Journal of Agriculture and Ecology Research International
6(2): 1-9, 2016; Article no.JAERI.22607
ISSN: 2394-1073

SCIENCEDOMAIN *international*
www.sciencedomain.org

Effect of Different Methods of Zn Application on Rice Growth, Yield and Nutrients Dynamics in Plant and Soil

Adel Mohamed Ghoneim[1*]

[1]Agricultural Research Center, Field Crops Research Institute, Rice Research and Training Center, Sakha, Kafr El-Sheikh, Egypt.

Author's contribution

The sole author designed, analyzed, interpreted and prepared the final manuscript.

Article Information

DOI: 10.9734/JAERI/2016/22607
Editor(s):
(1) Edward Wilczewski, Faculty of Agriculture, University of Technology and Life Sciences in Bydgoszcz, Poland.
(2) Daniele De Wrachien, Department of Agricultural and Environmental Sciences of the State University of Milan, Italy.
Reviewers:
(1) Anonymous, Agricultural Research Council, South Africa.
(2) N. Karmegam, Govt. Arts College, India.
(3) Manju Pande, Mississippi Valley State University, USA.
(4) Anonymous, Punjab Agricultural University, Ludhiana, India.
Complete Peer review History: http://sciencedomain.org/review-history/12924

Original Research Article

Received 14th October 2015
Accepted 31st December 2015
Published 9th January 2016

ABSTRACT

Zinc (Zn) deficiency is widely spread in Egyptian paddy soils and has negative impact on national rice (*Oryza sativa* L.) production. Field experiments were conducted at the research farm of the Rice Research and Training Center, Sakha, Egypt, to evaluate the effects of different methods of Zn application on rice growth, yield of Sakha 104 and nutrients dynamics in soil and plant. The experiment included four treatments: no Zn, root soaking, foliar and soil application. The results indicated that Zn application by different methods, significantly increased number of tillers, panicles, plant height, 1000-grain weight; filled grains% and grains yield of Sakha 104. Among the different of Zn application, soil application of 15 kg ha^{-1} as $ZnSO_4.H_2O$ caused highest increase in total N percentage, total K percentage and available Zn content in both grain and straw, however, the percentage of total P decreased significantly. Zinc content in soil after harvesting was significantly affected by Zn application. Different methods of Zn tend to increase the total N and total K contents of soil but decreased P concentration significantly.

**Corresponding author: E-mail: aghoneim@ksu.edu.sa;*

Keywords: Method of Zn application; soil properties; rice yield; rice nutrient uptake.

1. INTRODUCTION

Zinc deficiency in rice has been widely reported in many rice-growing regions of the world [1-3]. Zinc deficiency in crop plants results in not only yield reduction but also Zn malnutrition in humans, where a high proportion of rice is consumed as a staple food [4,5]. Low bioavailability of Zn in soil generally results in Zn deficiency in rice plants, and thus becomes one of the common constraints for Zn bio-fortification in rice grain. Zn deficiency in rice can be alleviated through Zn fertilization, which is considered to be a cost-effective method to alleviate Zn malnutrition [6].

Recently, water crisis in Egypt, has resulted in a move towards water-saving cultivation, from flooded to alternate wetting and drying to aerobic rice systems [7,8]. Importantly, adoption of these water saving systems may decrease Zn availability [9]. High-yielding varieties and greater fertilizer inputs in Egypt were the strategies to raise the crop yield potential and feed increasing population. The increased application of fertilizers was not sufficient to compensate for over-use of cultivated land. Zinc deficiency is considered as a major threat to the global and regional food security [10]. Amongst several factors of low plant Zn availability in paddy fields is soil pH, $CaCO_3$ content and low redox potential [11]. Widespread occurrence of Zn deficiency in traditional lowland [12] and newly developed alternate wetting and drying or aerobic rice systems [13] necessitates harnessing of breeding efforts to increase Zn uptake [14,15].

Widespread Zn deficiency has been found responsible for yield reduction in rice [16]. Globally, more than 30 % of soils are low in plant-available Zn [17]. Nonetheless, frequency of Zn deficiency is greater in rice than other crops, with more than 50 % of the crop worldwide prone to this nutritional disorder [18]. Zinc application methods and sources are aimed at improving Zn availability for plant uptake. Zn can be applied to soil, seed and leaves [18] and by dipping seedlings into a fertilizer solution. Zinc fertilization to cereal crops improves productivity and grain Zn concentration [19,20] and thus improves grain nutritional value for human beings. However, the vast majority of Zn fertilizer trials and resulting fertilizer recommendations in rice have been in the context of managing the Zn deficiency, with very few studies related to Zn bio-fortification [21]. Selection of appropriate Zn sources for soil application is considered to be an alternative strategy to improve plant availability of Zn under lowland conditions. Generally, $ZnSO_4$ is the most widely applied Zn source for its high solubility and low cost. In addition, Zn-EDTA (Ethylene Diamine Tetra acetic Acid) is also being recommended due to its efficiency of Zn availability for the plants [22].

Alternate wetting and drying (AWD) management is one of the most important water-saving strategies commonly practiced, which is being widely adopted in Egypt. It has been reported that AWD potentially results in decreased water inputs by 5%-35% when compared with contentious flooding, with the yield of rice grain either being maintained [23-25] or even increasing [26]. Hence, this study was aimed to investigate the effects of different methods of Zn applied through soil, root soaking and foliar on rice growth, yield and nutrients dynamics status in grain and straw of rice variety Sakha 104.

2. MATERIALS AND METHODS

2.1 Area Description and Soil Sampling

Field experiment was carried out at the research area of Rice Research and Training Center, Sakha, Kafr El-Sheikh, Egypt (31°6′42″N, 30°56′45″E). Represented soil samples were taken in bulk from 0-25 cm depth before the growing season. The samples were air-dried, ground and passed through 2-mm sieve. Composite samples were taken and analyzed for physical and chemical characteristics namely, EC, pH, texture, cations and anions following standard methods [27]. The characterization of the soil used is presented in Table 1.

Table 1. Selected soil characteristics of the experimental site

pH	EC ($dS\ m^{-1}$)	Cations ($meq\ L^{-1}$)				Anions ($meq\ L^{-1}$)				Particles size %			Zn ($mg\ kg^{-1}$)*
		Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	HCO_3^-	CO_3^{2-}	SO_4^{2-}	Sand	Silt	Clay	
7.89	1.60	2.70	1.65	3.75	2.69	3.80	2.25	3.69	2.67	12.0	28.9	59.1	0.29

** Extracted by using Diethylene Triamine Pentaacetic Acid (DTPA)*

2.2 Field Experiment

Field experiment was laid out in Randomized Complete Block Design (RCBD) with four treatments with plot size of 2x5 m. The experiment included four treatments as given in Table 2.

All plots expect T1 received 150 kg ha^{-1} N as urea, 81 kg ha^{-1} of P as P and 72 kg ha^{-1} K as K. Full dose of P and K was applied just before transplanting. Nitrogen fertilizers were applied in two split application: the first split (75 kg ha^{-1}) was applied at the time of finial land preparation and second split (75 kg ha^{-1}) was added at panicle initiation stage. The Zn applied in this study was in the form of as $ZnSO_4.H_2O$. All other cultural practices were kept same and uniform for all treatments. Plant height and number of tillers were recorded during the growth stage. At crop harvesting, rice plants were manually harvested from 1 m^2 area in the center of each plot. These plants were used to determine grain yield and its components [28] after separating into straw and grains. Dry weight of straw was determined after oven-drying at 70℃ to constant weight. Yield components included panicle number; spikelets per panicle, percentage of filled grain and 1000-grain weight were recorded.

2.3 Plant Analysis

Samples (0.10 g) from each treatment were digested with 5.0 ml HNO_3-H_2O_2 (4:1, v/v) using a hot block heater. After cooling, the digest was transferred to a 20-ml volumetric flask and then filtered. Zn concentrations of these samples were determined using inductively coupled plasma mass spectrometry (ICP-MS; Agilent Modell 7500a, Agilent Technologies, USA).

2.4 Soil Samples

Samples of rhizosphere soil were collected by gently shaking off from the root system; available Zn extracted by DTPA according to the method of [29] and determined using ICP-MS (Agilent 7500a, USA).

2.5 Statistical Analysis

All the data including soil and plant samples were analyzed for critical differences using the ANOVA statistical package [30].

3. RESULTS AND DISCUSSION

3.1 Growth Characters

The height of rice plant as affected by different methods of Zn application are shown in Fig. 1. It is observed from the figure that methods of Zn application significantly affected the plant height. Maximum plant height of 100 cm was recorded from the treatment with 15 kg Zn ha^{-1} as soil application which differs significantly from the other treatments. Minimum plant height was recorded with T1. The tillers (numbers/m^2) of rice plant as affected by different methods of Zn application are shown in Fig. 2. The application of different methods of Zn application significantly increased the tillers number over control.

Tillering capacity is one of the most important rice components which are responsible for yield production. Maximum tillers numbers/m^2 of 430 were recorded for T4 followed by T3; while the minimum tillers numbers was recorded in T1. The increased of tillers number by soil application of Zn may be attributed due to increase of nutrients availability in soil compared with other treatments. Similar results were reported [31,32].

3.2 Yield Components

The results indicated that different methods Zn application (T2, T3 and T4) significantly increased the number of panicles/m^2 compared with T1 (Table 3). The highest number of panicles/m^2 was recorded in T4 and T2 followed by T3, while the minimum number of panicles/m^2 rice plant was recorded in T1. The number of spikelets/panicle, percentage of filled grain and 1000-grain weight followed the same trend of response i.e. increased with different methods of Zn application compared to control but, no significant differences were found amongst the various methods. Similar results have been reported in previous research [33-35].

3.3 Grain and Straw Yield

The impact of different methods of Zn application on grains and straw yield of Sakha 104 are shown in Fig. 3. The results indicated that the different methods of Zn application significantly increased the grain yield compared to no Zn application (T1). Highest grain yield of 9.60 tones ha^{-1} was recorded by soil application of Zn. No significant differences were observed in grain yield with T2 or T3. The increase in yield with Zn as soil application may be attributed to Zn has more residual effect compared with root soaking or foliar. The results indicated that straw yield of rice significantly increased with different methods of Zn application (T2, T3 and T4) compared with T1, but, no significant difference were observed between Zn application methods. Similar findings have been reported in previous studies [36-38].

Table 2. Treatments

Symbolic names	Method of Zn application	Zn application rate (kg ha^{-1})
T1 (no Zn applied)	-	-
T2 (Root soaking)	Root soaking in 1.50% solution	7.50
T3 (Foliar spray)	Spray at 20 DAT	2.50
T4 (Soil application)	Soil application just after transplanting	15.0

DAT, Days after transplanting

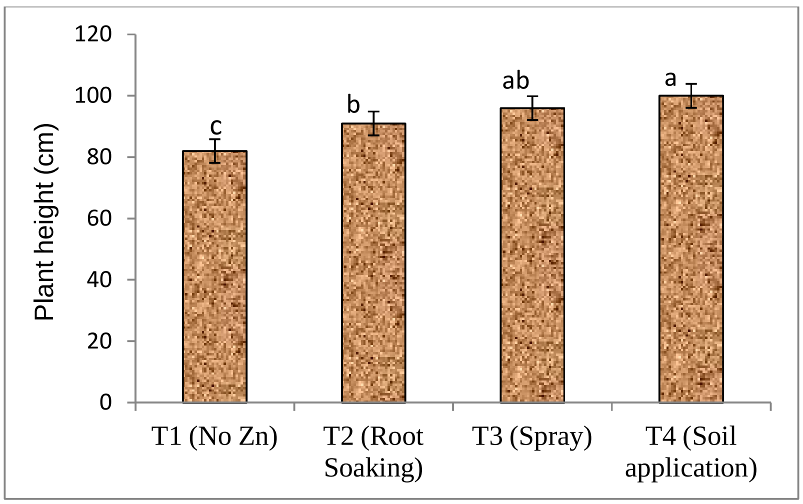

Fig. 1. Plant height of Sakha 104 as affected by different methods of Zn application. Mean followed by the same letters are not significantly different at 5% level of probability. Vertical bars represent ±standard error (SE, n=4)

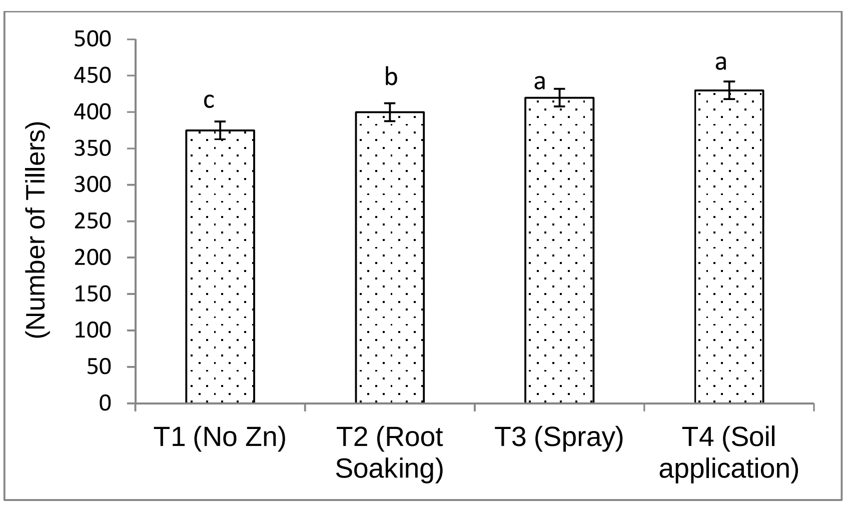

Fig. 2. Number of tillers of Sakha 104 as affected by different methods of Zn application. Mean followed by the same letters are not significantly different at 5% level of probability. Vertical bars represent ±standard error (SE, n=4)

3.4 Effect of Different Methods of Zn Application on Nutrients Content

Zinc content in grains and straw of rice as affected by different methods of Zn application are presented in Table 4. Highest Zn content of 31.1 mg kg^{-1} was recorded in T3 followed by T4 and T2. The lowest Zn content in grain and straw was recorded in T1. The treatment differences were significant at 5% level. Although foliar application is effective in increasing grains Zn content [39-41], time of foliar Zn application is an important factor in this regard [42].

The increases in Zn content by grain occur when it is applied as foliar at later stages of plant growth. Zinc translocation towards rice grains in a nutrient solution using aerobic rice genotypes was studied. The results indicated that, when Zn was applied to roots or as foliar spray; under sufficient Zn supply, Zn partitioning to the grain was greater from root-supplied than foliar form [43]. Foliar application can avoid the problems of Zn binding in soil, but the time of Zn application should be around flowering for increasing grain-Zn concentration. The increase in grain-Zn concentration may be due to improved leaf remobilization of Zn during grain filling.

Table 4 showed that, total N percentage in rice grain and straw of Sakha 104 affected significantly by different methods of Zn application compared with no Zn (T1). The highest total N percentage in grains was recorded in T2 and T4 followed by T3. The increases in total N percentage in grains by applying different methods of Zn application may be attributed due to the enhancing the micrograms for N recycling and organic N mineralization. The results are in agreement with findings of [44].

Table 3. Yield attributes of rice as affected by different methods of Zn application

Treatments	Number of panicles/m^2	Number of spikelet/panicle	Filled grain %	1000-grain weight (g)
T1 (No Zn)	325 d	110 b	80 b	20.1 b
T2 (Root soaking)	348 a	130 a	83 a	25.9 a
T3 (Foliar spray)	339 c	128 a	81 b	26.5 a
T4 (Soil application)	350 a	129 a	82 a	27.1 a

Mean values on each column followed by the same letters are not significantly different at 5% level of probability

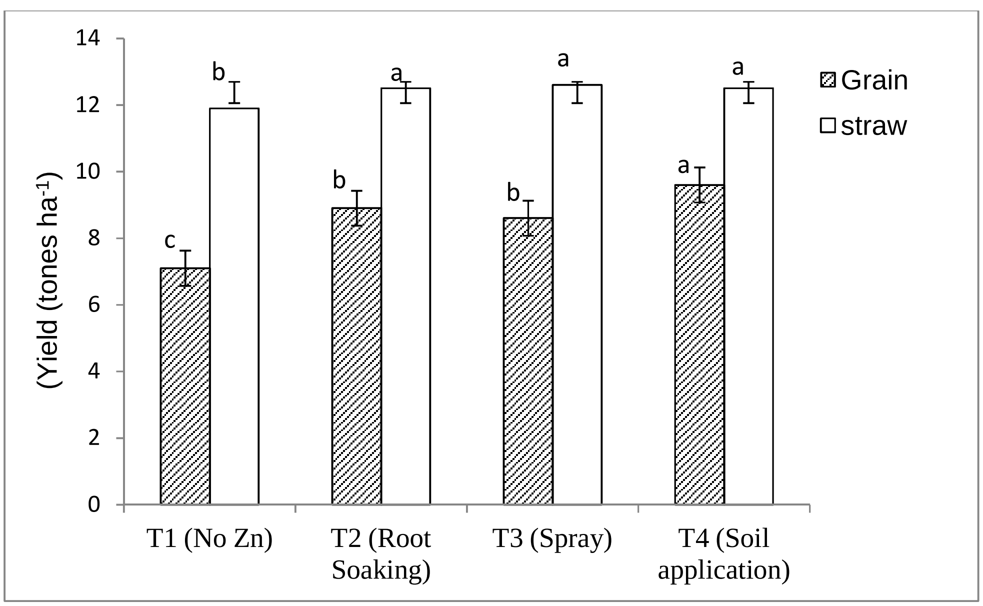

Fig. 3. Grain and straw yield of Sakha 104 as affected by different methods of Zn application. Means followed by the same letters are not significantly different at 5% level of probability. Vertical bars represent ±standard error (SE, n=4)

Phosphorus (P) content of plant as affected by different methods of Zn application is shown in Table 4. The results indicated that, application of different methods of Zn significantly decreased the total P percentage in grain and straw of Sakha 104 compared with T1. The highest total P percentage and were observed in T1, however, there was no significant difference was observed between different methods of Zn application.

All the Zn applied by different methods decreased the total P percentage. This may be attributed due to the antagonistic effect of Zn on P uptake. Application of P, not only decreased water-soluble and exchangeable-Zn, but also increased bound forms of adsorption of Zn with soil particles [45]. These effects were more pronounced under flooded than non-flooded water regime.

The data of total K percentage in grain and straw are presented in Table 4. The results showed that with application of different methods of Zn, total K percentage increased significantly compared with T1. These results are in agreement findings of [46] that reported increase of K concentration of both rice grain and straw with Zn fertilizer application.

3.5 Nutrients Dynamics in Soil

Zinc content of soil after harvesting as influenced by different methods of Zn application is presented in Table 5. The results indicated that the application of different methods of Zn application significantly increased Zn of soil compared with control (T1). Highest Zn content was recorded in T4. However, the Zn content of soil after harvesting time was increased compared with the initial Zn content of soil as presented in Table 1.

Zinc content in soil is present in a number of chemical forms with varying solubility. These forms include soluble Zn present in soil solution (water soluble), adsorbed on exchange sites (exchangeable), associated with OM, co-precipitated as secondary minerals or associated with sesquioxides [47]. These different forms mainly control solubility and availability of Zn to plants [48]. In addition, soil chemical properties such as pH, Rh, soil organic matter (OM), have strong influence on Zn adsorption-desorption reactions and play a critical role in regulating Zn solubility and its fractionation in soils [49]. Varied responses of rice to the Zn fertilizers have been reported, depending on the source, application time, methods of application and soil chemical properties [49].

Nitrogen (N) content of soil at harvesting time as affected by applying different methods of Zn are presented in Table 5. The data showed that, there is significant difference in total N percentage among the methods of Zn application. The highest total N percentage of 0.99 was recorded by T4, followed by T2 and T3, while the T1 has the lowest total N percentage value. Maximum total N percentage of soil content was observed with combined application of N and Zn. Among Zn application methods, soil application was considered superior treatment [50].

Table 4. Effect of different methods of Zn application on total N, P, K, and Zn content of rice plant

Treatments	Zn (mg kg^{-1})		N		P		K	
			%					
	Grains	Straw	Grains	Straw	Grains	Straw	Grains	Straw
T1 (No Zn)	22.1 c	23.2 b	0.73 c	0.33 b	0.26 a	0.041 a	0.160 c	1.40 b
T2 (Root soaking)	29.1 b	27.3 a	0.97 a	0.50 a	0.23 b	0.036 b	0.210 a	0.17 c
T3 (Foliar spray)	32.1 a	28.3 a	0.94 b	0.48 a	0.24 b	0.031 b	0.207 a	0.18 c
T4 (Soil application)	30.1 ab	29.1 a	0.96 a	0.47 a	0.24 b	0.026 c	0.180 b	1.80 a

Mean values on each column followed by the same letters are not significantly different at 5% level of probability

Table 5. Effect of different of methods of Zn application on available Zn, total N, P and K concentrations of soil after harvesting

Treatments	Zn content (mg kg^{-1})	N	P	K
		%		
T1 (No Zn)	0.35 c	0.73 d	0.26 a	0.15 b
T2 (Root soaking)	0.69 b	0.96 b	0.21 b	0.16 b
T3 (Foliar spray)	0.75 ab	0.91 c	0.22 b	0.18 a
T4 (Soil application)	0.81 a	0.99 a	0.23 b	0.19 a

Mean values on each column followed by the same letters are not significantly different at 5% level of probability

Phosphorus (P) content of soil after harvesting as affected by applying different methods of Zn are presented in Table 5. The application of different methods Zn application, content in soil decreased P significantly compared with no Zn. The highest P content observed in T1, however no significant differences were recorded among the methods of Zn application. Phosphorus interacts with Zn in soil which reduces Zn translocation from roots to the shoots [51] and also imbalanced P: Zn ratio in plant (dilution effect) has a negative effect on rice yield. Other studies also indicated that P application influenced Zn uptake by rice and translocation into shoots [52].

The content of total K percentage of soil at harvesting time as affected by different of methods Zn application are presented in Table 5. The results indicated that the application of different of methods Zn application has a little effect of increase the total N percentage compared with no Zn added (control). The highest total N percentage of 0.19% was recorded with T4, followed by T3 and T2. Similar results have been reported [52].

4. CONCLUSION

The present study aimed to provide the most suitable technology to overcome Zn deficiency problem in rice, by comparing the effects of different methods of Zn application on rice growth, yield and nutrients concentration. Zinc application by any of the methods increased significantly the rice growth parameters, straw and grain yield over control. Highest of soil Zn concentration was found in plots with soil Zn application as compared to foliar or root soaking application. Zinc content in soil after harvest was also significantly affected by methods of Zn application. The highest soil Zn concentration was found in soil Zn application treatment as compared with root soaking. The study suggested that, soil application of Zn resulted in better results and easier as compared to foliar and root soaking treatment. The obtained results of this study would be beneficial to mitigate Zn deficiency in rice and therefore, improve zinc use efficiency.

ACKNOWLEDGEMENTS

Agricultural Research Center, Field Crops Research Institute, Rice Research and Training Center, Sakha, Kafr El-Sheikh, Egypt is acknowledged for financially supporting of this study.

COMPETING INTERESTS

Author has declared that no competing interests exist.

REFERENCES

1. Fitzgerald MA, Mccouch SR, Hall RD. Not just a grain of rice: The quest for quality. Trends Plant Sci. 2009;14(3):133–139.
2. Mandal B, Hazra GC, Mandal LN. Soil management influences on zinc desorption for rice and maize nutrition. Soil Sci. Soc. Am. J. 2000;64:1699–1705.
3. Tiong J, McDonald GK, Genc Y, et al. HvZIP7 mediates zinc accumulation in barley (*Hordeum vulgare*) at moderately high zinc supply. New Phytol. 2014;201(1): 131–143.
4. Yao F, Huang J, Cui K, et al. Agronomic performance of high-yielding rice variety grown under alternate wetting and drying irrigation. Field Crops Res. 2012;126:16–22.
5. Zhang H, Xue Y, Wang Z, et al. An alternate wetting and moderate soil drying regime improves root and shoot growth in rice. Crop Sci. 2009;49(6):2246–2260.
6. Zhao FJ, Mcgrath SP. Biofortification and phytoremediation. Curr. Opin. Plant Biol. 2009;12(3):373–380.
7. Farooq M, Kobayashi NK, Wahid A, Ito O, Basra SMA. Strategies for producing more rice with less water. Adv Agron. 2009;101: 351–388.
8. Farooq M, Rehman A, Aziz T, Habib M. Boron nutripriming improves the germination and early seedling growth of rice (*Oryza sativa* L.). J Plant Nutr. 2011a; 34:1507–1515.
9. Gao XP, Zou CQ, Fan XY, Zhang FS, Hoffland E. From flooded to aerobic conditions in rice cultivation: Consequences for zinc uptake. Plant Soil. 2006;280:41–47.
10. Rana WH, Kashif SR. Effect of different zinc sources and methods of application on rice yield and nutrients concentration in rice grain and straw. Journal of Environmental and Agricultural Sciences. 2014;1–9.
11. Alloway BJ. Soils factors associated with zinc deficiency in crops and humans.

Environ Geochem Health. 2009;31(5):537–548.

12. Singh B, Natesan SKA, Singh BK, Usha K. Improving zinc efficiency of cereals under zinc deficiency. Curr Sci. 2003;88:36–44.
13. Dobermann A, Fairhurst TH. Nutrient disorders and nutrient management. Potash and Phosphate Institute, PPI of Canada and IRRT, Singapore. 2000;192.
14. Sharma PK, Lav B, Ladha JK, Naresh KK, Gupta RK, Balsubrananian BV, Bouman, BAM. Crop water relation in rice-wheat cropping under different tillage systems and water management practices in a marginally sodic, medium textured soil. In: Bouman BAM, Tuong TP, Ladha JK. (Eds) Water-wise production. IRRI, Los Baños, Philippines; 2002.
15. Rehman HU, Aziz T, Farooq M, et al. Zinc nutrition in rice production systems: A review. Plant Soil. 2012;361(1-2):203–226.
16. Fageria NK, Baligar VC, Clark RB. Micronutrients in crop production. Adv Agron. 2002;77:185–268.
17. Hajiboland R, Yang ZE, Romheld V. Effects of bicarbonate and high pH on growth of Zn efficient and Zn inefficient genotypes of rice, wheat and rye. Plant Soil. 2003;250:349–357.
18. Johnson SE, Lauren JG, Welch RM, Duxbury JM. A comparison of the effects of micronutrient seed priming and soil fertilization on the mineral nutrition of chickpea (*Cicer arietinum*), lentil (*Lens culinaris*), rice (*Oryza sativa*) and wheat (*Triticum aestivum*) in Nepal. Exp. Agric. 2005;41:427–448.
19. Cakmak I. Enrichment of cereal grains with zinc: Agronomic or genetic biofortification. Plant Soil. 2008;302:1–17.
20. Phattarakul N, Rerkasem B, Li LJ, et al. Biofortification of rice grain with zinc through zinc fertilization in different countries. Plant Soil. 2012;361(1-2):131-141.
21. Impa SM, Schulin R, Ismail A, Beebout JS. Unravelling the mechanisms influencing grain-zn content in rice genotypes. In: Abstracts, International Rice Congress, Hanoi Veitnam, Nov 8-12; 2010.
22. Quijano-Guerta C, Kirk GJD, Portugal AM, Bartolome VI, McLaren GC. Tolerance of rice germplasm to zinc deficiency. Field Crops Res. 2002;76:123–130.
23. Bouman BAM, Hengsdijk H, Hardy B, et al. Water-Wise rice production. International Rice Research Institute, Los Baños, Philippines. 2002;89–102.
24. Rehmani MIA, Wei G, Hussain N, Ding C, Li G, Liu Z, Wang S, Ding Y. Yield and quality responses of two Indica rice hybrids to post-anthesis asymmetric day and night open-field warming in lower reaches of Yangtze River delta. Field Crops Res. 2014;156:231–241.
25. Chapagain T, Yamaji E. The effects of irrigation method, age of seedling and spacing on crop performance, productivity and water-wise rice production in Japan. Paddy Water Envion. 2010;8(1):81–90.
26. Yang XE, Chen WR, Feng Y. Improving human micronutrient nutrition through biofortification in the soil plant system: China as a case study. Environ Geochem Health. 2007;29(5):413–428.
27. Page AI, Miller RH, Keeney DR. Methods of soil analysis. Madison, Wisconsin, USA; 1982.
28. Ramesh SA, Shin R, Eide D, Schachtman DP. Differential metal selectivity and gene expression of two zinc transporters from rice. Plant Physiol. 2003;133:126–134.
29. Lindsay WL, Norvell WA. Development of a DTPA soil test for Zn, Fe, Mn, and Cu. Soil Sci. Soc. Am. J. 1978;42:421–428.
30. Gomez KA, Gomez AA. Statistical Procedure for Agricultural Research, 2nd Edition. A Wiley Interscience Pub., John Wiley and Sons, New York. USA. 1984; 628.
31. Ghoneim AM, Ueno H, Asagi N, Watanabe T. Indirect ^{15}N Isotope techniques for estimating N Dynamics and N Uptake by rice from poultry manure and sewage sludge. Asian Journal of Earth Sciences. 2012;5(2):63–69.
32. Ghoneim AM. Nitrogen and carbon uptake by some rice cultivars from $^{15}NH_4Cl$ and ^{13}C-U-glucose labeling fertilizer. International Journal of Agronomy and Agricultural Research. 2014;4(4):20–27.
33. Cakmak I. Enrichment of fertilizers with zinc: an excellent investment for humanity and crop production in India. J Trace Elem Med Biol. 2009;23(4):281–289.
34. Beebout SJ, Tuyogon D, Rubianes F, Castillo O, Larazo W, Bunquin M, Laureles E. Improved zinc management strategies for rice scientists and farmers. In: Proceedings of 2010 International Annual Meetings of ASA-CSSA-SSSA, October 31 to November 04, 2010, Long Beach, California, USA; 2010.

35. Farooq M, Wahid A, Siddique KHM. Micronutrients application through seed treatments - A review. J. Soil. Sci. Plant Nutr. 2012;12:125–142.
36. Khan MU, Qasim M, Subhan M, Jamil M, Ahmad RD. Response of rice to different methods of Zn application in calcaerous soils. Pak J Appl. Sci. 2003;3:524–529.
37. Jiang W, Struik PC, Zhao M, van Keulen H, Fan TQ, Stomph TJ. Indices to screen for grain yield and grain zinc mass concentration in aerobic rice at different soil Zn levels. NJAS Wageningen J Life Sci. 2008b;55:181–197.
38. Bhaduri D, Purakayastha TJ. Soil available Zn: A potent soil quality indicator in a rice–wheat system. 3rd International Zinc Symposium, 10–14 October 2011, Hyderabad, India.
39. Welch RM. Breeding strategies for biofortified staple plant foods to reduce micronutrient malnutrition globally. J Nutr. 2002;132:495–499.
40. Hajiboland R, Salehi SY. Characterization of Zn efficiency in Iranian rice Genotypes I. Uptake efficiency. Gen Appl Plant Physiol. 2006;32:191–206.
41. Chasapis CT, Loutsidou AC, Spiliopoulou CA, et al. Zinc and human health: An update. Arch. Toxicol. 2012;86(4):521–534.
42. Stomph TJ, Hoebe N, Spaans E, van der, Putten PEL. The relative contribution of post-flowering uptake of zinc to rice grain zinc density. 3rd International Zinc Symposium 10-14 October 2011, Hyderabad, India.
43. Gao X, Hoffland E, Stomph TJ, Grant CA, Zou C, Zhang F. Improving zinc bioavailability in transition from flooded to aerobic rice. A review. Agron Sustain Dev. 2012;32:465–478.
44. Lal B, Majumdar B, Venkatesh MS. Individual and interactive effects of phosphorus and zinc in lowland rice. Indian J Hill Farming. 2002;13:44–46.
45. Iqbal M, Aslam M, Ranja AM, Akhtar J. Salinity tolerance of rice as affected by Zn application. Pakistan J. Biol. Sci. 2000;3: 2055–2057.
46. Arnold T, Kirk, GJD, Wissuwa M, Frei M, Zhao FJ, Mason TFD, Weiss DJ. Evidence for the mechanisms of zinc uptake by rice using isotope fractionation. Plant Cell Environ. 2010;33:380–381.
47. Almendros P, Gonzalez D, Obrador A, Alvarez JM. Residual zinc forms in weakly acidic and calcareous soils after an oilseed flax crop. Geophysical Research Abstracts. EGU General Assembly, 2008;10. EGU2008-A-12479.
48. Takrattanasaran N, Chanchareonsook J, Johnson PG, et al. Amelioration of zinc deficiency of corn in calcareous soils of Thailand: zinc sources and application methods. J. Plant Nutr. 2013;36(8):1275–1286.
49. Depar N, Rajpar I, Memon MY, Imtiaz M, Zia-ul-hassan. Mineral nutrient densities in some domestic and exotic rice genotypes. Pak J Agric. Eng Vet Sci. 2011;27:134–142.
50. Haldar M, Mandal LN. Influence of soil moisture regimes and organic matter application on the extractable Zn and Cu content in rice soils. Plant Soil. 1979;53: 203–213.
51. Lonergan PF, Pallotta MA, Lorimer M, et al. Multiple genetic loci for zinc uptake and distribution in barley (*Hordeum vulgare*). New Phytol. 2009;184(1):168–179.
52. Wu CY, Feng Y, Shohag MJ, et al. Characterization of 68Zn uptake, translocation, and accumulation into developing grains and young leaves of high Zn-density rice genotype. J. Zhejiang Univ.-Sci. B (Biomed. & Biotechnol.). 2011;12(5):408–418.

Peer-review history:
The peer review history for this paper can be accessed here:
http://sciencedomain.org/review-history/12924