2501.2 a		–	878.2 d	1303.0 c	1800.4 b	2516.2 a	
$LSD_{0.05}$	Variety = 168.85; Zn fertilization = 97.9						Variety = 156.37; Zn fertilization = 87.6					

Main effects sharing the same case letter, for a parameter during an experimental year, do not differ significantly ($P = 0.05$) by the LSD test. Likewise, the figures of main effects without lettering do not differ significantly ($P = 0.05$) by the LSD test.

Zn_0, control (no zinc); Zn_1, soil application of Zn at 5 kg ha^{-1} as $ZnSO_4 \cdot 7H_2O$ (ZnSHH); Zn_2, soil application of Zn at 2.5 kg ha^{-1} as ZnSHH + 0.5% foliar spray of ZnSHH at maximum tillering (MT) and panicle initiation (PI) stages; Zn_3, soil application of Zn at 2.5 kg ha^{-1} as Zn-EDTA; Zn_4, soil application of Zn at 1.25 kg ha^{-1} as Zn-EDTA + 0.5% foliar spray of Zn-EDTA at MT and PI stage.

Degrees of freedom for replication = 2; Variety = 5; Error I = 10; Zn fertilization = 4; Variety × Zn fertilization = 20; Error II = 48; Total = 89.

source, AE declined as the level of Zn application was increased. With respect to recovery efficiency (RE), 'PB 1401' (4.20%) and 'PB 1460' (4.25%) recovered more Zn than the other varieties in the first and second years, respectively. Likewise, 'PS 5' showed the highest increase in grain yield per kg of Zn uptake, in the first year. Higher agronomic, recovery and physiological efficiencies were observed in the plots supplied with soil + foliar application of Zn than in those with soil application alone. With respect to the source, application of Zn-EDTA by either soil or foliar fertilization proved superior to $ZnSO_4 \cdot 7H_2O$. However, treatment Zn_4 yielded the highest agronomic, recovery, and physiological efficiencies of applied Zn, followed by treatment Zn_3.

'PRH 10' produced more grain per kg of Zn applied (PFP) than the rest of the varieties (Table 4). The highest ZnHI and ZnMEI were recorded in 'PB 1509' (Table 5). Significant differences between varieties were also observed for ZniNRE. 'PRH 10' had the highest ZniNRE in 2013, whereas 'PB 1460' had the highest ZniNRE in 2014. 'PB 1509' showed the lowest ZniNRE among the varieties. Zn fertilization had significant effects on PFP, ZnHI, ZnMEI, and ZniNRE. The PFP and ZnHI of applied Zn declined as the level of its application was increased. The highest PFP, PE, and ZnMEI were found with the Zn_4 treatment. ZniNRE was significantly higher with treatments Zn_4 and Zn_2 than with the rest of the treatments.

Table 5 – Zn use efficiency of scented rice as influenced by rice variety and Zn fertilization strategy.

Variety	2013						2014					
	Zn$_0$	Zn$_1$	Zn$_2$	Zn$_3$	Zn$_4$	Mean	Zn$_0$	Zn$_1$	Zn$_2$	Zn$_3$	Zn$_4$	Mean
Zn harvest index (%)												
PB 1401	3.71	3.84	4.61	4.06	4.89	4.22 d	4.70	5.35	4.79	5.67	6.09	5.32 c
PB 1460	5.37	5.24	5.92	5.74	7.04	5.86 c	6.02	6.23	5.55	6.48	6.64	6.18b c
PRH 10	7.64	8.09	7.36	8.31	7.32	7.74 b	6.79	6.73	7.59	8.05	8.79	7.59 b
PB 1121	7.19	7.33	7.11	7.81	8.92	7.67 b	9.43	9.76	10.21	11.09	11.05	10.31 a
PB 1509	9.04	9.79	10.76	10.20	12.20	10.40 a	9.92	11.15	13.75	10.57	11.96	11.47 a
PS 5	7.90	9.46	9.79	8.29	9.24	8.94 b	10.06	11.18	11.40	10.70	9.64	10.59 a
Mean	6.81 c	7.29 bc	7.59 ab	7.40 bc	8.27 a		7.82 b	8.40 ab	8.88 a	8.76 a	9.03 a	
LSD$_{0.05}$	Variety = 1.31; Zn fertilization = 0.69						Variety = 1.39; Zn fertilization = 0.80					
Zn mobilization efficiency index												
PB 1401	0.20	0.23	0.22	0.24	0.24	0.22 e	0.22	0.25	0.22	0.25	0.22	0.23 d
PB 1460	0.30	0.31	0.32	0.31	0.34	0.31 c	0.30	0.31	0.33	0.31	0.34	0.32 b
PRH 10	0.20	0.22	0.20	0.23	0.25	0.22 e	0.20	0.21	0.22	0.22	0.25	0.22 d
PB 1121	0.34	0.34	0.33	0.32	0.37	0.34 b	0.37	0.35	0.37	0.43	0.36	0.38 a
PB 1509	0.37	0.39	0.41	0.37	0.44	0.40 a	0.36	0.36	0.42	0.37	0.39	0.38 a
PS 5	0.25	0.27	0.28	0.27	0.29	0.27 d	0.26	0.30	0.28	0.29	0.29	0.28 c
Mean	0.26 c	0.29 b	0.29 b	0.29 b	0.32 a		0.283 b	0.297 ab	0.310 ab	0.314 a	0.309 ab	
LSD$_{0.05}$	Variety = 0.02; Zn fertilization = 0.02						Variety = 0.03; Zn fertilization = 0.03					
Zn induced N recovery efficiency (%)												
PB 1401	–	16.08	15.02	17.60	18.37	13.41 ab	–	20.03	17.34	12.68	19.31	17.34 ab
PB 1460	–	10.68	25.91	7.42	18.07	12.42 ab	–	20.58	37.96	13.98	31.41	25.98 a
PRH 10	–	18.83	12.46	22.58	34.35	17.64 a	–	7.15	15.96	11.32	19.92	13.59 bc
PB 1121	–	20.93	17.51	14.57	17.51	14.10 ab	–	4.19	14.03	16.79	15.65	12.67 bc
PB 1509	–	6.65	12.44	7.80	6.06	6.59 c	–	2.24	5.81	12.12	5.57	6.43 c
PS 5	–	6.42	10.46	14.32	19.33	10.11 bc	–	13.37	16.78	18.08	17.05	16.32 b
Mean	–	13.26 b	15.63 ab	14.05 ab	18.95 a		–	11.26 b	17.98 a	14.16 ab	18.15 a	
LSD$_{0.05}$	Variety = 5.73; Zn fertilization = 4.72						Variety = 9.67; Zn fertilization = 5.64					

Main effects sharing the same case letter, for a parameter during an experimental year, do not differ significantly ($P = 0.05$) by the LSD test. Likewise, the figures of main effects without lettering do not differ significantly ($P = 0.05$) by the LSD test.

Zn$_0$, control (no zinc); Zn$_1$, soil application of Zn at 5 kg ha^{-1} as ZnSO$_4$·7H$_2$O (ZnSHH); Zn$_2$, soil application of Zn at 2.5 kg ha^{-1} as ZnSHH + 0.5% foliar spray of ZnSHH at maximum tillering (MT) and panicle initiation (PI) stages; Zn$_3$, soil application of Zn at 2.5 kg ha^{-1} as Zn-EDTA; Zn$_4$, soil application of Zn at 1.25 kg ha^{-1} as Zn-EDTA + 0.5% foliar spray of Zn-EDTA at MT and PI stage.

Degrees of freedom for replication = 2; Variety = 5; Error I = 10; Zn fertilization = 4; Variety × Zn fertilization = 20; Error II = 48; Total = 89.

3.3. Hull, bran, and white kernel yield

During the first year, 'PB 1401' produced a significantly greater hull yield than 'PB 1460', 'PB 1509', and 'PS 5'. During the second year, 'PS 5' produced the highest hull yield. However, on average, 'PRH 10' gave the highest bran yield, significantly higher than that of the rest of the varieties. 'PRH 10' also produced the highest white rice kernel yield (3.72 and 3.48 t ha^{-1}) followed by 'PS 5' and 'PB 1509' (Table 6). The different Zn sources failed to increase hull and bran yield significantly, but numerically the values were higher with soil application of either Zn-EDTA or ZnSHH along with two foliar sprays. However, treatment Zn$_4$ produced the highest white rice kernel yield (Table 6).

4. Discussion

Zn concentration in rice dry matter increased with plant age and was highest at maturity (Table 1). Rhizospheric traits such as root length, diameter, density, volume, and special configuration play important roles in plant Zn uptake [23,24]. Zn concentration in different parts of rice kernel followed the trend hull (50%) > bran (38%) > white rice kernel (11.5%); indicating that when hull and bran (aleurone + pericarp) are removed during hulling and milling, the grains lose a considerable proportion of their nutritional values. Variety 'PB 1509' had highest Zn concentration (Table 2), possibly owing to mobilization of most of its absorbed Zn to the kernels from vegetative tissues, as reflected in ZnHI and ZnMEI (Table 5). Similarly, 'PB 1401' had the highest Zn uptake in straw as well as total uptake (Fig. 1). This finding was probably due to the highest straw yield (9.36 Mg ha^{-1}, data not shown) which led to increased Zn uptake. The higher Zn content in straw, hull, and bran compared to the rice kernel reflects low mobilization of Zn from different parts to the kernel, producing the lowest Zn content in the kernel. Zn-efficient genotypes increased exudation of malate and also have high tolerance to Zn deficiency [25]. Thus, significant differences among tested varieties of rice with respect to Zn content might also be due to differential growth behavior leading to differential uptake of Zn from the soil. Nutrient content differences among varieties depend on their genetic makeup and their different abilities to absorb and use soil nutrients [3,26,27].

Zn application as Zn$_4$ treatment led to the highest Zn concentration. The slow-release pattern of Zn in Zn-EDTA

Table 6 – Yields of parts of rice kernel as influenced by scented rice variety and Zn fertilization strategy.

Variety	2013						2014					
	Zn_0	Zn_1	Zn_2	Zn_3	Zn_4	Mean	Zn_0	Zn_1	Zn_2	Zn_3	Zn_4	Mean
Hull yield (t ha^{-1})												
PB 1401	1.08	1.25	1.18	1.23	1.33	1.21 a	0.87	1.00	0.90	0.94	1.02	0.94 a
PB 1460	0.68	0.71	0.83	0.82	0.83	0.77 c	0.60	0.72	0.72	0.71	0.74	0.70 b
PRH 10	1.17	1.13	1.10	1.10	1.09	1.12 ab	1.03	0.97	1.03	1.04	1.05	1.02 a
PB 1121	1.09	1.17	1.20	1.11	1.20	1.15 ab	0.89	0.95	1.00	1.04	1.07	0.99 a
PB 1509	1.03	1.03	1.14	1.02	1.06	1.06 b	0.93	0.98	1.13	1.02	1.04	1.02 a
PS 5	1.01	1.01	1.04	0.96	1.01	1.01 b	1.07	1.05	1.09	1.01	0.93	1.03 a
Mean	1.01	1.05	1.08	1.04	1.09		0.90	0.94	0.98	0.96	0.98	
$LSD_{0.05}$	Variety = 0.14						Variety = 0.10					
Bran yield (t ha^{-1})												
PB 1401	0.48	0.53	0.50	0.48	0.45	0.49 cd	0.65	0.70	0.52	0.53	0.61	0.60 cd
PB 1460	0.36	0.36	0.36	0.38	0.47	0.38 d	0.49	0.41	0.47	0.48	0.42	0.45 e
PRH 10	0.78	0.95	1.15	1.21	1.14	1.04 a	0.97	0.96	1.16	0.88	0.76	0.95 a
PB 1121	0.59	0.55	0.63	0.51	0.61	0.58 c	0.88	0.78	0.79	0.79	0.74	0.80 b
PB 1509	0.68	0.54	0.61	0.58	0.60	0.60 c	0.89	0.59	0.61	0.58	0.67	0.67 bc
PS 5	0.89	0.86	0.80	0.75	0.74	0.81 b	0.36	0.47	0.51	0.58	0.70	0.52 de
Mean	0.63	0.63	0.68	0.65	0.67		0.71	0.65	0.68	0.64	0.65	
$LSD_{0.05}$	Variety = 0.12						Variety = 0.14					
White rice kernel yield (t ha^{-1})												
PB 1401	1.99	2.13	2.38	2.21	2.56	2.25 c	2.25	2.71	2.67	2.56	3.01	2.64 c
PB 1460	1.52	1.66	2.03	1.67	1.98	1.77 d	1.59	1.96	2.03	1.90	2.16	1.93 d
PRH 10	3.54	3.75	3.58	3.97	3.74	3.72 a	3.15	3.25	3.57	3.61	3.84	3.48 a
PB 1121	2.07	2.44	2.42	2.50	2.60	2.40 c	2.43	2.59	2.82	2.98	3.10	2.78 bc
PB 1509	2.67	2.89	3.23	3.10	3.00	2.98 b	2.65	2.99	3.33	3.06	3.03	3.01 bc
PS 5	2.78	3.16	3.22	3.04	3.34	3.11 b	2.99	3.28	3.41	3.31	3.03	3.20 ab
Mean	2.43 c	2.67 b	2.81 ab	2.75 ab	2.87 a		2.51 c	2.80 b	2.97 ab	2.90 ab	3.03 a	
$LSD_{0.05}$	Variety = 0.39; Zn fertilization = 0.18						Variety = 0.41; Zn fertilization = 0.19					

Main effects sharing the same case letter, for a parameter during an experimental year, do not differ significantly (P = 0.05) by the LSD. Likewise, the figures of main effects without lettering do not differ significantly (P = 0.05) by the LSD.

Zn_0, control (no zinc); Zn_1, soil application of Zn at 5 kg ha^{-1} as $ZnSO_4 \cdot 7H_2O$ (ZnSHH); Zn_2, soil application of Zn at 2.5 kg ha^{-1} as ZnSHH + 0.5% foliar spray of ZnSHH at maximum tillering (MT) and panicle initiation (PI) stages; Zn_3, soil application of Zn at 2.5 kg ha^{-1} as Zn-EDTA; Zn_4, soil application of Zn at 1.25 kg ha^{-1} as Zn-EDTA + 0.5% foliar spray of Zn-EDTA at MT and PI stage.

Degrees of freedom for replication = 2; Variety = 5; Error I = 10; Zn fertilization = 4; Variety × Zn fertilization = 20; Error II = 48; Total = 89.

might be due to lower retention and greater transport of chelated Zn to plant roots [28–30]. When Zn was applied as EDTA, amounts of water-soluble and exchangeable Zn content in soil profile increase [31]. Combined application of Zn (soil + foliar) as different Zn sources is appropriate for increasing kernel Zn concentration.

Shivay et al. [3] reported that soil + foliar application of Zn fertilization resulted in non-significant rice grain yield but significantly higher grain Zn concentration was recorded. A similar result was reported in different varieties of rice by Dhaliwal et al. [32]. Zn is more mobile than other nutrients within the plant and foliar application leads to translocation to leaves other than the treated leaf as well as to root tips. Among sources of Zn, Zn-EDTA supplies Zn relatively continuously for longer times or with lower fixation among soil components viz. humus, clay minerals, carbonates, oxides than $ZnSO_4 \cdot 7H_2O$, which leads to greater Zn fixation in the soil. Furthermore, Zn-EDTA, supplying Zn at half the rate of ZnSHH, led to a higher mobilization index (0.32; 0.31).

Varieties 'PB 1401', 'PS 5', 'PRH 10', and 'PB 1509' showed higher values of Zn use efficiency as AE, PE, PFP, and ZnHI in comparison to the rest of varieties, respectively (Tables 4, 5). Significant differences in Zn use efficiency might be due to different capacities of varieties to absorb and use Zn, resulting in different growth and biomass production and Zn uptake. Zn use efficiencies were higher at lower doses owing to its rapid adsorption on clay minerals and soil organic matter [33] and further subsequent slow desorption [34]. The higher PFP, AE, PE, and ZnHI in foliar-fertilized plots might be due to the very small amounts of Zn used (1.05 kg ha^{-1}). ZnHI for soil and foliar application was similar, but AE of Zn with foliar application as Zn-EDTA was about twice that of soil application (ZnSHH). The difference might be due to the much lower application rate of Zn-EDTA (Zn_4) when applied on foliage. Similarly, all the indices used for measuring ZnUE in basmati rice, namely PFP, AE, and RE, declined as the Zn application rate was increased from 0.5 to 5.0 kg Zn ha^{-1} [11,35]. Chelated Zn is likely to be fixed in lesser amounts in soil than Zn sulphate [31]. This might also be the reason for higher values of ZnUEs of applied Zn from EDTA chelates in comparison with other Zn sources [30,35]. Shivay et al. [35] found that ferti-fortification recovery with foliar application was about eight times that obtained with soil application. This is why split application is a better option to improve Zn concentration, uptake, and ZnUEs in scented rice varieties.

In different parts of rice kernel, Zn concentrations were in descending order of hull > bran > white rice kernel (Table 2). Jiang et al. [36] in Thailand reported that Zn concentration decreased during milling in various rice genotypes, remaining higher in long and slender grains. Naik and Das [29] reported that Zn concentration in rice kernel was significantly greater with 0.5 kg Zn-EDTA ha^{-1} than with 10 kg ZnSHH ha^{-1}.

Among Zn sources, Zn-EDTA + two foliar sprays (0.5% Zn-EDTA) seems to be the most efficient Zn fertilization strategy for increasing Zn concentration in rice kernel parts, uptake, ZnUEs, and productivity. Although Zn-EDTA supplied the lowest amount of Zn, it yielded the highest Zn-mobilization-efficiency index and led to the highest Zn uptake. Application of treatment Zn$_4$ in 'PB 1509' yielded the highest Zn concentration in hull, bran, and white rice kernel as well as ZnMEI and ZnHI. Milled rice always has lesser mineral contents due to removal of aleurone layer during milling. Thus, consumption of brown rice could be an alternative way to milled rice or white rice kernel for improving the zinc status in diets of Asian and African population. Overall, Zn applications through Zn-EDTA increased Zn concentration and uptake in scented rice varieties and helped to improve the grain yield by maintaining the proper supply of Zn, allowing higher accumulation of Zn in the white rice kernel.

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