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Improvement of rice grain zinc concentration through biofortification of zinc

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ABSTRACT

Enhancing the grain zinc concentration in staple food crops has been suggested as a sustainable strategy to solve the problem of zinc deficiency in humans, especially in rice (*Oryza sativa* L.) which is consumed in more than half of the world. Applying zinc fertilizer to the soil and/or foliage is the most common agronomic practices reported to improve zinc uptake and partitioning into different plant parts, and consequently potentially improving grain yield and nutritional quality in rice grain. Foliar zinc application can militate against nutrient deficiencies in crop plants and increase zinc accumulation in rice grain. In these consequences a field experiment was conducted during *kharif*, 2019 and 2020 at Agricultural Research Station, Bapatla. The experiment was laid out in randomized block design with 14 treatments, which were replicated thrice. Treatments were control (without application of zinc), soil application of $ZnSo_4$ @ 50 kg ha^{-1}, foliar application of zinc at panicle initiation stage, flowering stage andat grain filling stage@ 0.5%, foliar application of zinc at panicle initiation stage, at flowering stage and at grain filling stage@ 1%, soil application of $ZnSO_4$ @ 50 kg ha^{-1} with foliar application of zinc at panicle initiation stage, flowering stage and at grain filling stage @ 0.5%, soil application of $ZnSO_4$ @ 50 kg ha^{-1} with foliar application of zinc at panicle initiation stage, flowering stage and at grain filling stage @ 1%. Results revealed that the highest grain yield (5519 $kgha^{-1}$) was recorded with soil application of $ZnSO_4$ @ 50 kg ha^{-1} + foliar application of zinc at grain filling stage @ 1% over control treatment and it was on par with all other treatments. Significantly the highest zinc content (34) of in whole grain of rice was recorded with soil application of $ZnSO_4$ @ 50 kg ha^{-1} +foliar application of zinc at grain filling stage @ 0.5% followed by soil application of $ZnSO_4$ @ 50 kg ha^{-1} + foliar application of zinc at grain filling stage @ 1%. In brown rice significantly highest zinc content (22.4) was observed with soil application of $ZnSo_4$ @ 50kg ha^{-1}+ foliar application of zinc at grain filling stage @ 1% over control and it was on par with all other treatments. At 60 days, 120 days and 180 days after harvest of the crop data revealed that soil application of $ZnSO_4$ @ 50 kg ha^{-1} + foliar application of zinc at grain filling stage @ 0.5% recorded significantly the highest zinc content in single polished and double polished rice followed by soil application of $ZnSO_4$ @ 50 kg ha^{-1} + foliar application of zinc at grain filling stage @ 1%.

Key words: *Biofortification, Zinc, Rice, Post-harvest zinc concentrations, Polished and non-polished rice*

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Introduction

Cereals are the major source of zinc for the world's population, especially for the poor people living in rural areas. However, the zinc contents of cereal-based foods are quite inadequate to meet human demands. The problem is especially acute for rice consumers as rice (*Oryza sativa* L.) has the lowest zinc content among cereals (Juliano, 1993). Considerable variation in brown rice zinc when compared to polished rice. In rice germplasm zinc kg^{-1} ranges from 13.5 to 58.4 mg have been reported at International Rice Research Institute (IRRI) which averaged only 25.4 mg zinc kg^{-1} in rice compared with 35.0 mg zinc kg^{-1} in wheat (*Triticum aestivum* L.) (Welch and Graham, 2002). In most cases, rice cultivated soils are very low in plant-available zinc leading to further decreases in grain zinc concentration (Cakmak, 2008). Previous studies have reported that about 30% of the cultivated soils of the world are zinc deficient and about 50% of the soils used for cereal crop production have low levels of zinc available for plants (Cakmak, 2002). Several strategies have been suggested to improve zinc concentration in rice seed, raising concentration up to 60 mg zinc kg^{-1} for agronomic benefits and human health, such as conventional breeding, fertilizer management, seed priming and fortification (Prom-u-thai *et al.,* 2010).

When compared to soil applications, foliar zinc application is more effective in increasing grain zinc (Cakmak *et al.,* 2010). Although the foliar application of zinc is a promising method to increase seed zinc concentration, its effectiveness may also depend on several factors. One of these factors is the time of foliar zinc application. In the case of wheat, it was shown that the highest zinc concentration in seed was achieved when foliar zinc was applied after the flowering stage (Zadok *et al.,* 1974) compared to the applications realized before the flowering stage (Ozturk *et al.,* 2006; Cakmak *et al.,* 2010). In the case of rice, there is no published information on the effect of appropriate timing of foliar zinc application on zinc accumulation in the different forms of grain (paddy, brown and husk) and how the elevated level of seed zinc may consequently affect seedling growth. Enrichment of seeds with zinc benefits both crop production and the health of the consumers, especially those whose zinc intake comes primarily from cereal grains. The present study has been conducted to determine the appropriate timing of foliar zinc application that would maximize seed zinc concentration.

Materials and Methods

A field experiment was carried out during *kharif*, 2019 and 2020 at Agricultural Research Station, Bapatla. The soil was clay loam in texture. The soil was neutral (pH 7.23) in reaction with low electrical conductivity (0.34 dS m^{-1}). The soil was medium in organic carbon content, low in available nitrogen, and medium in available phosphorus and potash. Rice variety BPT 5204 was taken from Agricultural Research Station. Seeds were sown on the seedbed and grown for 25 days. Seedlings were transplanted into the field plots with 15cm x 10 cm between hills with a single seedling per hill. The experiment was laid out in a randomized block design with 14 treatments, which were replicated thrice. Treatments were T_1- Control (without application of zinc), T_2-Soil application of $ZnSO_4$ @ 50kg ha^{-1}, T3- Foliar application of zinc at panicle initiation stage @ 0.5%, T_4-Foliar application of zinc at flowering stage @ 0.5%, T_5-Foliar application of zinc at grain filling stage @ 0.5%, T_6- Foliar application of zinc at panicle initiation stage @ 1%, T_7- Foliar application of zinc at flowering stage @ 1%, T_8 - Foliar application of zinc at grain filling stage @ 1%, T_9-T_2 + foliar application of zinc at panicle initiation stage @ 0.5%, T_{10}-T_2 + foliar application of zinc at flowering stage @ 0.5%, T_{11}-T_2 + foliar application of zinc at grain filling stage @ 0.5%, T_{12} - T_2 + foliar application of zinc at panicle initiation stage @ 1%, T_{13} - T_2 + foliar application of zinc at flowering stage @ 1%, T_{14}-T_2 + foliar application of zinc at grain filling stage @ 1%. Nitrogen @120 kg ha^{-1} was applied to the treatments in three equal splits (1/3 as basal, 1/3 at maximum tillering and 1/3 at panicle initiation stage). Phosphorus (60 kg ha^{-1}) and potassium (40 kg ha^{-1}) were supplied through single super phosphate and muriate of potash and were uniformly applied to all plots as basal during the study period. Zinc was applied as soil application through zinc sulphate @ 50kg ha^{-1} and foliar application with 0.5% and 1% through chelated zinc at different stages during the crop growth period. Irrigation and weed management were done from time to time. The plant height was measured from ground level to the apex of the last fully opened leaf during the vegetative period and up to the tip of the panicle after flowering. The panicle length of ten randomly selected panicles from each plot was measured from the neck node to the tip of the panicle and then averaged and expressed in cm. The number of grains of 10 randomly selected panicles from each plot was counted and then averaged as grains panicle^{-1}. Samples of grain collected separately at the time of threshing from each plot were dried properly. 1000-grains from each of these samples were taken and their weights were recorded and expressed in grams. The border rows were harvested first and then, the net plot area was harvested and the produce was threshed by beating on a threshing bench, cleaned and sun dried to 14 per cent moisture level. The grain from the net plot area was thoroughly sun dried, threshed, cleaned and the weight of grains was recorded and expressed in yield per hectare. The data were analyzed statistically following the method given by Panse and Sukhatme (1978). Seed Zinc concentration was analyzed in three different forms of rice seed: paddy (unhusked seed), brown rice (husk removed) and the husk (palea and lemma). The chemical analysis was done by the dry ashing method, followed by Atomic Absorption Spectrophotometer (AAS) (Zarcinas *et al.*, 1987).

Results and Discussion

Zinc application through different sources and different growth stages showed significant differences in the growth parameters of paddy. Maximum plant height (100.3 and 97.3 cm) was recorded with soil application of $ZnSO_4$ @ 50kg ha^{-1} +foliar application of Zinc at panicle initiation stage @ 1% application which was significantly superior to control treatment (Table 1) and it was on par with all other treatments except control during 2019 and 2020. There is the significant difference was observed in tiller number during both the years of study by the application of different sources and time of zinc application. More number of tillers was observed with soil application of $ZnSO_4$ @ 50 kg ha^{-1} +foliar application of zinc at panicle initiation stage @ 1% (13.2) during 2019 and a maximum number of tillers was observed with soil application of $ZnSO_4$ @ 50 kg ha^{-1} +foliar application of zinc at panicle initiation stage @ 0.5% (14.4) during 2020 and the lowest number of tillers (11.3 and 12.2) was recorded in without zinc application treatment in both the years. The increased number of tillers by soil application of zinc may be attributed due to the increase of nutrient availability in soil compared with other treatments. Similar results were reported by Ghoneim *et al.*, 2012 and Ghoneim, 2014.

Yield parameters were significantly influenced by different sources and different stages of zinc application to the rice crop. A significant difference was observed in panicle length. Significantly the longest panicle was observed in the T_{12} treatment (22.2 and 22.6 cm) and the lowest panicle length (19.1 and 19.3 cm) was observed in the T1 treatment during the study period. The numbers of filled grains were sig-

Table 1. Effect of zinc application on growth of rice

Treatments	Plant height (cm)		No. of productive Tillers plant^{-1}	
	2019	2020	2019	2020
T_1 - Control (without application of zinc)	92.0	90.1	11.3	12.2
T_2 - Soil application of $ZnSo_4$ha^{-1} @ 50kg ha^{-1}	94.5	92.3	12.9	13.9
T_3- Foliar application of Zinc at panicle initiation stage @ 0.5%	95.3	92.8	12.5	13.6
T_4 - Foliar application of Zinc at flowering stage @ 0.5%	94.3	92.9	12.6	13.4
T_5- Foliar application of Zinc at grain filling stage @ 0.5%	93.9	93.4	12.3	13.5
T_6 - Foliar application of Zinc at panicle initiation stage @ 1%	94.0	93.6	12.9	13.8
T_{7-} Foliar application of Zinc at flowering stage @ 1%	93.1	92.9	12.0	13.7
T_{8-} Foliar application of Zinc at grain filling stage @ 1%	93.4	94.2	12.7	13.6
T_9 – T2+Foliar application of Zinc at panicle initiation stage @ 0.5%	98.2	96.2	13.1	14.4
T_{10} - T2+Foliar application of Zinc at flowering stage @ 0.5%	95.7	96.0	12.5	14.2
T_{11} - T2+Foliar application of Zinc at grain filling stage @ 0.5%	95.9	97.1	12.7	14.3
T_{12} - T2+Foliar application of Zinc at Panicle initiation stage @ 1%	100.3	97.3	13.2	14.1
T_{13}- T2+Foliar application of Zinc at flowering stage @ 1%	97.1	96.4	12.7	14.0
T_{14} - T2+Foliar application of Zinc at grain filling stage @ 1%	95.9	96.3	12.9	14.2
SEm±	2.6	2.2	0.5	0.6
CD (0.05)	7.8	6.6	1.5	1.8
CV (%)	6.3	7.5	12.5	8.3

nificantly influenced by zinc application. The maximum number of filled grains (188) were produced with soil application of $ZnSO_4$ @ 50 kg ha^{-1} + foliar application of zinc at panicle initiation stage @ 1% during 2019 and more filled grains were observed with T_{10} treatment (190) during 2020, which was significant over control treatment and it was on par with all other treatments in both the years. The lowest number of filled grains (158 and 162) per $panicle^{-1}$ was observed without zinc application treatment (Table 2). The zinc sprayed by foliar application is absorbed by the leaf epidermis, and remobilized and transferred into the rice grain through the phloem (Wu *et al.,* 2010) with the contribution of several zinc-regulating transporter proteins (Li *et al*., 2013). These processes have been demonstrated in other crops, such as wheat, which efficiently remobilizes zinc from leaves to grain (Grewal and Graham, 1999).

Different stages and sources of zinc application significantly influenced the grain yield and straw yield of rice. The highest grain yield (5519 and 5800 kg ha^{-1}) was recorded with T_{14} treatment, *i.e.,* soil application of $ZnSO_4$ @ 50 kg ha^{-1}+foliar application of zinc at grain filling stage @ 1% over control treatment and it was on par with all other treatments. Higher yield due to zinc fertilization is attributed to its involvement in many metallic enzyme systems, regulatory functions and auxin production (Sachdev *et al*., 1988), enhanced synthesis of carbohydrates and their transport to the site of grain production (Pedda Babu *et al*., 2007). Slaton *et al*. (2005) observed 12 to 180 %, while Fageria *et al*. (2011) reported a 97 % increase in rice yield due to zinc fertilization. Applying zinc fertilizers in the soil also increases dry matter, grain yield and grain zinc concentration in rice (Shehu and Jamala, 2010; Fageria *et al.,* 2011).

Significantly the highest straw yield (7240 and 7382 kg ha^{-1}) was recorded with soil application of ZnSo4 @ 50 kg ha^{-1} + foliar application of zinc at grain filling stage @ 1% treatment and it was superior over T_1 treatment. The lowest straw yield (5616 and 5797 kg ha^{-1}) was recorded with control treatment in both the years of study. There is no significant difference was observed in the harvest index among different sources and times of zinc application (Table 3).

Data revealed that there is a significant difference was observed in different stages and sources of zinc application on grain and straw zinc content of rice. Significantly the highest zinc content (34 mg kg^{-1}) of the whole grain of rice was recorded with T_{11} treatment *i.e* soil application of $ZnSO_4$ @ 50 kg ha^{-1} + foliar application of zinc at grain filling stage @ 0.5% followed by T_{14} treatment, *i.e.* soil application of $ZnSO_4$ @ 50 kg ha^{-1} + foliar application of zinc at grain filling stage @ 1% during 2019 and the highest

Table 2. Effect of zinc application on yield attributes of rice

Treatments	Panicle length (cm)		Total No. of filled grains $panicle^{-1}$	
	2019	2020	2019	2020
T_1 - Control (without application of zinc)	19.1	19.3	158	162
T_2 - Soil application of $ZnSo_4 ha^{-1}$ @ 50kg ha^{-1}	21.3	22.1	177	180
T_3 - Foliar application of Zinc at panicle initiation stage @ 0.5%	21.5	22.2	185	183
T_4 - Foliar application of Zinc at flowering stage @ 0.5%	21.7	22.2	182	185
T_5 - Foliar application of Zinc at grain filling stage @ 0.5%	21.8	22.3	184	189
T_6 - Foliar application of Zinc at panicle initiation stage @ 1%	21.3	22.4	180	184
T_7 - Foliar application of Zinc at flowering stage @ 1%	21.4	22.3	183	188
T_8 - Foliar application of Zinc at grain filling stage @ 1%	21.4	22.5	184	181
T_9 – T2+Foliar application of Zinc at panicle initiation stage @ 0.5%	21.6	22.8	186	188
T_{10} - T2+Foliar application of Zinc at flowering stage @ 0.5%	21.4	22.3	187	190
T_{11} - T2+Foliar application of Zinc at grain filling stage @ 0.5%	21.2	22.2	187	188
T_{12} - T2+Foliar application of Zinc at Panicle initiation stage @ 1%	22.2	22.6	188	185
T_{13} - T2+Foliar application of Zinc at flowering stage @ 1%	22.0	22.2	186	180
T_{14} - T2+Foliar application of Zinc at grain filling stage @ 1%	21.7	22.3	187	180
SEm+	0.6	0.6	6.0	5.4
CD (0.05)	1.8	1.9	18.3	16.3
CV (%)	6.0	8.1	7.4	9.2

zinc content (32.6 mg kg^{-1}) of the whole grain of rice was recorded with T_{14} treatment, *i.e.,* soil application of $ZnSO_4$ @ 50 kg ha^{-1} + foliar application of zinc at grain filling stage @ 1% during 2020. In brown rice significantly the highest zinc content (22.4 and 21.2 mg kg^{-1}) was observed with T_{14} treatment, *i.e.* soil application of $ZnSO_4$ @ 50 kg ha^{-1} + foliar application of zinc at grain filling stage @ 1% over control and it was on par with all other treatments. This result is in close agreement with Phattarakul *et al.,* (2012) who showed that a foliar zinc spray applied at late growth to rice grown under field conditions caused a greater increase in grain zinc than a foliar zinc spray before the flowering stage. Similar results were also found in field grown-wheat (Cakmak *et al*., 2010).

The highest zinc content in double polished rice was recorded with soil application of $ZnSO_4$ @ 50 kg ha^{-1} +foliar application of zinc at grain filling stage @ 0.5% treatment (17.9 and 16.7 mg kg^{-1}). Paddy straw is also significantly influenced by different sources and times of zinc application. The highest zinc content in paddy straw (24.8 and 23.6 mg kg^{-1}) was recorded with T_{11} treatment, *i.e* soil application of $ZnSO_4$ @ 50 kg ha^{-1} + foliar application of zinc at grain filling stage @ 0.5% and it was significantly superior to T_1 and T_2 treatments and on par with all other treatments (Table 3). A foliar spray of zinc represents an effective practice to improve grain zinc significantly. In wheat, foliar application of zinc fertilizer improved both productivity and grain zinc concentration up to three or four-fold as a foliar spray (Cakmak, 2008). In rice, the foliar application of zinc significantly increased zinc accumulation in the grain (Yuan *et al.*, 2013). In China, foliar application with 0.4% $ZnSO_4$ increased whole grain zinc concentration in wheat by 58%, while foliar application of 0.2%, 0.4% and 0.5% $ZnSO_4$ increased the zinc concentration in flour by 60%, 76% and 76%, respectively, compared with the control treatment (Zhang *et al.,* 2012).

The results revealed that biofortification of zinc significantly influenced the zinc content of the whole grain, brown rice and double polished rice. At 60 days, 120 days and 180 days after harvest of the crop data revealed that T_{11} treatment *i.e.,* soil application of $ZnSO_4$ @ 50 kg ha^{-1} + Foliar application of zinc at grain filling stage @ 0.5% recorded significantly the highest zinc content in single polished and double polished rice followed by T_{14} treatment *i.e.,* soil application of $ZnSO_4$ @ 50 kg ha^{-1} + foliar application of zinc at grain filling stage @ 1% (Table 4). The lowest zinc content in whole grain, brown rice and double polished rice was observed without zinc application treatment. The remobilization of zinc from vegetative parts via the phloem to the developing grain after foliar spraying is a key process in the effectiveness of the treatment protocol. This remobilization is influenced by factors such as the plant cultivar and physiological characteristics, in-

Table 3. Effect of zinc application on grain and straw yields and harvest index of rice

Treatments	Grain yield (kg ha^{-1})		Straw yield (kg ha^{-1})		Harvest Index (%)	
	2019	2020	2019	2020	2019	2020
T_1 - Control (without application of zinc)	4576	4622	5616	5797	42.2	44.2
T_2 - Soil application of $ZnSo_4 ha^{-1}$ @ 50kg ha^{-1}	5128	5375	6244	6602	44.5	43.9
T_3 - Foliar application of Zinc at panicle initiation stage @ 0.5%	5211	5500	6422	6645	44.8	44.9
T_4 - Foliar application of Zinc at flowering stage @ 0.5%	5238	5562	6489	7165	44.7	44.9
T_5 - Foliar application of Zinc at grain filling stage @ 0.5%	5236	5584	6506	7770	44.6	44.5
T_6 - Foliar application of Zinc at panicle initiation stage @ 1%	5210	5543	6305	6774	45.2	45.0
T_7 - Foliar application of Zinc at flowering stage @ 1%	5157	5438	6450	6617	44.4	44.8
T_8 - Foliar application of Zinc at grain filling stage @ 1%	5292	5469	6567	6665	44.6	44.8
T_9 – T2+Foliar application of Zinc at panicle initiation stage @ 0.5%	5332	5566	6528	6827	45	44.8
T_{10} - T2+Foliar application of Zinc at flowering stage @ 0.5%	5321	5759	6594	6902	44.7	44.2
T_{11} - T2+Foliar application of Zinc at grain filling stage @ 0.5%	5454	5700	7154	7070	42.7	45.3
T_{12} - T2+Foliar application of Zinc at Panicle initiation stage @ 1%	5257	5778	6578	6715	44.4	44.2
T_{13} - T2+Foliar application of Zinc at flowering stage @ 1%	5345	5533	6683	7010	44.4	44.4
T_{14} - T2+Foliar application of Zinc at grain filling stage @ 1%	5519	5800	7240	7382	42.4	44.4
SEm±	180	235	290	262	1.2	1.1
CD (0.05)	545	708	874	791	NS	NS
CV (%)	8.1	7.9	7.5	8.5	8.2	6.7

cluding phonological stage and/or environmental conditions (Kutman *et al.*, 2010). The growth conditions have an important role in the contribution of xylem (root uptake) and phloem transport (remobilization) to grain zinc accumulation. Under conditions with a complete zinc supply during the whole growth stage, continuous root uptake and transportation of zinc into seeds would be a dominant pathway for zinc accumulation in grain. However, in the case of limited zinc supply to roots (e.g., dry field conditions), remobilization of zinc from the vegetative tissues into seeds would be a more relevant method for grain zinc accumulation (Waters and Grusak, 2008; Cakmak *et al.*, 2010).

Conclusion

In conclusion, the present study has shown that zinc

Table 4. Effect of Zinc levels and sources on grain and straw zinc contents (mgkg^{-1}) of rice at harvest

Treatments	Whole grain	Brown rice	Double Polished rice	Straw
T_1 - Control (without application of zinc)	25.4	16.3	11.4	18.4
T_2 - Soil application of $ZnSo_4$ha^{-1} @ 50kg ha^{-1}	27.3	18.3	12.3	20.0
T_3 - Foliar application of Zinc at panicle initiation stage @ 0.5%	27.7	21.1	12.8	21.1
T_4 - Foliar application of Zinc at flowering stage @ 0.5%	27.9	22.0	14.5	22.2
T_5- Foliar application of Zinc at grain filling stage @ 0.5%	31.8	21.6	15.6	22.5
T_6 - Foliar application of Zinc at panicle initiation stage @ 1%	27.6	21.3	15.2	22.3
T_{7-} Foliar application of Zinc at flowering stage @ 1%	27.9	21.4	15.2	22.4
T_{8-} Foliar application of Zinc at grain filling stage @ 1%	31.6	22.0	16.9	22.7
T_9 – T2+Foliar application of Zinc at panicle initiation stage @ 0.5%	29.4	21.1	15.9	22.8
T_{10} - T2+Foliar application of Zinc at flowering stage @ 0.5%	28.9	21.5	16.7	22.8
T_{11} - T2+Foliar application of Zinc at grain filling stage @ 0.5%	34.0	22.2	17.9	24.8
T_{12} - T2+Foliar application of Zinc at Panicle initiation stage @ 1%	29.6	21.9	15.6	23.4
T_{13}- T2+Foliar application of Zinc at flowering stage @ 1%	29.4	21.8	15.9	22.9
T_{14} - T2+Foliar application of Zinc at grain filling stage @ 1%	33.8	22.4	16.9	23.5
SEm±	1.8	1.63	0.93	1.3
CD (0.05)	5.5	4.9	2.8	3.9
CV (%)	10.9	13.6	11.6	10.7

Table 5. Effect of Zinc levels and sources on brown rice and double polished rice zinc contents (mgkg^{-1}) at 60, 120 & 180 days after harvest during 2019

Treatments	60 days after harvest		120 days After harvest		180 days after harvest	
	Single polished	Double polished	Single polished	Double polished	Single polished	Double polished
T_1 - Control (without application of zinc)	16.3	11.4	14.5	11.1	14.1	9.1
T_2- Soil application of $ZnSO_4$ ha^{-1} @ 50 kg ha^{-1}	18.3	12.3	18.2	11.8	16.3	11.0
T_3- Foliar application of Zinc at panicle initiation stage @ 0.5%	21.1	12.8	18.5	12.1	17.1	12.5
T_4 - Foliar application of Zinc at flowering stage @ 0.5%	22.0	14.5	19.3	13.8	16.1	13.8
T_5- Foliar application of Zinc at grain filling stage @ 0.5%	21.6	15.6	18.6	14.2	17.3	14.0
T_6- Foliar application of Zinc at panicle initiation stage @ 1%	21.3	15.2	17.7	14.7	17.5	13.4
T_7- Foliar application of Zinc at flowering stage @ 1%	21.4	15.2	18.2	14.5	18.1	14.2
T_8- Foliar application of Zinc at grain filling stage @ 1%	22.0	16.9	19.4	16.4	18.2	16.2
T_9– T2 + Foliar application of Zinc at panicle initiation stage @ 0.5%	21.1	15.9	18.4	14.8	18.3	14.4
T_{10}- T2 + Foliar application of Zinc at flowering stage @ 0.5%	21.5	16.7	18.3	16.2	18.0	16.0
T_{11}- T2 + Foliar application of Zinc at grain filling stage @ 0.5%	22.4	17.9	19.5	17.4	19.3	17.2
T_{12}- T2 + Foliar application of Zinc at Panicle initiation stage @ 1%	21.9	15.6	18.4	15.2	17.9	15.0
T_{13}- T2 + Foliar application of Zinc at flowering stage @ 1%	21.8	15.9	18.2	14.7	17.0	14.4
T_{14}- T2 + Foliar application of Zinc at grain filling stage @ 1%	22.2	16.9	18.6	16.5	18.5	16.3
SEm±	1.63	0.93	1.2	0.2	0.7	0.8
CD (0.05)	4.9	2.8	3.6	0.6	2.1	1.6
CV (%)	13.6	11.6	13.3	7.7	9.3	13.9

Table 6. Effect of zinc application on grain and straw zinc contents (mg kg^{-1}) during 2020

Treatments	After harvest of the crop			
	Whole grain	Brown rice	Double Polished rice	Straw
T_1 - Control (without application of zinc)	24.2	15.1	10.2	17.2
T_2- Soil application of $ZnSo_4ha^{-1}$ @ 50kg ha^{-1}	26.1	17.4	11.1	18.8
T_3- Foliar application of Zinc at panicle initiation stage @ 0.5%	26.5	19.9	11.6	19.9
T_4 - Foliar application of Zinc at flowering stage @ 0.5%	26.7	20.8	13.3	21.2
T_5- Foliar application of Zinc at grain filling stage @ 0.5%	30.6	20.4	14.4	21.3
T_6 - Foliar application of Zinc at panicle initiation stage @ 1%	26.4	20.1	14.2	21.1
T_{7-} Foliar application of Zinc at flowering stage @ 1%	26.7	20.2	14.3	21.2
T_{8-} Foliar application of Zinc at grain filling stage @ 1%	30.4	20.8	15.3	21.5
T_9 – T2+Foliar application of Zinc at panicle initiation stage @ 0.5%	28.2	19.9	14.7	21.6
T_{10} - T2+Foliar application of Zinc at flowering stage @ 0.5%	27.7	20.3	15.5	21.6
T_{11} - T2+Foliar application of Zinc at grain filling stage @ 0.5%	32.6	21.2	16.7	23.6
T_{12} - T2+Foliar application of Zinc at Panicle initiation stage @ 1%	28.4	20.7	14.4	22.2
T_{13}- T2+Foliar application of Zinc at flowering stage @ 1%	28.2	20.6	14.7	21.7
T_{14} - T2+Foliar application of Zinc at grain filling stage @ 1%	32.4	21.0	15.7	22.3
SEm±	2.2	1.3	1.9	1.8
CD (0.05)	6.6	4.0	5.7	5.4
CV (%)	7.3	8.2	10.2	9.3

Table 7. Effect of Zinc levels and sources on brown rice and double polished rice zinc contents (mgkg^{-1}) at 60, 120 & 180 days after harvest during 2020

Treatments	60 days after harvest		120 days After harvest		180 days after Harvest	
	Single polished	Double polished	Single polished	Double polished	Single polished	Double Polished
T_1 - Control (with out application of zinc)	15.2	10.3	14.4	11.6	13.8	10.1
T_2- Soil application of $ZnSO_4$/ha @ 50 kg ha^{-1}	17.2	11.2	16.6	12.5	15.1	12.3
T_3- Foliar application of Zinc at panicle initiation stage @ 0.5%	20.2	11.7	17.4	12.7	15.2	12.6
T_4 - Foliar application of Zinc at flowering stage @ 0.5%	20.9	13.4	18.2	12.8	14.9	12.6
T_5- Foliar application of Zinc at grain filling stage @ 0.5%	20.5	14.5	17.5	13.0	15.4	12.9
T_6 - Foliar application of Zinc at panicle initiation stage @ 1%	20.2	14.1	15.8	13.5	15.6	13.3
T_{7-} Foliar application of Zinc at flowering stage @ 1%	20.3	14.1	16.8	13.3	16.6	13.1
T_{8-} Foliar application of Zinc at grain filling stage @ 1%	20.9	15.8	18.5	14.3	18.2	14.1
T_9 – T2+Foliar application of Zinc at panicle initiation stage @ 0.5%	20.2	14.8	17.3	13.8	17.1	13.7
T_{10} - T2+Foliar application of Zinc at flowering stage @ 0.5%	20.4	15.6	17.2	14.3	16.5	14.1
T_{11} - T2+Foliar application of Zinc at grain filling stage @ 0.5%	21.3	16.8	18.6	15.4	18.4	15.1
T_{12} - T2+Foliar application of Zinc at Panicle initiation stage @ 1%	20.8	14.5	17.3	13.6	16.4	13.5
T_{13}- T2+Foliar application of Zinc at flowering stage @ 1%	20.7	14.8	17.2	14.2	15.2	14
T_{14} - T2+Foliar application of Zinc at grain filling stage @ 1%	21.1	15.8	18.2	14.5	17.1	14.2
SEm ±	1.52	1.2	1.32	0.56	0.67	0.62
CD (0.05)	4.6	3.6	4.1	1.9	2.0	1.9
CV (%)	12.2	11.2	7.3	8.2	8.9	12.4

content in rice grain can be effectively raised by soil application of zinc combined with foliar application, which was particularly when zinc was sprayed after flowering. Data revealed that at 60 days, 120 days and 180 days after harvest of the crop; soil application of $ZnSO_4$ @ 50 kg ha^{-1} + foliar application of zinc at grain filling stage @ 0.5% recorded significantly the highest zinc content in single polished and double polished rice followed by soil application of ZnSo4 @ 50 kg ha^{-1}+ foliar application of zinc at grain filling stage @ 1%. As shown in this paper for rice, this agronomic practice is highly effective and quick in increasing grain zinc.

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