Journal of Agricultural Science; Vol. 13, No. 5; 2021
ISSN 1916-9752 E-ISSN 1916-9760
Published by Canadian Center of Science and Education

Basmati Rice Quality Enhancement by Zinc Fertilization and Green Manuring on a Sub-tropical Inceptisol in Indo-Gangetic Plains of India

Amarpreet Singh[1,2], Yashbir Singh Shivay[1], Radha Prasanna[3] & Ashok Kumar[4]

[1] Division of Agronomy, ICAR-Indian Agricultural Research Institute, New Delhi, India

[2] ICAR-Central Institute for Cotton Research (ICAR-CICR), Regional Station, Sirsa, Haryana, India

[3] Division of Microbiology, ICAR-Indian Agricultural Research Institute, New Delhi, India

[4] NASF, ICAR-KAB-I, Pusa Campus, New Delhi, India

Correspondence: Yashbir Singh Shivay, Division of Agronomy, ICAR-Indian Agricultural Research Institute, New Delhi 110012, India. Tel: 91-965-023-0379. E-mail: ysshivay@hotmail.com

Received: February 2, 2021 Accepted: March 6, 2021 Online Published: April 15, 2021

doi:10.5539/jas.v13n5p125 URL: https://doi.org/10.5539/jas.v13n5p125

Abstract

Basmati (aromatic) rice is premier rice grown in north-western India and Pakistan. This rice is preferred for their long and slender kernels which expand 3-4 times in length and remain fluffy and are well known all over the world, especially in the Middle East and South Asia for their long fluffy grains on cooking. Paddy soils are usually deficient in organic matter because of high temperature and moisture, which causes rapid decomposition of organic matter. The importance of leguminous green manure crops in improving soil fertility, and soil physical properties received increasing attention. Also, the zinc (Zn) deficiency in soils is prevalent worldwide, especially in high pH calcareous soils. No reports were available on combining green manuring crops and Zn fertilization on productivity, Zn content and kernel quality of *Basmati* rice. Therefore, the current investigation was undertaken to quantify the combined effects of summer green manuring crops and zinc fertilization on productivity, Zn content and kernel quality of *Basmati* rice in summer green manuring-*Basmati* rice cropping system. A field study was therefore conducted for two years (2009 and 2010) on a sandy clay-loam soil (*typic Ustochrept*) at the research farm of the ICAR-Indian Agricultural Research Institute, New Delhi, India. The experiments were conducted in split plot design, keeping three green manuring crops viz. *Sesbania aculeata* (Dhaincha), *Crotalaria juncea* (Sunhemp), and *Vigna unguiculata* (Cowpea) and one summer fallow treatment as main-plot treatments and six Zn sources viz. control (no Zn application), $ZnSO_4{\cdot}7H_2O$ (21% Zn), $ZnSO_4{\cdot}H_2O$ (33% Zn), ZnO (82% Zn), $ZnSO_4{\cdot}7H_2O$ + ZnO (50% + 50%) and EDTA-chelated Zn (12% Zn) in sub-plots and was replicated thrice. The experiments in both the years were conducted with a fixed lay-out plan on the same site. The results showed that incorporation of green manures along with zinc (Zn) fertilization increased grain and straw yield, enhanced Zn concentrations and improved the kernel quality before and after cooking in *Basmati* rice 'Pusa *Basmati* 1'. The application of EDTA-chelated Zn (12% Zn) was the best in terms of grain and straw yield and Zn concentrations in grain and straw and kernel quality before and after cooking *Basmati* rice. Application of $ZnSO_4{\cdot}7H_2O$ (21% Zn) was the second-best treatment followed by $ZnSO_4{\cdot}H_2O$ (33% Zn) and $ZnSO_4{\cdot}7H_2O$ + ZnO (50% + 50%). Application of ZnO (82% Zn) had least effect in increasing the studied parameters. The lowest values were observed with control (no Zn application). Among the summer green manuring crops, incorporation of *Sesbania aculeata* (Dhaincha) was found to be the best over *Crotalaria juncea* (Sunhemp), *Vigna unguiculata* (Cowpea) and summer fallow in terms of grain and straw yield, Zn concentrations in grain and straw and kernel quality before and after cooking in *Basmati* rice. Zn fertilization with EDTA-chelated Zn (12% Zn) lead to 25.91 and 21.26% higher grain yield; 60.66 and 82.14% Zn-denser grains; with 13.33 and 10.92% increase in head rice recovery in *Basmati* rice over control (no Zn application) during 2009 and 2010, respectively.

Keywords: *Basmati* rice, India, kernel quality parameters, South Asia, sub-tropical region, summer green manuring crops, yields, zinc concentration, zinc sources

1. Introduction

Basmati (aromatic) rice is the premier rice grown in north-western India and Pakistan. This rice is preferred for their long and slender kernels which expand 3-4 times in length and remain fluffy. The varieties of *Basmati* rice differ greatly in kind and intensity of aroma. The aroma in rice is due to chemical diacetyl 1-pyrolline (V. P. Singh & A. K. Singh, 2009). These type of rice are well known all over the world, especially in the Middle East and South Asia for their long fluffy grains on cooking, a desirable characteristic for the dish *Biryani* or *Pulao* made by cooking rice with vegetables, mutton or chicken and flavoured with special oriental spices (Shivay et al., 2010). Traditional *Basmati* rice in India's Doon valley is tall *indicas* yielding 1.5 to 2.0 tonnes per hectare and lodge on heavy fertilization. Therefore, attempts were made at the ICAR-Indian Agricultural Research Institute, New Delhi to develop *Basmati* rice varieties having high yielding qualities of semi-dwarf *indicas* rice and having better quality aromas than the traditional one. Considering the great demand of *Basmati* rice globally, the researchers made concerted research efforts at the ICAR-Indian Agricultural Research Institute, New Delhi, India to develop rice varieties having both *Basmati* traits and high yield potential. This involved convergent breeding and simultaneous selection at field and laboratory for the complex inherited key characteristics of *Basmati* quality (extra-long slender grain, excessive elongation on cooking, aroma and ideal physico-chemical properties of starch) and high yield potential of new semi-dwarf rice varieties (Shivay et al., 2010). Pusa *Basmati*-1 resulted from this research, which took about 25 years and now occupies the largest area in north-western India and fetches about the US $ 500 million in the international market (Siddiq, 2006). 'Pusa *Basmati*-1' is high yielding *Basmati* rice with long and slender kernels as per classification by Jennings et al. (1979). *Basmati* rice varieties developed from IARI now covered about 60% of the total area under rice in north-western India, which is estimated at 5 million hectares.

Paddy soils are usually deficient in organic matter because of high temperature and moisture, which causes rapid decomposition of organic matter (Mohammed et al., 2005). The application of green manures to the soil is considered a good management practice in any agricultural production system because it can increase cropping system sustainability by reducing soil erosion and ameliorating soil physical properties, by increasing soil organic matter and fertility levels (Mandal et al., 2003), by increasing nutrient retention and by reducing global warming potential (Robertson et al., 2000). Leguminous and non-leguminous plants are used in the production of green manures. Leguminous plants form symbiotic associations with *Rhizobium* bacteria to fix N_2. This fact causes the green manures, which their principal component are leguminous plant debris, supply to the important soil amounts of N in relation to the green manures obtained from non-leguminous plants.

The importance of leguminous green manure crops in improving soil fertility, and soil physical properties received increasing attention (Whitbread et al., 2000; Ray & Gupta, 2001). The improvement in physical soil conditions as a result of build-up of organic matter by incorporation of green manure or crop residue is associated with a decrease in bulk density, increase in total pore space, water-stable aggregates and hydraulic conductivity of the soil (Tejada et al., 2008a, 2008b). Fast-growing leguminous green manures with their adaptability to fit in rice-based cropping patterns and their ability to fix atmospheric nitrogen may offer opportunities to increase and sustain productivity and income in the rice-based cropping systems (Yadvinder-Singh et al., 1991). Green manures enhance organic matter which is the most important benefit credited to green manures. The positive effect of green manures on paddy yield has been reported by Sharma and Prasad (1999). Hemalatha et al. (1999) observed that *in-situ* incorporation of cowpea before transplanting of rice increased the grain yield by 18% and straw yield by 16% and the quality of rice.

Similarly, Bhatti et al. (1983) reported that *Sesbania* green manuring substantially improved grain yield to 72%. Incorporation of green manures before transplanting rice can ameliorate the Fe and Zn deficiency by promoting reduced condition and improving other physico-chemical properties of soil. *Sesbania aculeata* (Dhaincha), *Crotalaria juncea* (Sunhemp) and *Vigna unguiculata* (Cowpea) are some of the important leguminous green manuring crops for north-western Indian region. It is expected that regular incorporation of green manuring crops before transplanting of rice may improve not only the physico-chemical properties of the earth but also the availability of macro and micronutrients in soil and zinc fertilization in *Basmati* rice may help in improving its grain quality.

Zinc deficiency in soils is prevalent worldwide, especially in high pH calcareous soils (Adriano, 2001; Fageria et al., 2003; Norman et al., 2003; Prasad, 2006; Alloway, 2008; Cakmak, 2002, 2008a, 2008b). A recent analysis of two hundred forty-one thousand soil samples in India showed that 49% soils are deficient in Zn (Behera et al., 2009) and Zn deficiency is widespread in north Indian rice-wheat cropping system belt (Prasad, 2005). In rice, zinc deficiency is characterized by brown spots, which appear first in the younger leaves and later in the lower leaves. In severe Zn deficiency, burnt dark brown patches of plants in rice fields (Dobermann & Fairhurst, 2000). Zinc deficiency in rice was first reported by Nene (1966).

The response of rice to Zn has been reported by several workers in India (Srivastava et al., 2006; Shivay et al., 2007, 2010; Pooniya et al., 2012; Ghasal et al., 2018; Yadav et al., 2019), China (Shihua & Wenqiang, 2000) and the USA (Slaton et al., 2005). Zinc is now recognized as the fifth leading health risk factor in developing Asian countries, where rice is the staple food (Anonymous, 2007) and Zn nutrition of humans and animals has recently received considerable attention (WHO, 2002). Hotz and Brown (2004) estimated that 1.2 billion (20% of the world population) are at risk of inadequate Zn uptake. There is a HarvestPlus Global Challenge Programme of the Consultative Group on International Agricultural Research (CGIAR) focusing on breeding Zn efficient cultivars (HarvestPlus, 2009) to evolve rice and other cereals varieties with the denser-Zn grain. Nevertheless, there are problems in developing rice varieties with high grain yields and denser-Zn grains. However, as pointed out by Prasad (2009) this can be achieved at a faster rate through application of Zn fertilizers and that too without any compromise on grain yield under Zn stress conditions. Even when Zn-efficient cultivars are developed, adequate Zn fertilizers would be required to make up the Zn depletion of soils (Shivay et al., 2010; Prasad & Shivay, 2020).

Zn fertilizers (oxides, sulphates and other Zn salts) since, as with most crops, the normal way of correcting Zn deficiencies in soils is to apply these fertilizers (Brennan & Bolland, 2006; Alvarez et al., 2009). However, In India, Zn deficiency is usually corrected through the application of inorganic salt, mainly $ZnSO_4{\cdot}7H_2O$. Soil application of 5 kg Zn ha^{-1} (25 kg $ZnSO_4{\cdot}7H_2O$ ha^{-1}) is recommended for rice in India. However, the product is quite costly and generally not available to farmers', resulting in reduced rice yield. Other sources are the chelated forms of Zn such as Zn-EDTA, which supplies a substantial amount of Zn to the plants without interacting with soil components (Karak et al., 2005) because the central metal ion Zn^{2+} is surrounded by chelate ligands (Mortvedt, 1979), needs to be investigated.

However, no reports are available on combining green manuring crops and Zn fertilization on productivity, Zn content and kernel quality of *Basmati* rice. Therefore, the current investigation was undertaken to quantify the combined effects of summer green manuring crops and zinc fertilization on productivity, Zn content and kernel quality of *Basmati* rice in summer green manuring-*Basmati* rice cropping system.

2. Materials and Methods

2.1 Description of the Study Area

The field experiments were conducted for two consecutive years at the ICAR-Indian Agricultural Research Institute, New Delhi, India during summer-*Kharif*/rainy seasons (April-October) of 2009 and 2010 on a sandy clay-loam soil (*typic Ustochrept*). The experiments in both the years were conducted with a fixed layout plan on the same site. The institute farm is located at a latitude of 28°38′ N, longitude of 77°10′ E and altitude of 228.6 m above the mean sea level. The mean annual rainfall of New Delhi is 650 mm, and more than 80% generally occurs during the south-west monsoon season (July-September) with mean yearly evaporation of 850 mm.

The soils of the experimental field had 135.75 kg ha^{-1} alkaline permanganate oxidizable nitrogen (N) (Subbiah & Asija, 1956), 16.04 kg ha^{-1} available phosphorus (P) (Olsen et al., 1954), 292.10 kg ha^{-1} 1 *N* ammonium acetate exchangeable potassium (K) (Hanway & Heidel, 1952) and 0.53% organic carbon (C) (Walkley & Black, 1934). The pH of the soil was 7.5 (1:2.5 soil and water ratio) (Prasad et al., 2006) and diethylene triamine penta acetic acid (DTPA)-extractable Zn (Lindsay & Norvell, 1978) in soil was 0.67 mg kg^{-1} of soil. The critical level of DTPA-extractable Zn for rice grown on alluvial soils in the rice-wheat belt of North India varies from 0.38-0.90 mg kg^{-1} soil (Takkar et al., 1997).

2.2 Experimental Treatments and Design

The experiment was conducted in a split-plot design, keeping three green manuring crops viz. *Sesbania aculeata* (Dhaincha), *Crotalaria juncea* (Sunhemp), and *Vigna unguiculata* (Cowpea) and one summer fallow treatment as main-plot treatments and five Zn sources viz. $ZnSO_4{\cdot}7H_2O$ (21% Zn), $ZnSO_4{\cdot}H_2O$ (33% Zn), ZnO (82% Zn), $ZnSO_4{\cdot}7H_2O$ + ZnO (50% + 50%), EDTA-chelated Zn (12% Zn) and a control (no Zn application), in sub-plots and was replicated thrice.

2.3 Application of Treatments and Fertilizers

During summer seasons three summer green manuring crops viz. *Sesbania aculeata* (Dhaincha), *Crotalaria juncea* (Sunhemp), and *Vigna unguiculata* (Cowpea) were planted as main plot treatments. A summer fallow treatment was also considered as the control. After 40 days the summer green manuring crops were incorporated into the soil before transplanting of rice. After incorporating green manuring crops, each main plot (with green manure incorporation or otherwise) was divided into six sub-plots, which received the Zn-fertilization treatments. The experimental field was disk-ploughed twice, puddled three times with a puddler in standing water and levelled. At final puddling 26 kg, P ha^{-1} as single superphosphate and 33 kg K ha^{-1} as muriate of potash was broadcasted. Addition of 26 kg P as single super phosphate also supplied 45 kg S ha^{-1} and took care of S deficiency (if any). It also takes care of the S advantage of $ZnSO_4 \cdot 7H_2O$ and permits a fair comparison of $ZnSO_4 \cdot 7H_2O$ and ZnO or EDTA-chelated Zn as a source of Zn. Nitrogen at 150 kg ha^{-1} as prilled urea was applied into two equal splits, half at the time of transplanting and remaining half at panicle initiation stage (40 DAT). In all the Zn treatments, uniformly 5 kg Zn ha^{-1} was applied at the time of transplanting.

2.4 Rice Transplanting

Three 25-day-old seedlings of *Basmati* rice (*Oryza sativa* L.) variety 'Pusa *Basmati* 1' was transplanted per hill at 20 cm × 10 cm in the first fortnight of July in both the years of study. It is a *Basmati* (aromatic) variety released from ICAR-Indian Agricultural Research Institute, New Delhi, India during 1989 for its commercial cultivation. It is a cross between 'Pusa 150' and 'Karnal Lokal'. It produces long slender grains with good aroma and excellent cooking qualities (Rani et al., 2009; V. P. Singh & A. K. Singh, 2009; Siddiq et al., 2012). Irrigation channels measuring 1 m wide were placed between the replications to ensure an easy and uninterrupted irrigation water flow. An individual plot was independently irrigated from the irrigation channels. Rice crop was grown as per recommended package of practices and was harvested in the second fortnight of October in both the years of experimentation.

2.5 Measurements of Yields of Rice

Harvesting of the *Basmati* rice was undertaken as soon as it attained the harvest maturity. The harvesting was done with the help of sickles after leaving the border area. Net plots were demarcated at first from the portion of the plot kept for recording grain yield. Plants from the demarcated net plot area were harvested, tied in bundles and taken to the threshing floor for drying and threshing. The harvested plants were dried for three days to bring down the moisture content to around 14%. After threshing, the seeds were cleaned, sun-dried and their weight was recorded. The yields in kg plot^{-1} were converted to tonnes ha^{-1}. The weight of the harvested plants after sun drying and before threshing was recorded. The straw yield was obtained by deducting the seed weight from the total weight. The grain and straw yields were expressed in tonnes ha^{-1}. The 1000-filled grains, taken at harvest, were first counted by a seed counter and then weighed to compute the 1000-grain weight.

2.6 Chemical Analysis of Zn Concentration in Rice Grain and Straw

At harvest, the dried plants were separated into grain and straw, ground in a milling machine, sieved through 0.7 mm sieve and analysed for Zn content separately. Dried plant samples were digested with di-acid [perchloric acid ($HClO_4$) + nitric acid (HNO_3) in 3:10 ratio] as per procedures described by Prasad et al. (2006). After digestion and extraction of samples, total Zn was estimated with the atomic absorption spectrophotometer (Perkin Elmer; Model-A. Analyst 100).

2.7 Kernel Quality Parameters

2.7.1 Milling Quality Parameter

Hulling (%): Well sun-dried paddy (rough or unhulled rice) samples of each treatment weighing 100 g from each replication were hulled in a mini "Satake Rice Mill" (Satake, 1990), the weight of brown rice was recorded, and the hulling percentage was calculated as:

$$\text{Hulling (\%)} = [\text{Weight of brown rice (g)}/\text{Weight of rough rice (g)}] \times 100 \quad (1)$$

Milling (%): To obtain uniformly polished grains, the hulled brown rice was passed through a 'Satake Rice Polishing Machine' (Satake, 1990) for 2 minutes. The polished rice was weighed, and milling percentage was worked out as under:

$$\text{Milling (\%)} = [\text{Weight of milled rice (g)}/\text{Weight of rough rice (g)}] \times 100 \quad (2)$$

Head Rice Recovery: The milled rice was passed through an appropriate sieve to separate whole kernels from the broken ones. Head rice recovery (%) was computed as:

$$\text{Head rice recovery (\%)} = [\text{Weight of whole milled rice (g)}/\text{Weight of rough rice (g)}] \times 100 \quad (3)$$

2.7.2 Kernel Cooking Quality Parameters

(1) Kernel Length and Breadth Before Cooking

Ten milled kernels from each plot were taken at random and placed separately on a graph paper, and their length and breadth were measured using a 'Photo Enlarger' with a magnification of 3X. The actual mean kernel length and breadth was expressed in mm.

(2) Kernel Length and Breadth After Cooking

Rice cooking technique was a simple modification of the technique used by Juliano and Perez (1984). A sample of ten kernels was taken in 15 cm long and 2.5 cm wide test tubes and pre-soaked in 5 ml of tap water for 30 minutes. The tubes were then placed in a water bath maintained at boiling temperature (using a Thermotech temperature controller TH-013; Thermotech, Gujarat, India) for 6-7 minutes. After cooking, the tubes were taken out and cooled under running water for 2 minutes. Cooked kernels were taken out of the tubes, and excess water was removed with a blotting paper. Length and breadth of cooked kernels were measured, as mentioned above.

(3) Kernel Elongation Ratio

Kernel Length Expansion Ratio: The kernel length expansion ratio was calculated by dividing the cooked kernel's length by its original length.

$$\text{Length expansion ratio} = L_2/L_1 \quad (4)$$

where, L_1 and L_2 are kernel length before and after cooking, respectively.

Kernel Breadth Expansion Ratio: The kernel breadth expansion ratio was calculated by dividing the cooked kernel's breadth by its original breadth.

$$\text{Breadth expansion ratio} = B_2/B_1 \quad (5)$$

where, B_1 and B_2 are grain length before and after cooking, respectively.

2.8 Protein Content

Protein content in *Basmati* rice grain was obtained by multiplying N concentration with a coefficient factor 5.95 (Juliano, 1979; Juliano, 1985). This factor is based on the nitrogen content (16.8%) of the major rice protein (Glutelin). The protein content was expressed in percentage.

2.9 Amylose Content

A sample of 1 g milled rice grains was gently crushed and made into fine powder in a vitreous pestle and mortar. The flour samples were stored to uniform moisture of 12%. One hundred mg sample was weighed carefully on an electric meter balance and transferred to a 100 milliliter (ml) volumetric flask. One ml of distilled ethanol was added and mixed well. Ten ml of freshly prepared 1 *N* NaOH solution was added to it. After gelatinization, the sample suspension was heated for 10 minutes in a boiling water bath. The volume was made up to 100 ml with distilled water. After thoroughly shaking the content, an aliquot of 2.5 ml was pipetted out into a 50 ml volumetric flask and added about 20 ml of water. Three drops of phenolphthalein indicator were added mixed well. The content was acidified by adding 0.1 *N* HCl drop by drop until the pink colour disappears. Then one ml of iodine reagent was added to develop blue colour and volume was made up to 50 ml. The absorbance at 590 nm was recorded with the help of a Spectrophotometer.

A standard curve was prepared based on the absorbance values of known quantities of pure amylose (rice amylose). The amount of amylose in the sample using the standard curve was prepared from pure amylose (range 0.2-1.0 mg) against a blank for which diluted 1 ml of iodine reagent to 50 ml with distilled water was used (Sadasivam & Manickam, 1992; Thanyumanavan & Sadasivam, 1984; Thimmiah, 1999).

$$\text{Absorbance corresponds to 2.5 ml of test solution} = \text{'}\times\text{' mg amylose in a test solution} \quad (6)$$

$$\text{100 ml contains} = [X/2.5] \times 100\% \text{ amylose} \quad (7)$$

2.10 Statistical Analysis

All the data obtained from rice crop for consecutive two years of study were statistically analyzed using the F-test as per the procedure given by K. A. Gomez and A. A. Gomez (1984). Least significant difference (LSD) values at $P = 0.05$ were used to determine the significance of differences between treatment means.

3. Results

3.1 Grain and Straw Yields of Basmati Rice

In general, the grain and straw yields were higher during the second year of experimentation (Table 1). *Basmati* rice yields were significantly influenced by incorporating summer green manuring crop residues and Zn sources. The significantly higher grain and straw yields of *Basmati* rice were recorded when it was grown after *Sesbania aculeata* (Dhaincha) incorporation compared with *Crotalaria juncea* (Sunhemp), *Vigna unguiculata* (Cowpea) and summer fallow treatments.

Table 1. Effect of summer green manuring crops and Zn fertilizer sources on the grain and straw yields and Zn concentration in grain and straw of *Basmati* rice

Treatment	Grain yield (tonnes ha^{-1})		Straw yield (tonnes ha^{-1})		Zn concentration in grain (mg kg^{-1} grain)		Zn concentration in straw (mg kg^{-1} straw)	
	2009	2010	2009	2010	2009	2010	2009	2010
Summer-green manuring crops								
Sesbania aculeata (Dhaincha)	4.89	5.56	9.04	10.21	31.5	32.4	167.5	172.1
Crotalaria juncea (Sunhemp)	4.74	5.34	8.83	10.02	29.8	29.6	162.1	162.4
Vigna unguiculata (Cowpea)	4.58	5.12	8.64	9.82	27.2	26.7	155.6	156.2
Summer fallow	4.30	4.86	8.36	9.63	24.2	23.7	150.2	151.0
SEm±	0.041	0.026	0.039	0.031	0.47	0.55	2.05	2.37
LSD (P = 0.05)	0.141	0.091	0.135	0.105	1.61	1.90	7.08	8.16
Zn sources								
Control	4.09	4.75	8.13	9.39	21.1	19.6	146.4	146.8
$ZnSO_4{\cdot}7H_2O$ (21% Zn)	4.92	5.41	9.04	10.18	30.3	30.3	164.4	165.9
$ZnSO_4{\cdot}H_2O$ (33% Zn)	4.74	5.27	8.81	10.02	29.3	29.1	159.6	161.3
ZnO (82% Zn)	4.32	4.98	8.40	9.61	26.5	25.6	152.5	153.2
$ZnSO_4{\cdot}7H_2O$ + ZnO (50% + 50%)	4.54	5.15	8.61	9.85	28.1	28.1	156.7	158.1
EDTA–chelated Zn (12% Zn)	5.15	5.76	9.30	10.48	33.9	35.7	173.5	177.4
SEm±	0.043	0.027	0.046	0.032	0.29	0.35	0.68	0.94
LSD (P = 0.05)	0.123	0.077	0.131	0.090	0.84	0.99	1.96	2.70

Zn fertilizer sources also significantly influenced grain and straw yields of *Basmati* rice during 2009 and 2010. Among the Zn fertilization treatments, application of EDTA-chelated Zn (12% Zn) resulted into statistically higher values of grain (5.15 and 5.76 tonnes ha^{-1}) and straw yields (9.30 and 10.48 tonnes ha^{-1}) compared with all other Zn fertilizer sources and control (no Zn application), respectively during 2009 and 2010. Application of $ZnSO_4{\cdot}7H_2O$ (21% Zn) was second-best treatment with respect to grain (4.92 and 5.41 tonnes ha^{-1}) and straw yields (9.04 and 10.18 tonnes ha^{-1}). The lowest values of grain and straw were recorded with control (no Zn application). The performance of Zn sources in terms of yields of *Basmati* rice was in the order; EDTA-chelated Zn (12% Zn) > $ZnSO_4{\cdot}7H_2O$ (21% Zn) > $ZnSO_4{\cdot}H_2O$ (33% Zn) > $ZnSO_4{\cdot}7H_2O$ + ZnO (50% + 50%) > ZnO (82% Zn). The per cent increase in grain and straw yields with EDTA-chelated Zn (12% Zn) application over control (no Zn application) was 25.91, 21.26% and 14.39, 11.60%, respectively during 2009 and 2010.

3.2 Zn Concentration in Grain and Straw of Basmati Rice

Different green manures and Zn sources had significantly influenced on the Zn concentrations in grain and straw of *Basmati* rice (Table 1). In our studies, the Zn concentration in rice straw was higher compared with rice grains. The significantly higher Zn concentration in grain and straw of rice was recorded with *Sesbania aculeata* (Dhaincha) incorporation and application of EDTA-chelated Zn (12% Zn) during both the years. Zn concentration in grain and straw were significantly higher with *Sesbania aculeata* (Dhaincha) incorporation compared with *Crotalaria juncea* (Sunhemp), *Vigna unguiculata* (Cowpea) and summer fallow treatments.

In general, application of Zn fertilizers, irrespective of its source, significantly increased the Zn concentration in grain and straw compared with control (no Zn application). Among the Zn fertilization treatments, the application of EDTA-chelated Zn (12% Zn) resulted in statistically higher values of Zn content in grain and straw than all other Zn sources and control (no Zn application) during 2009 and 2010, respectively. Application of $ZnSO_4{\cdot}7H_2O$ (21% Zn) was the second best treatment with respect to Zn concentration in grain and straw. The lowest values were recorded with control (no Zn application). A significantly higher correlation was recorded between grain yield and Zn uptake by grain (Figures 1A and 1B). This might be because zinc affects carbohydrate metabolism through its effects on photosynthesis, sugar transformations and seed development. Thus, increased Zn content and its uptake in grains which helped to produce bolder grains, thus increasing the grain yield (Alloway, 2008).

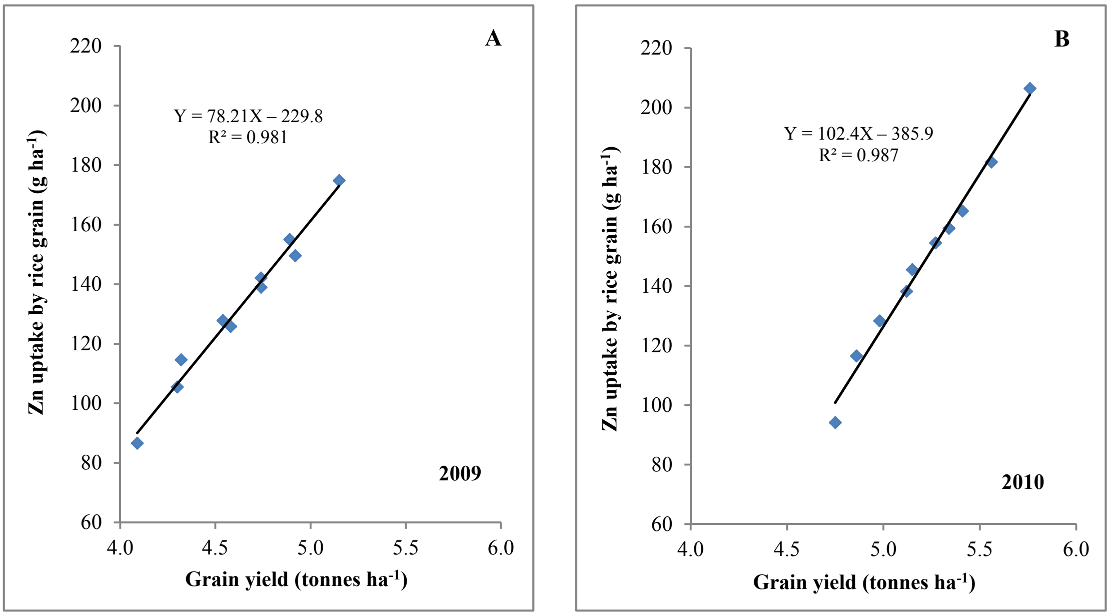

Figure 1. Rice grain yield correlation and regression with Zn uptake by *Basmati* rice grain

Percent increase in Zn concentration in grain and straw of rice with EDTA-chelated Zn (12% Zn) application over control (no Zn application) was 60.66, 82.14% and 18.51, 20.84%, respectively during 2009 and 2010. The per cent Zn concentration in grain and straw of rice was higher during 2010 as compared to 2009. It may be due to the higher residual effect (applied during 2009) of EDTA-chelated Zn in the experimental field as the same site with fixed lay out plan was used during both the years of experimentation. The performance of Zn sources in terms of Zn concentration in grain and straw was in the order; EDTA-chelated Zn (12% Zn) > $ZnSO_4 \cdot 7H_2O$ (21% Zn) > $ZnSO_4 \cdot H_2O$ (33% Zn) > $ZnSO_4 \cdot 7H_2O$ + ZnO (50% + 50%) > ZnO (82% Zn).

3.3 Milling Quality Parameters of Basmati Rice

The data on hulling, milling and head rice recovery are presented in Table 2. Milling quality parameters of *Basmati* rice got significantly influenced by incorporating summer green manuring crop residue and Zn sources. In general, hulling, milling and head rice recovery percentages significantly improved with green manuring over summer fallows, irrespective of the type of green manure. The significantly higher values of milling quality parameters were recorded when it was grown after *Sesbania aculeata* (Dhaincha) incorporation compared with *Crotalaria juncea* (Sunhemp), *Vigna unguiculata* (Cowpea) and summer fallow treatments.

Table 2. Effect of summer green manuring crops and Zn fertilizer sources on the hulling, milling and head rice recovery of *Basmati* rice

Treatment	Hulling (%)		Milling (%)		Head rice recovery (%)	
	2009	2010	2009	2010	2009	2010
Summer-green manuring crops						
Sesbania aculeata (Dhaincha)	78.7	79.0	68.7	69.2	58.8	59.0
Crotalaria juncea (Sunhemp)	77.6	77.7	67.3	68.5	57.3	57.8
Vigna unguiculata (Cowpea)	76.9	77.1	66.6	67.0	56.0	56.5
Summer fallow	75.9	76.0	65.2	66.0	54.4	55.2
SEm±	0.23	0.30	0.33	0.25	0.44	0.31
LSD (P = 0.05)	0.80	1.04	1.12	0.88	1.51	1.08
Zn sources						
Control	75.7	76.0	64.6	65.7	53.3	54.0
$ZnSO_4 \cdot 7H_2O$ (21% Zn)	78.1	78.3	68.4	68.9	58.6	59.0
$ZnSO_4 \cdot H_2O$ (33% Zn)	77.2	77.6	67.0	68.0	57.5	57.7
ZnO (82% Zn)	76.2	76.5	65.7	66.6	54.6	55.5
$ZnSO_4 \cdot 7H_2O$ + ZnO (50% + 50%)	76.7	77.0	66.4	67.1	55.6	56.7
EDTA-chelated Zn (12% Zn)	79.7	79.4	69.7	69.8	60.2	59.9
SEm±	0.23	0.18	0.22	0.16	0.37	0.24
LSD (P = 0.05)	0.64	0.51	0.63	0.44	1.04	0.69

Zn fertilization to *Basmati* rice also significantly influenced the hulling, milling and head rice recovery percentages. Among the Zn fertilization treatments, application of EDTA-chelated Zn (12% Zn) resulted in statistically higher values of milling quality parameters than all other Zn fertilizer sources including control (no Zn application), respectively during 2009 and 2010. Application of $ZnSO_4 \cdot 7H_2O$ (21% Zn) was the second best treatment with respect to milling quality parameters, but was statistically inferior to it. The lowest hulling values, milling and head rice recovery, were recorded with control (no Zn application). The performance of Zn sources in terms of milling quality parameters of *Basmati* rice was in the order; EDTA-chelated Zn (12% Zn) > $ZnSO_4 \cdot 7H_2O$ (21% Zn) > $ZnSO_4 \cdot H_2O$ (33% Zn) > $ZnSO_4 \cdot 7H_2O$ + ZnO (50% + 50%) > ZnO (82% Zn). There was 13.33 and 10.92% increase in head rice recovery with EDTA-chelated Zn (12% Zn) application over control (no Zn application) during 2009 and 2010.

3.4 Kernel Length Before and After Cooking and Length Expansion Ratio

Incorporation of green manures and Zn sources had influenced significantly the kernel length before and after cooking (Table 3). Our results indicate that the rice kernels were significantly lengthier, both before and after cooking with *Sesbania aculeata* (Dhaincha) incorporation and application of EDTA-chelated Zn (12% Zn) during both the years. Kernel length before and after cooking and length expansion ratio were significantly higher with *Sesbania aculeata* (Dhaincha) incorporation compared with *Crotalaria juncea* (Sunhemp), *Vigna unguiculata* (Cowpea) and summer fallow treatments.

Table 3. Effect of summer green manuring crops and Zn fertilizer sources on the rice kernel length before and after cooking and kernel length expansion ratio and 1,000-grain weight of *Basmati* rice

Treatment	Rice kernel length before cooking (mm) (L_1)		Rice kernel length after cooking (mm) (L_2)		Rice kernel length expansion ratio (L_2/L_1)		1,000-grain weight (g)	
	2009	2010	2009	2010	2009	2010	2009	2010
Summer-green manuring crops								
Sesbania aculeata (Dhaincha)	6.84	6.90	14.26	14.41	2.08	2.09	25.37	25.88
Crotalaria juncea (Sunhemp)	6.74	6.80	14.05	14.17	2.07	2.08	24.95	25.13
Vigna unguiculata (Cowpea)	6.66	6.69	13.69	13.83	2.05	2.08	24.25	24.63
Summer fallow	6.56	6.57	13.42	13.55	2.04	2.06	23.47	24.01
SEm±	0.009	0.022	0.023	0.030	0.002	0.002	0.132	0.162
LSD (P = 0.05)	0.032	0.076	0.081	0.103	0.009	0.008	0.456	0.558
Zinc sources								
Control	6.52	6.52	13.38	13.38	2.03	2.06	22.54	22.69
$ZnSO_4 \cdot 7H_2O$ (21% Zn)	6.83	6.88	14.22	14.42	2.08	2.09	25.71	26.14
$ZnSO_4 \cdot H_2O$ (33% Zn)	6.73	6.78	13.94	14.10	2.07	2.08	24.82	25.21
ZnO (82% Zn)	6.59	6.60	13.54	13.67	2.05	2.07	23.33	23.96
$ZnSO_4 \cdot 7H_2O$ + ZnO (50% + 50%)	6.64	6.71	13.68	13.84	2.06	2.06	24.07	24.69
EDTA-chelated Zn (12% Zn)	6.89	6.94	14.38	14.53	2.09	2.10	26.59	26.77
SEm±	0.015	0.028	0.032	0.052	0.003	0.069	0.153	0.148
LSD (P = 0.05)	0.043	0.080	0.090	0.148	0.008	N.S.	0.438	0.422

Application of Zn fertilizers, in general, irrespective of its source, appreciably increased the kernel length before and after cooking compared with control (no Zn application). Among the Zn fertilization treatments, application of EDTA-chelated Zn (12% Zn) resulted in statistically higher kernel length values before and after cooking compared with all Zn fertilizer sources and control (no Zn application), respectively during 2009 and 2010. Application of $ZnSO_4 \cdot 7H_2O$ (21% Zn) was second best treatment with respect to kernel length after EDTA-chelated Zn (12% Zn) however; it was statistically inferior to it. The lowest values were recorded with control (no Zn application). The kernel length expansion ratio was affected significantly with Zn sources during 2009 only. Length expansion ratio got increased with Zn application during 2010 also, but up to non-significant levels. However, it was highest with EDTA-chelated Zn (12% Zn) application.

3.5 Kernel Breadth Before and After Cooking and Breadth Expansion Ratio

Application of Zn and green manure incorporation significantly influenced the kernel breadth of *Basmati* rice both before and after cooking (Table 4). Kernel breadth increased significantly, both before and after cooking with *Sesbania aculeata* (Dhaincha) incorporation and application of EDTA-chelated Zn (12% Zn) during both the years. Kernel breadth before and after cooking was significantly higher with *Sesbania aculeata* (Dhaincha) incorporation compared with *Vigna unguiculata* (Cowpea) and summer fallow treatments.

Table 4. Effect of summer green manuring crops and Zn fertilizer sources on the rice kernel breadth before and after cooking and kernel breadth expansion ration of *Basmati* rice

Treatment	Rice kernel breadth before cooking (mm) (B_1)		Rice kernel breadth after cooking (mm) (B_2)		Rice kernel breadth expansion ratio (B_2/B_1)	
	2009	2010	2009	2010	2009	2010
Summer-green manuring crops						
Sesbania aculeata (Dhaincha)	1.72	1.74	2.46	2.47	1.43	1.42
Crotalaria juncea (Sunhemp)	1.70	1.72	2.42	2.43	1.42	1.41
Vigna unguiculata (Cowpea)	1.68	1.71	2.39	2.40	1.41	1.41
Summer fallow	1.66	1.68	2.34	2.36	1.40	1.41
SEm±	0.006	0.006	0.009	0.005	0.008	0.003
LSD (P = 0.05)	0.022	0.019	0.033	0.018	NS	NS
Zinc sources						
Control	1.64	1.67	2.32	2.35	1.40	1.41
$ZnSO_4{\cdot}7H_2O$ (21% Zn)	1.72	1.74	2.45	2.46	1.42	1.42
$ZnSO_4{\cdot}H_2O$ (33% Zn)	1.70	1.72	2.41	2.42	1.42	1.41
ZnO (82% Zn)	1.66	1.69	2.35	2.37	1.41	1.41
$ZnSO_4{\cdot}7H_2O$ + ZnO (50% + 50%)	1.68	1.70	2.38	2.40	1.41	1.41
EDTA-chelated Zn (12% Zn)	1.75	1.76	2.50	2.49	1.43	1.42
SEm±	0.006	0.005	0.008	0.005	0.002	0.023
LSD (P = 0.05)	0.016	0.014	0.022	0.014	NS	N.S.

Kernel breadth before and after cooking was significantly higher with Zn application, irrespective of its source, compared with control (no Zn application). Among the Zn fertilization treatments, application of EDTA-chelated Zn (12% Zn) resulted in statistically higher kernel breadth values before and after cooking compared with all other Zn fertilizer sources and control (no Zn application), respectively during 2009 and 2010. Application of $ZnSO_4{\cdot}7H_2O$ (21% Zn) was the second best treatment with respect to kernel breadth increase. Application of ZnO (82% Zn) was least effective in affecting the kernel breadth of *Basmati* rice. The lowest values were recorded with control (no Zn application). However, incorporating green manures or Zn application could not significantly influence the kernel breadth expansion ratio during both the years.

3.6 Protein Content

Protein content in *Basmati* rice grain got significantly influenced by Zn application and green manure incorporation (Table 5). Significantly higher protein content in *Basmati* rice grain was observed when grown after *Sesbania aculeata* (Dhaincha) incorporation and application of EDTA-chelated Zn (12% Zn) during both the years. Protein content was significantly higher with *Sesbania aculeata* (Dhaincha) incorporation compared with *Crotalaria juncea* (Sunhemp), *Vigna unguiculata* (Cowpea) and summer fallow treatments.

Table 5. Effect of summer green manuring crops and Zn fertilizer sources on the quality parameters of *Basmati* rice

Treatment	Protein (%)		Amylose (%)	
	2009	2010	2009	2010
Summer-green manuring crops				
Sesbania aculeata (Dhaincha)	8.1	8.3	24.6	24.9
Crotalaria juncea (Sunhemp)	8.0	8.2	24.3	24.6
Vigna unguiculata (Cowpea)	7.9	8.0	23.8	24.1
Summer fallow	7.7	7.8	23.4	23.7
SEm±	0.03	0.03	0.06	0.07
LSD (P = 0.05)	0.09	0.10	0.20	0.23
Zn sources				
Control	7.6	7.7	22.9	23.5
$ZnSO_4·7H_2O$ (21% Zn)	8.1	8.3	24.6	24.7
$ZnSO_4·H_2O$ (33% Zn)	8.0	8.2	24.3	24.4
ZnO (82% Zn)	7.7	7.9	23.6	23.9
$ZnSO_4·7H_2O$ + ZnO (50% + 50%)	7.8	8.0	23.9	24.1
EDTA-chelated Zn (12% Zn)	8.3	8.4	24.9	25.3
SEm±	0.04	0.02	0.09	0.06
LSD (P = 0.05)	0.11	0.06	0.25	0.18

Zn application, irrespective of its source, appreciably increased the grain protein compared with control (no Zn application). Among the Zn fertilization treatments, application of EDTA-chelated Zn (12% Zn) resulted in statistically higher grain protein values compared with all other Zn fertilizer sources and control (no Zn application), respectively during 2009 and 2010. Application of $ZnSO_4·7H_2O$ (21% Zn) was the second best treatment. The lowest values were recorded with control (no Zn application). Grain protein was 9.21 and 9.09% higher with EDTA-chelated Zn (12% Zn) application over control during 2009 and 2010, respectively. Application of $ZnSO_4·7H_2O$ (21% Zn) increased the grain protein content to the tune of 6.57 and 7.79% over control during 2009 and 2010, respectively. The performance of Zn sources in improvement in grain protein content was in the order; EDTA-chelated Zn (12% Zn) > $ZnSO_4·7H_2O$ (21% Zn) > $ZnSO_4·H_2O$ (33% Zn) > $ZnSO_4·7H_2O$ + ZnO (50% + 50%) > ZnO (82% Zn).

3.7 Amylose Content

Amylose content in *Basmati* rice grain got significantly influenced by Zn application and green manure incorporation (Table 5). The significantly higher amylose content values in *Basmati* rice grain were observed when it was grown after *Sesbania aculeata* (Dhaincha) incorporation and application of EDTA-chelated Zn (12% Zn) during both the years. It was significantly higher with *Sesbania aculeata* (Dhaincha) incorporation compared with *Crotalaria juncea* (Sunhemp), *Vigna unguiculata* (Cowpea) and summer fallow treatments.

Zn application, irrespective of its source, significantly improved the amylose content compared with control (no Zn application). Among the Zn fertilization treatments, application of EDTA-chelated Zn (12% Zn) resulted in statistically higher amylose content values than all other Zn fertilizer sources and control (no Zn application), respectively during 2009 and 2010. Application of $ZnSO_4·7H_2O$ (21% Zn) was the second best treatment. The lowest values were recorded with control (no Zn application) during both the years.

3.8 1,000-Grain Weight

Zn application and green manure incorporation significantly improved the 1,000-grain weight of *Basmati* rice (Table 5). Significantly higher values of 1,000-grain weight were recorded with *Sesbania aculeata* (Dhaincha) incorporation and EDTA-chelated Zn (12% Zn) application during both the years. It was significantly higher with *Sesbania aculeata* (Dhaincha) incorporation compared with *Crotalaria juncea* (Sunhemp), *Vigna unguiculata* (Cowpea) and summer fallow treatments.

Significantly higher values of 1,000-grain weight were observed with Zn application, irrespective of its source, compared with control (no Zn application). Among the Zn fertilization treatments, the application of EDTA-chelated Zn (12% Zn) resulted in a statistically higher 1,000-grain weight than all other Zn fertilizer sources and control (no Zn application), respectively during 2009 and 2010. Application of $ZnSO_4·7H_2O$ (21% Zn) was the second best treatment. However, application of ZnO (82% Zn) was least effective in affecting the

1,000-grain weight during both the years. The lowest values were recorded with control (no Zn application). The performance of Zn sources in improvement in 1,000-grain weight was in the order of; EDTA-chelated Zn (12% Zn) > $ZnSO_4 \cdot 7H_2O$ (21% Zn) > $ZnSO_4 \cdot H_2O$ (33% Zn) > $ZnSO_4 \cdot 7H_2O$ + ZnO (50% + 50%) > ZnO (82% Zn).

4. Discussion

Zinc deficiency is a well-documented problem in food crops, causing decreased crop yields and nutritional quality. Generally, the regions in the world with Zn-deficient soils are also characterized by low crop productivity. Cereal crops, especially rice play an important role in satisfying daily calorie intake in the developing world. They are still inherently very low in Zn concentrations in grain, particularly when grown on Zn-deficient soils or under intensive cropping systems. Soil Zn deficiency is also a well-documented problem that reduces crop production. It brings about a significant decrease in plant performance, as shown in various countries such as in India, Pakistan, Australia, Turkey, USA and China (Alloway, 2008; Prasad, 2009; Prasad & Shivay, 2020). Earlier studies have shown that the inclusion of a green manure crop like *Sesbania aculeata* and other legumes in the rotation improves soil organic matter status and nutrient content and increases crop productivity (Yadvinder-Singh et al., 1991). However, the role of different types of Zn fertilizers, combined with the incorporation of green manure crops on grain quality parameters had not been undertaken so far.

This present study showed that there was a significant improvement in grain and straw yields, grain and straw Zn concentrations and kernel quality parameters of *Basmati* rice with summer green manure incorporation and Zn fertilization. This could be attributed to the higher supply of N and other micronutrient cations by incorporating leguminous green manures into the soil (Bisht et al., 2006; Pooniya & Shivay, 2011; Yadav et al., 2019). The increase in studied parameters of *Basmati* rice might also be due to higher nutrient availability and better physico-chemical soil properties under green manure incorporated plots. The increased availability of Fe and other micronutrients in soil with regular summer green manuring every year before transplanting rice in the rice-wheat system was responsible for higher yields in the green manuring plot than the non-green manuring plot (Nayyar & Chhibba, 2000). *Sesbania aculeata* (Dhaincha) supplied a significantly higher amount of readily decomposable organic materials (data not shown in this manuscript), which improved soil organic matter and nutrient status. It leads to recycling of nutrients into the soil and increased availability of nutrients and thus improved the yields and quality parameters of *Basmati* rice. Increase in the Zn concentrations in rice grains through soil Zn applications were positively stimulated by increasing soil N availability (Kutman et al., 2010). The positive effect of increasing N supply through leguminous green manure crops' residue incorporation on the Zn concentration of rice grain and straw was reflected in our studies. Nitrogen nutritional status of plants may also exert positive effects on Zn's root uptake (Cakmak et al., 2010). There are several steps during uptake and transport of Zn in plants which might be affected by N nutrition (Cakmak et al., 2010). By affecting root growth and stimulating root exudation of organic compounds (Marschner, 1995; Paterson et al., 2006), N may influence Zn's mobility and root uptake from soils (Cakmak et al., 2010). Nitrogen status in soil tended to affect the endosperm Zn concentrations to a greater extent than the whole grain Zn concentrations. The positive effects of high N on the endosperm Zn concentration have important implications for human nutrition. This part of the grain is the most commonly eaten part in many countries (Kutman et al., 2011). Enhanced nitrogen and other nutrients' supply through green manure residue incorporation resulted in significantly larger/bolder grains, improving the 1,000-grain weight (Table 5), and larger grains most probably have greater endosperm-to-whole grain ratios.

The positive effect of increasing N and other nutrients' supply through leguminous green manure crops' residue incorporation on rice grain protein content was reflected in our studies. This could be attributed to the higher supply of N and other micronutrient cations by incorporating legumes into the soil (Bisht et al., 2006; Pooniya & Shivay, 2011; Yadav et al., 2019). Grain protein concentration is an important quality parameter for rice, as it is the major staple food for the people in Asian and other developing countries.

The performance of Zn sources was in the order of; EDTA-chelated Zn (12% Zn) > $ZnSO_4 \cdot 7H_2O$ (21% Zn) > $ZnSO_4 \cdot H_2O$ (33% Zn) > $ZnSO_4 \cdot 7H_2O$ + ZnO (50% + 50%) > ZnO (82% Zn). Application of ZnO (82% Zn) was least effective in affecting the studied parameters during both the years. The increase in *Basmati* rice yields with the application of EDTA-chelated Zn (12% Zn) might be due to the relatively greater amount of Zn uptake compared with other Zn sources. The relatively higher maintenance of available Zn in soil due to applied EDTA-chelated Zn (12% Zn) may be attributed from the very little or no interaction between soil components preventing various harmful reactions occurring in the soil as compared to soil treated with other Zn sources, which enhances greater fixation, adsorption etc., resulting from the greater interaction between soil components. Ortiz and Garcia (1998) reported that the chelated-Zn (Cosmo-Quel-Zn) is fixed lesser in soil than the sulphate source. Srivastava et al. (1999) also studied the comparative efficiency of different Zn sources for low land rice production. They reported that out of various sources, the chelated-Zn (Zn-EDTA) was the most efficient Zn for low land rice production. These results are in the agreement with the findings of Karak et al. (2005) who reported that chelated Zn was the most efficient source of Zn for lowland rice production. Further, incorporating green manuring crops before transplanting of *Basmati* rice improves the organic matter content in soil. The applied Zn might have been complexed with the humic substances present in soil due to organic matter addition and there might have been lesser Zn fixation by the formation of insoluble Zn complexes. Thus, resulting into increase in the availability of soil applied Zn to rice plants. Improvement in the applied fertilisers' nutrient use efficiency by transplanted rice after green manure incorporation was also reported by Yadvinder-Singh et al. (1991). These results also confirmed those reported by Maftoun and Karimian (1989). Further, they concluded that Zn-EDTA's has greater influence over other sources of Zn in terms of growth and its utilisation by plants might be due to lesser retention and greater transport and movement of chelated Zn to plant roots. This could be attributed to lesser fixation in soil of Zn applied as Zn-EDTA than $ZnSO_4$ (Ortiz & Garcia, 1998). The higher increase in the Zn content in rice with EDTA-chelated Zn (12% Zn) might be due to increased amounts of Zn in soil solution that facilitates greater absorption of Zn as compared to other Zn sources. Application of $ZnSO_4{\cdot}7H_2O$ (21% Zn) was second best treatment with respect to Zn concentration in grain and straw and its uptake after EDTA-chelated Zn (12% Zn). Singh et al. (1999) reported that applying the different sources of Zn up to 10 mg kg^{-1} increased the Zn concentration of rice leaves, being a higher uptake with Zn-EDTA than $ZnSO_4$. Zinc content of rice grain and straw during the present investigation confirmed the results reported by Ugurluoglu and Kacar (1996) who studied the efficiency of ZnO, $ZnSO_4{\cdot}7H_2O$ and Zn-EDTA on rice and reported that the application of Zn at the rate of 8 mg kg^{-1} as Zn-EDTA was found most effective in the enhancement of Zn content in rice plants. Rattan and Shukla (1991) studied the efficiency of Zn sources on rice cv. Pusa-33 in *Typic Ustipsament* and reported that the Zn content and uptake by rice were in the order of Zn-EDTA > Zn-DTPA > $ZnSO_4$. Application of ZnO (82% Zn) was found to be least effective among all the Zn sources. This might be due to the fact that the EDTA-chelated Zn (12% Zn), $ZnSO_4{\cdot}7H_2O$ (21% Zn) and $ZnSO_4{\cdot}H_2O$ (33% Zn) are more water-soluble and therefore readily available, making its effects visible in the plants. In comparison, ZnO (82% Zn) is sparingly soluble and is not readily available. The water solubility of zinc sources is considered as an important criterion for Zn availability (Slaton et al., 2005a, 2005b). Mikkleson and Brandon (1975); Nayyar et al. (1990) also showed that ZnO was inferior to $ZnSO_4$, both in grain yield and Zn uptake. Our results indicated that Zn applied through EDTA-chelated Zn (12% Zn) remained available to crops for a longer period of time than that with the rest of the Zn sources. This might be due to lesser transformation of applied Zn through EDTA-chelated Zn (12% Zn) into unavailable forms (Naik & Das, 2008).

The increase in rice's studied parameters with Zn fertilization may also be due to higher Zn availability to plants in treated plots than control (no Zn application). This might have lead to higher Zn uptake with Zn fertilization, resulting into higher biomass production (Shivay et al., 2008; Shivay & Prasad, 2012; Pooniya et al., 2012; Prasad & Shivay, 2018) and photosynthates translocation to reproductive parts (Ozkutlu et al., 2006; Alloway, 2008). A significantly high correlation was recorded between grain yield and Zn uptake by grain (Figures 1A and 1B). This might be because zinc exerts an effect on carbohydrate metabolism through its effects on photosynthesis, sugar transformations and seed development. Thus, increased Zn content and its uptake in grains help in production of bolder grains, hence increasing the grain yield (Alloway, 2008). Our result showed that there was a significant improvement in grain and straw Zn concentrations with Zn application. High grain Zn concentration is considered a desirable quality factor that could increase the grains nutritional value for humans (Cakmak et al., 1998; Prasad, 2006; Shivay & Prasad, 2012; Prasad & Shivay, 2020). Also, the increased Zn concentration in rice straw is of immense importance from the viewpoint of cattle nutrition since in developing countries of Asia, rice straw is the major feed for farm cattle (Shivay et al., 2008). The positive correlations between Zn and protein content in grains of various cereal crops were observed by Cakmak et al. (2010). Strongly positive correlations between grain protein and Zn indicate that grain proteins represent a sink for Zn. Increase in protein content with Zn application in our results are in good agreement with the hypothesis that protein represents a sink for Zn in the grain (Morgounov et al., 2007; Cakmak et al., 2010; Kutman et al., 2010). The strength of the correlation between Zn and protein depends on sufficiently high Zn availability to the plants (Kutman et al., 2011). Application of Zn fertilizers in soil increased the Zn availability to the plants. Given that Zn plays a particular role in protein synthesis (Cakmak et al., 1989; Marschner, 1995; Kutman et al., 2011), enhancement in protein biosynthesis results from the increased N supply through leguminous green manures may also increase the sink strength for Zn. Ozturk et al. (2006) concluded that the highest accumulation of Zn in cereal grains occurs in the early stage of seed formation, the same stage during which the highest protein synthesis occurs (Kutman et al., 2011). In biological systems, proteins are highly dependent on Zn ions to maintain their activities. Zinc is needed for numerous proteins, having both a catalytic and a structural role

(Anzellotti & Farrell, 2008). Further, the higher N supply by incorporating large amounts of plant biomass as leguminous green manures resulted in higher protein concentrations in rice grains, accompanied by higher Zn concentrations. In addition to N contribution, these summer legumes' biomass also recycled considerable quantities of P, K and other nutrients; and thus improving the rice grain quality parameters. Our results show the beneficial effect of summer green manure crops and Zn fertilizer application on grain protein content. The presence of protein, and likely of starch-protein interactions, affect the packing arrangement of starch polymers within the granule resulted in better kernel quality parameters. Also, zinc affects carbohydrate metabolism through its effects on photosynthesis, sugar transformations and seed/grain development (Alloway, 2008). Shivay et al. (2007) and Shivay and Prasad (2012) also reported the improvement in kernel quality parameters of rice with Zn fertilization. Thus, increased Zn content and its uptake in grains help in production of bolder grains, and hence improving the quality characters of *Basmati* rice. The present study also demonstrates that summer green manure incorporation and Zn fertilization improve the milling and cooking quality of *Basmati* rice. The increase in kernel length varied from 0.27 to 0.86 mm with green manuring and from 0.29 to 1.15 mm after cooking due to Zn fertilization, a quality for which *Basmati* rices are preferred and sold on a premium price all over the world for making rice *Biryani* (a dish made by cooking rice with mutton/chicken/peas and spices etc.).

5. Conclusions

Zinc fertilization and summer green manure incorporation increased the grain and straw yield, enhanced Zn concentrations and improved kernel quality in *Basmati* rice. The application of EDTA-chelated Zn (12% Zn) was the best in terms of grain and straw yield and Zn concentrations in grain and straw and kernel quality before and after cooking of *Basmati* rice. Application of $ZnSO_4 \cdot 7H_2O$ (21% Zn) was second-best treatment followed by $ZnSO_4 \cdot H_2O$ (33% Zn) and $ZnSO_4 \cdot 7H_2O$ + ZnO (50% + 50%). Application of ZnO (82% Zn) was least effective in affecting the studied parameters. The lowest values were observed with control (no Zn application). Among the summer green manuring crops, incorporation of *Sesbania aculeata* (Dhaincha) was found to be the best over *Crotalaria juncea* (Sunhemp), *Vigna unguiculata* (Cowpea) and summer fallow in terms of grain and straw yield, Zn concentrations in grain and straw and kernel quality before and after cooking in *Basmati* rice. Zn fertilization with EDTA-chelated Zn (12% Zn) lead to 25.91 and 21.26% higher grain yield; 60.66 and 82.14% Zn-denser grains; with 13.33 and 10.92% increase in head rice recovery in *Basmati* rice over control (no Zn application) during 2009 and 2010, respectively. The best results were obtained with *Sesbania aculeata* (Dhaincha) green manure among different green manures and EDTA-chelated Zn (12% Zn) among various Zn sources. Incorporation of summer green manures and adequate Zn fertilizer application in *Basmati* rice can thus lead to higher grain yield and Zn-denser grains with improved cooking quality in *Basmati* rice. Such positive effects of green manuring and Zn application can help sustaining good crop yields over time without deteriorating grain quality and nutritional value, especially in intensive cropping systems.

Acknowledgements

The authors duly acknowledge to ICAR–Indian Agricultural Research Institute, New Delhi, India, for providing financial support. The authors also sincerely thank to the Division of Agronomy, ICAR-Indian Agricultural Research Institute, New Delhi, India, for providing facilities required for field experiment and as well as laboratory facilities.

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