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Influence of Agronomic Zinc Fortification on Quality, Productivity and Profitability of Rice: A Review

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Abstract

Deficiency of zinc is a worldwide nutritional problem and intensity of the problem is even severe in developing countries. Rice grainis the key to meet a person’s daily energy requirements, but they are very low in zinc concentration, especially when grown in Zn-deficient soil. There are ways to address zinc deficiency *viz.*, nutritional diversification, food enrichment and biofortification. There are several limitations regarding nutritional diversification and food enrichment which favors biofortification of zinc as a perpetual solution of malnutrition. Among the potential biofortification methods to rectify Zn deficiency, plant breeding approaches and agronomic biofortification offers major advantage. This review appraised the role of Zn in plants, zinc uptake, translocation and partitioning efficiencies in rice that is driven by various agronomic, breeding and biotechnological approaches. There is a genuine need to integrate zinc in rice production systems using agronomic and conventional breeding methods. Agronomic biofortification is economically sustainable and practically adoptable solution to overcome the Zn deficiency problem in rice.

Keywords: Biofortification, agronomic fortification, zinc enriched rice

Introduction

Today, increasing grain Zn concentration of rice represents an important challenge to be met by using agricultural tools such as breeding and fertilization. Zinc concentrations of both polished and unpolished rice are inherently too low to meet human demands for Zn (Lee *et al.* 2009; Bouis and Welch 2010). The Zn concentration of rice germplasm at the International Rice Research Institute, which included advanced breeding lines, modern and traditional varieties and grown at Los Banos, Philippines averaged only 25.4 mg Zn kg^{-1} for brown rice, compared with an average of 35.0 mg Zn kg^{-1} for wheat germplasm of the International Maize and Wheat Improvement Center grown at El Batan in Mexico (Graham *et al.* 1999). In a screening study including about 1,000 genotypes, it has been found that there is a four-fold range of rice grain Zn concentration among the rice genotypes (e.g., 13.5–58.4 mg Zn kg^{-1}) (Graham *et al.* 1999). This impressive genotypic variation has led to a suggestion that such substantial genetic potential for Zn concentration in rice should be exploited through plant breeding (Welch and Graham 2004; Bouis and Welch 2010). Raising the Zn concentration of rice appears to be one of the most costeffective means to overcome this malnutrition problem among low income rice eaters. In addition, sowing seeds containing high Zn concentration has a potential to benefit crop growth and yield by improving germination and seedling vigor, especially in Zn deficient soils (Cakmak 2008; Rengel and Graham 1995; Yilmaz *et al.* 1998). For example, in the US Zn coated rice seed (with 1.0– 4.7 g Zn kg^{-1}) germinated better and more rapidly into seedlings with longer roots and better shoot growth than untreated seed (Slaton *et al.* 2001).

Nutrient management is an important issue in autumn rice and a precise schedule should be followed to get optimum result. Besides major nutrients, zinc is an essential micronutrient and have particular physiological functions in all living systems, such as the maintenance of structural and functional integrity of biological membranes and facilitation of protein synthesis and gene expression. Around 30% of the world’s human population is diets deficient in zinc.

Zinc deficiency in human affects physical growth, the functioning of the immune system, reproductive health and neuro-behavioral development. Therefore, the zinc content of staple foods, such as rice and wheat are of major importance. When the supply of zinc to the plant is inadequate, one or more of the many important physiological functions of zinc are unable to operate normally and plant growth is adversely affected.

Application of proper dose of zinc and at right time determines the availability of zinc in plant system, more particularly in grain. Zinc deficiency is a well-documented global health problem, affecting nearly 2 million people, near about 1.5 million children die each year from Zinc malnutrition, particular in developing countries, where high proportion of cereal crops, such as rice and wheat, consumed as a staple food. The total area under Zn deficiency is about 10 mha in India. On average, 50% of the Indian soils are deficient in zinc (Zn), rising to 63% by 2025, particularly in calcareous soils due to the formation of insoluble zinc hydroxide and its carbonate. Zn in soil and rice yield focused on basal application of $ZnSO_4$ along with the foliar application too. Zinc fertilizers could potentially be improved by using chelates that facilitate metal absorption by plant roots e.g. Zn-EDTA. Zn-EDTA was the most efficient source of Zn for lowland rice production. Zn-EDTA supplies a substantial amount of Zn to the plant without interacting with soil components because the central metal ion (Zn^{2+}) is surrounded by chelate ligand and farmers use Zn-EDTA because of its cost effectiveness.

Zn is deficient in 50% of the world's agricultural soils and is recognized as the world's most critical micronutrient deficiency in crop. About 2 billion people in the world suffer from Zinc deficiency and near about 1.5 million children die each year fromZinc malnutrition. Globally, about0.8 million people and nearly about 0.45millionchildren are at risk of dying each year from Zinc deficiency (WHO, 2015). India has one of the highest rates of Zn deficiencies in soils and diet of people. 50%ofIndiansoilsareZn deficient, rising to 63% by2025, if no management is done. About 0.15millionchildren die each year in India due to Zn deficiency. Lack of Zinc is contributing to cases of diarrhea, 25% of global diarrhea deaths amongst children under the age of five (IZA, 2014). Zn fortification in staple food could save the lives around 48,000 Indian children per year (WHO, 2015).

Reason for rice biofortification

Rice is a staple food crop for more than a billion people. The rice endosperm (starchy and most edible part of rice seed) is deficient in many nutrients including vitamins, proteins, micronutrients etc. The aleurone layer of dehusked rice grain is nutrient reach but is lost during milling and polishing. Unprocessed rice becomes rancid i.e. smelly or unpleasant in taste. Rice supplies 30-50% of daily calorie intake. Rice farming is the major source of employment in most of the part in India and globally. Rice plays an important role in food security for its wider adaptability.

What is Biofortification?

Biofortification is the development of nutrient dense staple food crops using the best conventional breeding practices and modern biotechnology, without sacrificing agronomic performance and important consumer preferred traits. Biofortification focused on making plant foods more nutritious as the plants are growing. In conventional fortification nutrients are added to the foods as they are being processed (Nestel *et al*., 2006) [43].

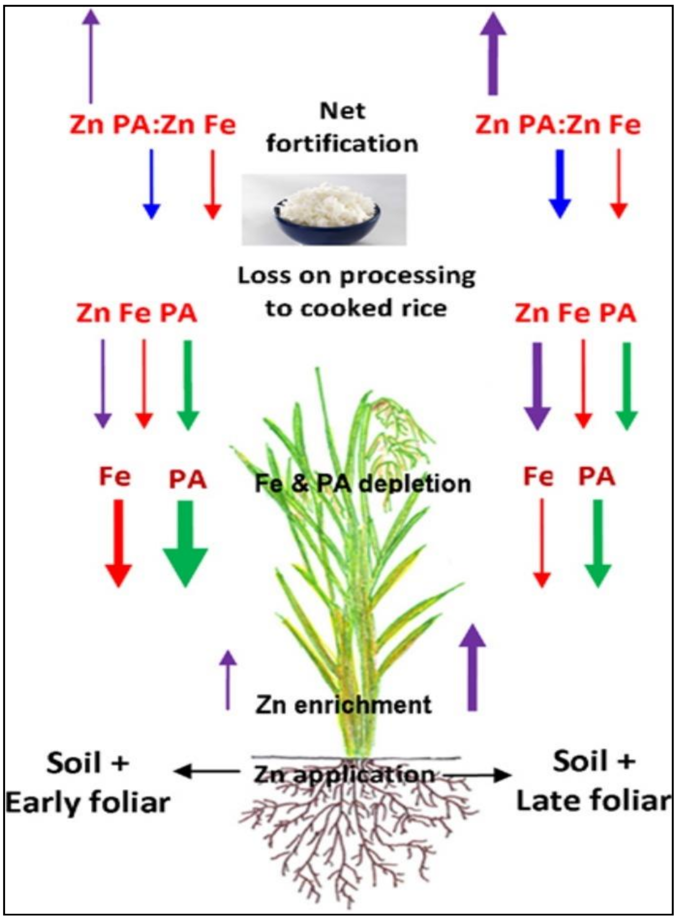


Fig 1: Process of biofortification of rice.

Types of biofortification

There are several options for biofortification, among which genetic and agronomic biofortification are mostly used. Agronomic biofortification alternatively termed as ferti-fortification. Ferti-fortification, a term coined by Prasad (2009) involves fertilizing crops with micronutrients.

Conventional breeding (genetic) method of bio fortification

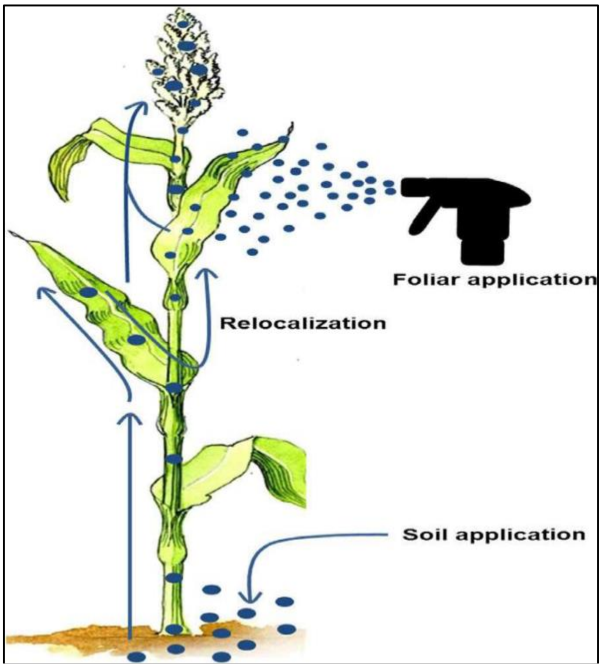
This can be done either through conventional selective breeding, or through genetic engineering. Biofortification differs from ordinary fortification because it focuses on making plant foods more nutritious as the plants are growing, rather than having nutrients added to the foods when they are being processed. E.g. Golden rice **-** A GM food crop It is a genetically modified provitamin A (β-carotene) enriched rice genome. All the credits of golden rice go to Rockefeller foundation, EU and the Swiss federal institute of technology. Professor Ingo Potrycus and Dr. Peter Beyer considered as the founder of β-carotene enriched golden rice. They used crtl gene from soil bacterium (Agrobacterium tumifascience) and Daffodil gene for modification of the genetic makeup. Golden rice cannot be achieved by breeding. There are two grades of golden rice;

- **Golden rice 1 (SGR1):** Promoter is modified here and it contains 5-7μg β-carotene per gram of rice.
- **Golden rice 2:** Replacement of daffodil Pys with maize gene and contain 31 μg β- carotene per gram of rice.

Agronomic biofortification

Agronomic biofortification of food crops, where fertilizers are used to increase micronutrient contents in edible crop parts, can be an effective component of a food system approach to reduce micronutrient malnutrition inhuman populations. Reasonably good responses to Zn fertilization have been obtained for a number of crops including rice and wheat (Katyal and Rattan, 2003; Prasad, 2006) [25].

Agronomic biofortification alternatively termed as ferti-fortification. Ferti- fortification, a term coined by Prasad (2009) involves fertilizing crops with micronutrients. It gives immediate results and in, general, goes well along with an increase in yield. Agronomic biofortification is usually done through soil application of efficient Zn sources at the right rate, time, and stage. The maximum level of Zn biofortification in rice ensured when Zn was applied through soil treatment (Nattinee *et al.* 2009) [42]. Furthermore, increased absorption of Zn into the leaves was noticed when Zn was applied with urea fertilizer, indicating that Zn-coated urea fertilizer is a very useful combination, increasing the values of both Zn and protein. In the future, there will be a need to monitor the available forms of Zn to ensure that Zn is not stored in the rhizosphere to a degree that can generate lethal effects (Velu *et al.* 2014) [59]. In agronomic biofortification, the seed treatment and foliar application techniques add less Zn to the total reserves, as most of the applied Zn will be retained by the foliage (Jiang *et al.* 2007) [23]. Most of the Zn accumulation in grains is taken up by the roots and not remobilize in the cells. This suggests that, Zn application to the soil is much more likely to be an efficient form of biofortification as compared with foliar application (Liu *et al*. 2016) [3].



Important biofortification projects

- **Iron:** Biofortification of rice, beans, sweet potato, cassava and legumes
- **Zinc:** Biofortification of wheat, rice, beans, sweet potato and maize
- **Provitamin:** A carotenoid- biofortification of rice, sweet potato, maize and cassava
- **Amino acid and protein:** Biofortification of maize, sorghum and cassava

β - carotene enriched popular rice varieties

- **IR 64, IR 36:** Mega varieties with broad Asian coverage.
- **BRRI Dhan 29:** The most popular boro rice variety in Bangladesh.
- **PSB Rc 82:** The most popular Rice variety of Philippines.
- **OS 6561:** Most popular in Vietnam.
- **Chehirang:** Leading variety in Indonesia.

Swarna (MTU 7029): Swarna is the most widely grown and consumed rice variety in India which constitutes 0.78mg Fe/100g white rice and 2.28mg Zn/100g brown rice. By consuming twice or thrice a day taking 100-150g rice/meal a person can get hardly 2-3mg Fe and 7- 8mg Zn which is 1/5th and respectively half of the recommended daily intake of Fe and Zn.

Need of biofortification in rice

Among the cereals, rice contains low nutritional value. Therefore, rice alone cannot meet the recommended daily allowance (RDA). Healthy and productive populations require adequate amounts of essential vitamins and minerals. As staple foods are eaten in large quantities everyday by malnourished poor, addition of even small quantities of micronutrients is beneficial. High zinc seeds are more vigorous and better able to withstand weed competition, and pathogen and pest attack (Gregorio *et al.* 2000) [16]. Deficiencies of zinc, iron and vitamin A in human population of developing countries were noticed and particularly, zinc deficiency is the fifth major cause of diseases and deaths in these countries. Health problems caused by zinc deficiency include anorexia, dwarfism, weak immune system, skin lesions, hypogonadism and diarrhea (McClain *et al*. 1985) [35]. Males aged 15 to 74 years need about 12 to 15 mg of zinc daily while females aged 12 to 74 years need about 68 mg of zinc daily (Sandstead, 1985) [49]. Iron dependent anemia in turn leads to maternal mortality, preterm births (Scholl *et al.* 1992) [50], decreases immunity (Kandoi *et al.* 1991) [24] and increases placental weight (Wingerd *et al.* 1976) [61] during pregnancy.

Table 1: Protein, iron and zinc status of rice in comparison of other cereals [Source: Singh *et al*., 2013]

Crops	Protein (%)	Iron (ppm)	Zinc (ppm)
Rice	6-7	2-34	10-33
Wheat	13-14	25-55	25-65
Maize	8-11	10-63	13-58
Sorghum	10-15	10-65	14-55
Pearl millet	6-21	130-146	25-85

Singh *et al*. (2013) reported that rice contains low nutritional value as compare to other cereals. Malnutrition is the most common cause of zinc deficiency and 25% of the world's population is at risk of zinc deficiency. Swarna is the most widely grown and consumed rice variety in India which constitutes 0.78mg Fe/100g white rice and 2.28mg Zn/100g brown rice. By consuming twice or thrice a day taking 100-150g rice/meal a person can get hardly 2-3mg Fe and 7-8mg Zn which is 1/5th and half of the recommended daily intake of Fe and Zn respectively. Rice endosperm, Embryo and bran contain 32%, 13% and 55% of Iron respectively and they also contain 57%, 9% and 34% of Zinc respectively. During de-hulling, polishing and cooking about 20.7%, 17.05% and 36.61% Zn loss occurs. Rice is mainly grown in flooded soil where zinc is not much available to the crop as they bound to sulphur and carbonate in reduced condition.

Advantages of rice biofortification

Rice biofortification have certain advantages *i.e.* increase in nutritional value, reduced adult and child micronutrient caused mortality, reduced dietary deficiency diseases and healthier population with strong and quick immune responses to infections.

Disadvantages of rice biofortification

1. High production cost *i.e.* equipments, technology, patentingetc.
2. Potential negative interaction of biofortified rice on other plants/ non- GM rice crops causing loss of wild type rice varieties.
3. Low substantial equivalence *i.e.* inability to provide high micronutrient and protein content compared to supplements
4. Poor rural populations have limited access and resources to purchase biofortifiedrice.
5. Genetic engineering methods used may compromise immunity introduced in human increased risk of allergenicity

Growth and productivity of rice as influenced by zinc fortification

Varsheny *et al.* (2008) [58] evaluated the efficiency of different rates and frequency of Zinc application on yield, Zinc concentration and uptake of hybrid rice-wheat sequence and reported that zinc application significantly increased the grain yield of wheat and rice crop. Jat *et al.* (2011) [21] also studied the effect of zinc (Zn) fertilization on productivity and Zn-use efficiency of aromatic hybrid rice cv ‘Pusa Rice Hybrid 10’ (‘PRH 10’) and reported that zinc fertilization in aromatic hybrid rice increased yield attributes, grain and straw yield. Similar results were reported by Singh *et al.* (2008) [53].

Mustafa *et al.* (2011) [37-39] reported that maximum productive tillers per m^2 (249.80) were noted with basal application at the rate 25 kg ha^{-1} 21% $ZnSO_4$ and minimum (220.28) were recorded with foliar application at 60 DAT @ 0.5% Zn solution. Zinc application methods and timing had significantly pronounced effect on paddy yield. Maximum paddy yield (5.21 t ha^{-1}) was achieved in treatment Zn_2 (Basal application at the rate of 25 kg ha^{-1} 21% $ZnSO_4$) and minimum paddy yield (4.17 t ha^{-1}) was noted in Zn_7 (foliar application at 75 DAT @ 0.5% Zn solution). Zinc application increases the crop growth rate of rice. Similar results were reported by Arif *et al.* (2006) [5] and Naik and Das (2007) [41].

Keram *et al.* (2013) reported that treatments applied with increasing levels of Zn produced more grain and straw yields as compared to treatments applied with NPK alone. Naik and Das (2010) [40] reported that the application of zinc in low land rice soil of West Bengal caused an increase in yield of grain and straw respectively over the control to the tune of 37.8% and 20.9%. In an experiment, Abbas *et al.,* (2013) [2] studied that Zn and B application increased the paddy yield. Similar results were observed by Arif and Muhammad (2012).

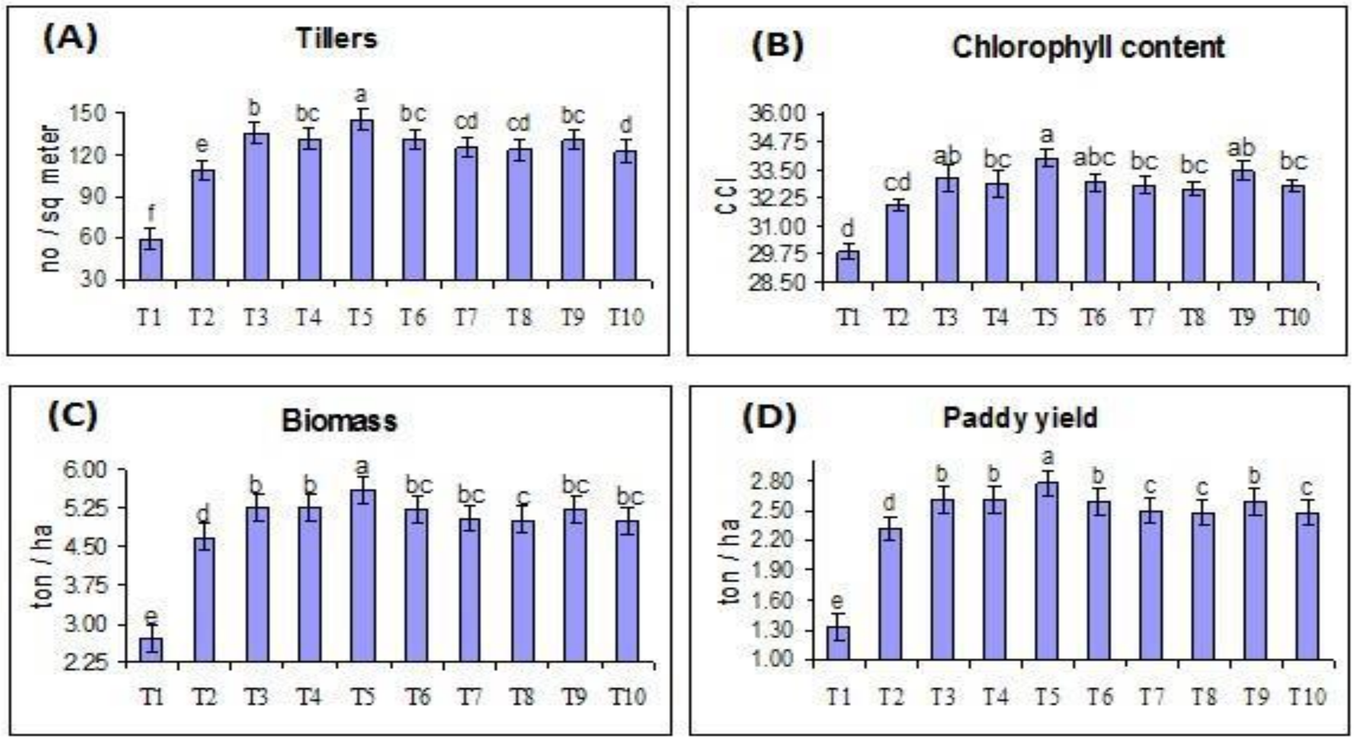


Fig 1: Number of tillers, chlorophyll content, total biomass and paddy yield as affected by soil and foliar applications of different sources of zinc. Values are means of three replicate plots. Means with different letters are statistically different from each other at 5% level.

Rana and Kashif (2014) [27] satated that in cereals, tillering capacity is one of the main components of grain yield. Higher yield potential can be achieved by greater tillers per plant. The data regarding the number of tillers as influenced by Zn application is presented in Fig. 1.A. Zn application significantly increased number of tillers per plant ($P<0.05$). Among the Zn sources, soil applied Zn-EDTA (10.0 kg ha-1) produced maximum number of tillers per plant (145 tillers), which was significantly different from all other treatments. Minimum of 60 tillers per plant were observed under treatment T1 (without fertilizer) followed by T2 (recommended N:P2O5:K2O @ 110:90:60 kg ha-1). In case of foliar Zn application, T9 produced significantly higher (131) number of tillers m-2, when Zn-EDTA was applied @

1.00 kg ha-1, which was statistically similar to other Zn sources applied as foliar fertilizer, except T10 (ZnO @ 0.65 kg ha-1). Increased tiller production can be attributed to Zn induced enzymatic activity and auxin metabolism in plants. These results are similar to the findings of Ghani *et al.* (1990). Content of plant pigments like chlorophyll determines color and appearance, and is an indicator of plant health (Abbot, 1999). Zn is proposed to be involved in chlorophyll formation through regulation of nutrients homeostasis in cytoplasm (Aravind and Prasad, 2004). The analysis of the data showed that various treatments had significant effect ($P<0.05$) on chlorophyll content (Fig. 1B). The highest value (34.05 CCI) was obtained in T5 (Zn-EDTA was applied @ 10.00 kg ha-1 in soil) followed value (32.83 CCI) of T10 (ZnO was applied @ 0.650 kg ha-1 as foliar). The minimum value (29.90 CCI) was obtained in T1 (No fertilizer, no zinc). The maximum biomass ton ha-1 was recorded in T5 (5.61) when Zn-EDTA was applied @ 10.00 kg ha-1 in soil followed by T3 (5.28) when ZnSO4.H2O was applied @ 12.50 kg ha^{-1} and T_6 (5.22) when ZnO was applied @ 5.00 kg ha-1 in soil as compared to T_1 (2.72). Srivastava *et al.* (1999) also presented similar findings.

Beutler *et al.* (2014) [9] conducted an experiment to study the effect of zinc sources in rice and reported that treating rice seeds by coating with $ZnCl_2$ provided 6.4% higher grain yield compared to that of $ZnSO_4 .7H_2O$. Applying Zn by coating the seeds promoted 5.8% higher rice grain yield. Khaliq *et al.* (2014) [27] also concluded that zinc application significantly increased the total biomass and paddy yield. Similar findings were reported by Mustafa *et al.* (2011) [37-39].

Singh *et al.* (2014) evaluated the effect of zinc on rice activity and observed that application of zinc recorded the highest Basmati rice grain (5.46 t ha^{-1}) and straw yields (9.89 t ha^{-1}) and the grain and straw yield increase by 23.5% and 12.9%, 5.6% and 2.9%, 8.98% and 5.1%, 17.4% and 9.8% with the application of $ZnSO_4$. $7H_2O$, $ZnSO_4.H_2O$, ZnP and $ZnSO_4.7H_2O$+ZnO (50%+50%), respectively over control (no Zn application). Grain yield of genotypes (Nipponbare and Jiaxing27), on an average, increased by 11.4%. (Wang *et al.*, 2014).

Sudha and Stalin (2015) [55] reported that reduced rice grain yields with low zinc concentrations when there is low supply of zinc. Flood-irrigated rice is more prone to Zn deficiency (Rehman *et al.*, 2012)

as submergence condition of rice cultivation influences electrochemical and biochemical reactions and alters pH, PCO2 as well as the concentration of certain ions.

Khattak *et al.* (2015) conducted an experiment to study the effect of zinc fortification in rice through different sources of zinc and reported that both soil addition and foliar spray of $ZnSO_4$ significantly increased grain yield, 1000 grain weight and grain protein content, and biological yield however grain protein composition was not significant. Foliar spray of 0.5% and 1.0% $ZnSO_4$ increased grain yield by 10 and 18.8%, respectively while its soil application at the rate of 5, 10 and 15 kg ha^{-1} increased grain yield by 18, 32 and 41%, respectively over the control.

Ghoneim (2016) [14, 15] conducted an field experiment 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 and reported that the Zn application by different methods, significantly increased 1000-grain weight; filled grains% and grains yield of Sakha 104.

Kulhare *et al.* (2017) conducted a field experiment in kharif during 2010 and 2011 to study the effect of foliar spray of 0.5, 1.0% Zn salts and 1.0% Zn salts +0.5% lime concentration of different sources of Zn ($ZnSO_4.7H_2O$, $ZnCl_2$, $Zn_3(PO_4)_2$, ZnO and Na_2Zn-EDTA) on yield, Zn content, uptake and Zn use efficiency in rice (Pusa Basmati) grown on Typic Haplusterts and reported that the rice grain yield significantly increased with the foliar application of Zn-EDTA over all the sources of Zn but the other Zn sources were found at par amongst themselves.

Table 2: Effect of zinc fertilization on growth attributes of rice [Source: Ghasal *et al.*, 2015]

Treatments	Plant height (cm)	Tillers/hill	DMA (g/hill)
Control	99.9	11.1	38.3
5 kg Zn ($ZnSO_4.7H_2O$)	101.2	11.5	39.5
2.5 kg Zn ($ZnSO_4.7H_2O$) + 0.5% Foliar spray at MT and PI	101.2	11.6	41.2
2.5 kg Zn-EDTA	101.4	11.5	40.6
1.5 kg Zn (Zn-EDTA) + 0.5% Foliar spray at MT and PI	102.7	11.7	41.9
CD $_{(p=0.05)}$	NS	NS	2.4

Ghasal *et al.* (2015) stated that application of Zn significantly increased yield attribute viz. DMA, and the highest value was recorded with 1.25kgZn/ha through Zn-EDTA+0.5%FSatMT and PIstages, which was very close to 2.5 kg Zn (ZnSHH) + 0.5% FS at MT and PI. Chelated Zn source, i.e. Zn-EDTA proved superior to Zn sulphate in increasing DMA and total Zn content. In the case of plant height at harvest and tillers/hill at harvest, the improvement owing to Zn treatments was non-significant. Reports indicated that Zn fertilization in rice has a stimulating DM A and yield attributes. Application of chelated Zn-EDT A remained available to crops for longer time than other source so wing to less trans formation of EDTA-chelated Zn into unavailable forms.

Table 3: Effect of zinc application on performance of rice [Source: Barua and Saikia, 2018]

Treatments	Effective tillers/ m row length	Grains/panicle	Panicle length (cm)	Grain yield (q/ha)	Straw yield (q/ha)
Control	40.8	84.4	19.7	16.12	35.3
$ZnSO_4$ @ 25 kg/ha as basal	49.2	88.9	20.9	18.16	37.9
$ZnSO_4$ @ 25 kg/ha as basal + seed priming with 2% $ZnSO_4$	52.7	93.3	23.1	20.72	40.1
$ZnSO_4$ @ 25 kg/ha as basal + foliar spray @ 0.5% at three stages	56.1	95.7	25.1	21.46	42.9
Seed priming with 2% $ZnSO_4$ +foliar spray @ 0.5% at three stages	50.7	92.0	21.9	19.73	39.0
CD $_{(p=0.05)}$	3.8	6.2	1.5	1.28	2.7

Barua and Saikia (2018) [7] revealed that significant variations in yield attributing characters were recorded due to different zinc fertilization. Plots receiving $ZnSO_4$ @ 25 kg/ha as basal + 0.5% foliar application produced significantly higher number of effective tillers/meter, more number of grains/panicle and length of panicle than that of other zinc fertilization treatments. This might be due to increase synthesis of carbohydrates and their transport to the site of grain formation (source to sink) causing high yield under this treatment (T_4) as compared to other zinc treatments. Similar results were also observed by Peda Babu *et al.*, (2007) [45]. The higher grain yield was obtained under treatment T_4, where $ZnSO_4$ was applied @ 25 kg/ha as basal + 0.5% foliar application. This might be due to the positive combined effect of yield attributing characters; like number of effective tillers per meter row length, number of grains per panicles and panicle length. The process of Zn storage in stem and Zn loading into the grains during grains filling have influence on more dry matter production. 0.5% foliar application of Zn under this treatment might have helped in transport process which ultimately resulted in about 33.13% yield over control. Significant increase in grain yield and straw contents were observed with foliar application of Zn as $ZnSO_4$. Application of Zn in rice have shown similar results as reported by Singh *et al.*, (1996) [51]; Maqsood *et al.*, (1999) [34]; Kausar *et al.*, (2001) [26] and Mehla *et al.*, (2006) [36]. The effect of zinc fertilization on straw yield was also found significant. However, highest straw yield was recorded with treatment T_4, when $ZnSO_4$ was applied @ 25kg/ha as basal + 0.5% foliar application, which might be due to favorable effect of zinc on the proliferation of roots and thereby increasing the uptake of plant nutrients from the soil supplying it to the aerial parts of the plant and ultimately enhancing the vegetative growth of plants, similar result was also reported by Beebout *et al.* (2011) [8].

Chhabra and Kumar (2018) [10] stated that direct seeded rice observed higher grain yield as compared to transplanted rice. Out of the methods of zinc application (basal and foliar spray @ 0.5%) basal application of zinc proved to be beneficial in getting higher grain yield when applied to direct seeded rice. Both basal application and foliar spray of zinc had the similar effect on transplanted rice as grain yield in both the treatments are at par. Direct seeded rice superseded in terms of grain yield production as compared to transplanted rice even in control plots also.

Table 4: Rice yield as influenced by zinc fortification [Source: Kumar *et al.*, 2019]

Treatments	Biomass yield (q/ha)	Grain yield (q/ha)	Straw yield (q/ha)	Harvest index (%)
(T_1) Control	97.52	40.87	56.65	41.91
(T_2) Seedling treatment with 1% ZnO solution (5 min.).	106.79	44.87	61.92	42.04
(T_3) 5 kg Zn/ha through $ZnSO_4$ (21% Zn) as soil application.	120.80	52.50	68.30	43.46
(T_4)0.5 kg Zn/ha through Chelated zinc (Zn EDTA) as soil application.	111.22	46.54	64.68	41.84
(T_5) 7.5 kg Zn/ha through $ZnSO_4$ (21% Zn) as soil application.	122.65	53.30	69.35	43.50
(T_6) 1 kg Zn/ha through Chelated zinc (Zn EDTA) as soil application.	119.90	51.90	68.00	43.29
(T_7) Foliar spray of $ZnSO_4$ with lime (0.1% Zn solution).	110.61	47.60	63.01	43.06
(T_8)Foliar spray of $ZnSO_4$ with urea (0.1% Zn solution).	111.29	48.27	63.02	43.37
(T_9) Foliar spray of $ZnSO_4$ with lime (0.15% Zn solution).	112.75	48.67	64.09	43.18
(T_{10}) Foliar spray of $ZnSO_4$ with urea (0.15% Zn solution).	113.31	49.17	64.14	43.41
SEm±	2.68	0.90	2.31	-
CD (P= 0.05)	8.04	2.69	6.93	-

Kumar *et al.* (2019) reported that among the various zinc sources and methods of zinc application T_5 (7.5 kg Zn/ha through $ZnSO_4$ (21% Zn) as soil application) gave maximum grain, straw and biological yield (Table 4). Crop productivity is the rate at which a crop accumulate biomass which depends primarily on the photosynthesis and conversion of light energy into chemical energy by green plants. The yield of rice is composed of yield components like as number of panicles, panicle length and 1000 grain weight. Though, 1000 grain weight an influence on grain yield but its effect is lower than panicle length and number of grains panicle^{-1}. All sources and methods of zinc application differ significantly from each other except T_5 and T_3 and T_6. Positive effects of zinc application by soil and foliar sprays on grain yield of rice might be due to increase chlorophyll content of leaves of rice which might have increased photosynthesis and resulted in more dry matter accumulation and leaf area and hence lead to more capture of solar radiation that resulted in enhanced values of growth parameters and yield contributing characters and ultimately resulted in higher grain yield. These results are in line with Slaton *et al.* (2005) [54], Khattak *et al.* (2015) [28, 29] and Ghoneim (2016) [14, 15].

Zinc fortification and grain quality of rice

Table 4: Amylose content of grain of different varieties of rice as influenced by zinc fortification [Source: Ghasal*et al.*, 2016] [13]

Treatments	Amylose content (%)						
	PB-1401	PB-1460	PRH-10	PB-1121	PB-1509	PUSA-2511	Mean
Control	25.9	25.8	22.8	24.8	22.8	22.4	23.1
5 kg Zn ($ZnSO_4.7H_2O$)	25.9	25.6	22.6	24.0	23.0	22.8	24.0
2.5 kg Zn ($ZnSO_4.7H_2O$) + 0.5% Foliar spray at MT and PI	26.0	25.7	22.59	24.3	23.8	22.7	24.4
2.5 kg Zn-EDTA	25.8	25.7	22.7	24.0	23.0	22.6	24.1
1.25 kg Zn (Zn-EDTA) + 0.5% Foliar spray at MT and PI	26.7	25.8	22.9	24.9	23.9	22.9	24.8
Mean	25.9	25.7	22.0	24.2	23.1	22.7	
CD $_{(p=0.05)}$	Varieties (V)- 3.19, Zn fertilizers (Zn)- 2.08, Zn x V- NS						

Ghasal *et al.* (2016) [13] reported significant differences in different varieties of rice with respect to amylose content. The amylose content in different varieties were in the order of ‘Pusa Basmati 1401’>‘Pusa Basmati 1460’>‘Pusa Basmati 1121’>‘Pusa Basmati 1509’>‘Pusa 2511’>‘Pusa Rice Hybrid 10. The highest amylose content was observed with application of 1.25 kg Zn ha^{-1} as Zn-EDTA as soil application + 0.5% foliar spray at maximum tillering and panicle initiation stages.

Table 5: Crude protein content in white rice kernel of different varieties of rice as influenced by zinc fortification [Source: Ghasal *et al.*, 2016] [13]

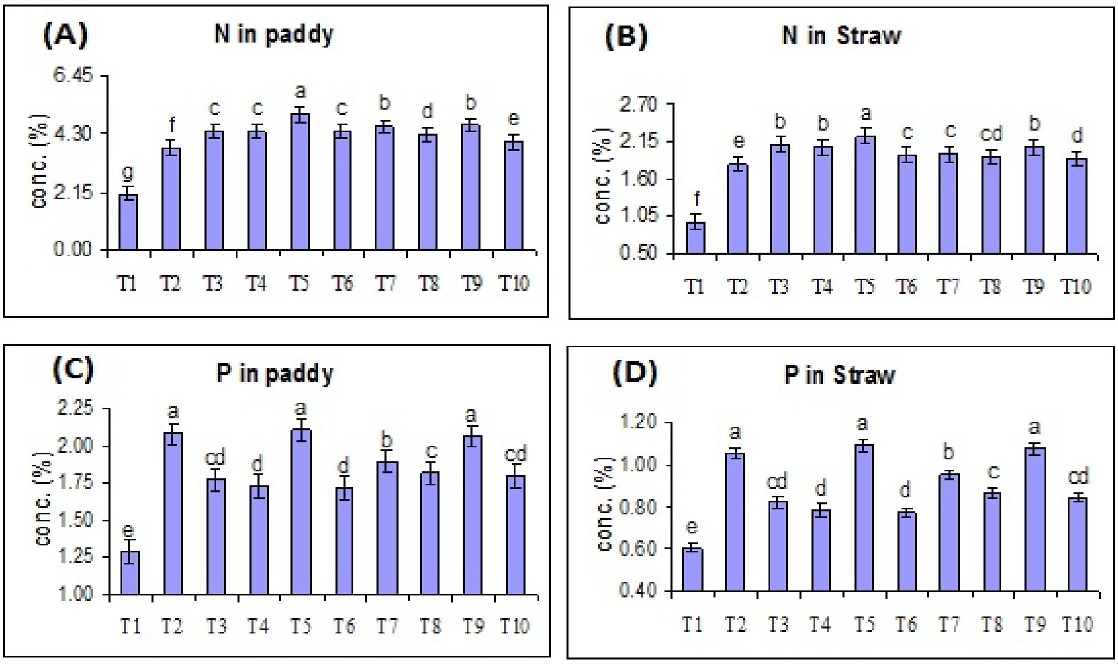
Treatments	Crude protein content in white rice kernel (%)						
	PB-1401	**PB-1460**	**PRH-10**	**PB-1121**	**PB-1509**	**PUSA-2511**	**Mean**
Control	9.8	9.9	9.9	9.9	10.2	9.9	9.7
5 kg Zn ($ZnSO_4.7H_2O$)	9.9	9.8	10.3	9.8	10.6	9.6	10.0
2.5 kg Zn ($ZnSO_4.7H_2O$) + 0.5% Foliar spray at MT and PI	9.8	10.4	9.9	9.7	10.7	9.8	10.1
2.5 kg Zn-EDTA	9.8	10.0	9.9	9.9	10.6	9.9	10.0
1.25 kg Zn (Zn-EDTA) + 0.5% Foliar spray at MT and PI	10.1	10.8	10.9	10.1	10.8	10.0	10.3
Mean	9.9	10.2	10.9	9.7	10.7	9.8	
CD $_{(p=0.05)}$	Varieties (V)- 0.31, Zn fertilizers (Zn)- 0.33, Zn x V- NS						

Ghasal *et al.* (2016) [13] also stated that the protein content in white rice kernel was found in order of ‘Pusa Basmati 1509’>‘Pusa Basmati 1460’>‘Pusa Rice Hybrid 10’>‘Pusa Basmati 1401’>‘Pusa 2511’>‘Pusa Basmati 1121. Zn fertilization significantly increased crude protein content in white rice kernel and higher values were recorded in soil + foliar application of Zn as compared to soil application alone. The highest protein content was observed with application of 1.25 kg Zn ha-1 as Zn-EDTA as soil application + 0.5% foliar spray at maximum tillering and panicle initiation stages. Increase in crude protein content with Zn application is in agreement with the hypothesis that protein represents a sink for Zn in the grain. Application of Zn fertilizers in soil increased the Zn availability to the plants and Zn plays an important role in protein synthesis.

Table 6: Effect of zinc fortification on concentration and uptake of potassium by rice [Source: Pooniya and Shivay, 2012]

Treatment	K Content in grain (%)	K Content in straw (%)	Total K uptake (kg/ha)
Absolute control	0.27	1.48	197.6
Control (only N)	0.30	1.61	255.9
2.0% ZEU ($ZnSO_4.2H_2O$)	0.33	1.67	297.9
2.0% ZEU (ZnO)	0.32	1.66	285.5
5 kg Zn/ha ($ZnSO_4.2H_2O$)	0.31	1.65	181.5
5 kg Zn/ha (ZnO)	0.30	1.63	169.2
ZnO slurry	0.30	1.62	265.4
0.2% foliar spray ($ZnSO_4.2H_2O$)	0.30	1.65	274.8
CD $_{(p=0.05)}$	0.02	0.05	9.6

Pooniya and Shivay (2012) stated that the application of 2.0% ZEU as $ZnSO_4.H_2O$ increased K concentration in rice grain significantly over remaining Zn fertilization treatments except 5 kg Zn ha^{-1} through $ZnSO_4$.H2O as soil application. In case of basmati rice straw, 2.0% ZEU as $ZnSO_4.H_2O$ recorded highest K concentration viz. 1.66 and 1.67%, and it remained on par with 2.0% ZEU as ZnO, 5 kg Zn ha^{-1} through $ZnSO_4.H_2O$ as soil application and 0.2% foliar spray of $ZnSO_4.H_2O$. 2.0% ZEU as $ZnSO_4.H_2O$ recorded significantly higher K uptake in grain, straw and total (grain+straw) of rice. The total K uptake in basmati rice was almost 23–25 times higher than that in grain.



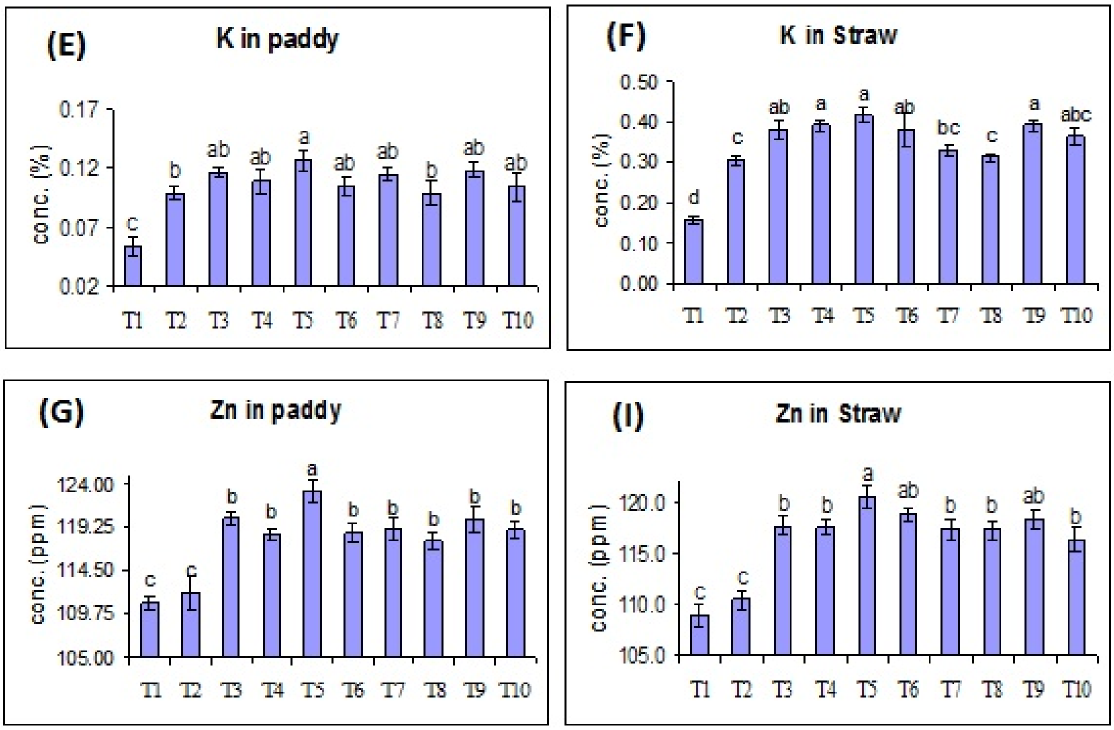


Fig 2: Nitrogen, phosphorus, potassium and zinc contents in rice paddy and straw as affected by soil and foliar applications of different sources of zinc. Values are means of three replicate plots. Means with different letters are statistically different from each other at 5% level.

Rana and Kashif (2014) [27] reported that the N content in paddy and straw were significantly ($P<0.05$) increased with Zn application over both absolute and Zn-control (2014) (Fig.2A & 2B). Maximum N content in paddy (5.02%) and straw (2.22%) were recorded in T5 (Zn-EDTA applied @ 10.00 kg ha-1 in soil). The minimum N content in paddy (2.10%) and straw (0.97%) were observed under absolute control (T1). Concentration of N in paddy grains was higher as compared to straw, under all applied treatments. These results are in agreement with findings of Singh *et al*. (1990) and Takkar (1996). Lowest P concentrations for paddy and straw were recoded under absolute control (T1). When compared with Z-control (T2) different sources of Zn application resulted in decreased P content in paddy and straw (except Zn-EDTA application, both soil and foliar). Maximum value of P content in paddy (2.11%) and straw (1.09%) were obtained in T5 (Zn-EDTA applied @ 10.00 kg ha-1 in soil) followed by T2. Among the Zn treatments, T6 (ZnO applied @ 5.00 kg ha-1 in soil) recorded lower P contents in paddy (1.72%) and straw (0.77%). Similar results also reported Chaudhry *et al*. (1992) and Yaseen *et al*. (1999). Significantly maximum K contents in paddy (0.13%) and straw (0.42%) were observed in T5 (Zn-EDTA applied @ 10.00 kg ha-1 in soil) while minimum K content in paddy (0.05%) and straw (0.16%) were observed in T_1 (Absolute control). Overall, paddy grains have significantly lower concentration of K as compare to that in straw. These results are confirmation findings of Iqbal *et al*. (2000), they reported that K concentration of both paddy and straw showed increasing trend with Zn fertilizer application. Zinc concentration in both paddy and straw significantly enhanced by Zn application as compared to absolute control (T1) and Zn-control (T2) ($P < 0.05$). Different sources of Zn were statistically similar except Zn-EDTA application. Maximum Zn contents in paddy (123.18 ppm) and straw (120.5 ppm) were observed in T5 (Zn-EDTA applied @ 10.00 kg ha-1 in soil), while minimum Zn content in paddy (111.07 ppm) and straw (108.9 ppm) were observed in T1 (Absolute control). Stunted growth of rice plants under Zn deficient conditions may reduce Zn uptake and ultimately compromised Zn concentration in paddy and straw. These results are in agreement with the finding of Devarajan and Ramanathan (1995).

Zinc fortification and economics of rice

Kumar *et al.* (2019) revealed that crop fertilized with zinc based nutrients application (T_5) 7.5 kg Zn/ha through $ZnSO_4$ (21% Zn) as soil application gave more ruminative in terms of gross return (117003 ha^{-1}), net return (86605 ha^{-1}) and B:C ratio (3.85) over rest of the treatments (Table 7). It was mainly because of more increase in grain yield and gross income in comparison to increase in cost of cultivation (Kumar *et al*., 2017). Higher B:C ratio might have been attributed to dual advantage *i.e.* saving in inputs and additional returns due to higher yields (Ghasal*et al*., 2015) [11, 12]. Whereas, maximum cost of cultivation (29517 ha^{-1}) was recorded with the application of (T_6) 1 kg Zn/ha through Chelated zinc (Zn EDTA) as soil application. It may be due to high cost of fertilizer (Abbas *et al*., 2010) [1].

Table 7: Effect of zinc fortification on profitability of rice [Source: Kumar *et al*., 2019]

Treatments	**Cost of cultivation (Rs/ha)**	**Gross return (Rs/ha)**	**Net return (Rs/ha)**	**Benefit: cost ratio**
(T_1) Control	28898	90237	61339	3.12
(T_2) Seedling treatment with 1% ZnO solution (5 min.).	30715	99028	68313	3.22
(T_3) 5 kg Zn/ha through $ZnSO_4$ (21% Zn) as soil application.	29898	115245	85347	3.85
(T_4) 0.5 kg Zn/ha through Chelated zinc (Zn EDTA) as soil application.	31058	102775	71717	3.31
(T_5) 7.5 kg Zn/ha through $ZnSO_4$ (21% Zn) as soil application.	30398	117003	86605	3.85
(T_6) 1 kg Zn/ha through Chelated zinc (Zn EDTA) as soil application.	33218	114000	80782	3.43
(T_7) Foliar spray of $ZnSO_4$ with lime (0.1% Zn solution).	29452	104652	75200	3.55
(T_8) Foliar spray of $ZnSO_4$ with urea (0.1% Zn solution).	29392	105987	76595	3.61
(T_9) Foliar spray of $ZnSO_4$ with lime (0.15% Zn solution).	29517	106946	77429	3.62
(T_{10}) Foliar spray of $ZnSO_4$ with urea (0.15% Zn solution).	29457	107962	78505	3.67

Conclusion

This review paper emphasized the role and importance of zinc fortification in rice. The excess use of inorganic fertilizers in agriculture can lead to soil deterioration, soil acidification and environment pollution. Balanced applications of macro nutrient and zinc improve soil fertility, productivity and reduce the impact of heavy use of inorganic fertilizers on environment. So, it is an alternative way for sustainable soil fertility and productivity. On the basis of foregoing discussion, it can be concluded that zinc fortification enhanced the quality and productivity of rice. Combined application of zinc with 100% RDF resulted in good growth parameters, yield attributes, significantly higher yield and grain quality of rice. Use of zinc with macronutrients provides the scientific basis for balanced fertilization not only between the fertilizer nutrients themselves but also that with the soil available nutrients. Moreover, the application of $ZnSO_4$ as soil application + foliar spray at different stages recorded the highest grain yield with high Zn content in grain and brown rice. Application of Zn through Zn-EDTA as soil application better growth and yield parameters as well as Zn content in grain too. Split applications (soil + foliage) of zinc proved better than the basal application in terms of growth characteristics. There is more impact of chelated Zn than other fertilizer sources in respect of growth. There are several aspects of biofortification but agronomic aspect (Ferti-fortification) is simpler one and is mostly followed.

References

1. Abbas G, Hassan G, Ali MA, Aslam M, Abbas Z. Response of wheat to different doses of ZnSO4 under Thal desert environment. Pakistan Journal of Botany. 2010; 46(6):4079-4085.
2. Abbas M, Zahida TM, Uddin R, Sajjid I, Akhlaq A, Moheyuddin K *et al*. Effect of Zinc and Boron Fertilizers Application on Some Physicochemical Attributes of Five Rice Varieties Grown in Agro-Ecosystem of Sindh, Pakistan. American-Eurasian J Agric. & Environ. Sci., 2013; 13(4):433-439.
3. Anonymous. Food and Agricultural organization.
4. Arif M, Muhammad AS. Chlorophyll contents and yield attributes in rice. African J Biotech. 2016; 11(48):10851-10858.
5. Arif M, Chohan MA, Ali S, Gul R, Khan S. Response of wheat to foliar application of nutrients. J Agric. Biol. Sci., 2006; 1:30-34.
6. Babu VR. Importance and advantages of rice biofortification with iron and zinc. Journal of ICRISAT Agricultural Research. 2013, 11.
7. Barua D, Saikia M. Agronomic biofortification in rice varieties through zinc fertilization under aerobic condition. Indian Journal of Agricultural Research. 2018; 52(1):89- 92.
8. Beebout SJ, Francis HCR, Dennis SJT, Ranee CM. Reasons for variation in rice (*Oryza sativa*) grain zinc response to zinc fertilization. In: 3rd International Zinc Symposium 10–14 October 2011, Hyderabad, India, 2011.
9. Beutler AN, Silva1 VN, Deak EA, Burg GM, Schmidt MR, Toebe M. Effect of zinc sources in rice. Australian journal of crop science JCS 2014; 8(11):1517-1525
10. Chhabra V, Kumar R. Role of zinc application on rice growth and yield. Plant Archives. 2018; 18(2):1382-1384.
11. Ghasal PC, Shivay YS, Pooniya V. Response of basmati rice (*Oryza sativa*) varieties to zinc fertilization. Indian Journal of Agronomy. 2015; 60(3):403-409
12. Ghasal PC, Shivay YS, Pooniya V. Response of basmati rice (*Oryza sativa*) varieties to zinc fertilization. Indian Journal of Agronomy, 2015; 60(3):403-409.
13. Ghasal PC, Shivay YS, Pooniya V, Verma RK. Zinc fertilization enhances growth and quality parameters of aromatic rice (*Oryza sativa* L.) varieties. Indian Journal of Plant Physiology, 2016. DOI 10.1007/s 40502-016-0243-2.
14. Ghoneim AM. Effect of Different Methods of Zn Application on Rice Growth, Yield and Nutrients Dynamics in Plant and Soil. Journal of Agriculture and Ecology Research International. 2016; 6(2):1-9
15. Ghoneim AM. Effect of Different Methods of Zn Application on Rice Growth, Yield and Nutrients Dynamics in Plant and Soil. Journal of Agriculture and Ecology Research International. 2016; 6(2):1-9.
16. Gregorio GB, Senadhira D, Htut H, Graham RD. Breeding for trace mineral density in rice. Food and Nutrition Bulletin. 2000; 21:382-386.
17. Haas JD, Beard JL, Murraykolb LE, del Mundo AM, Felix A, Gregorio GB. Iron-biofortified rice improves the iron stores of non anemic Filipino Women. Journal of Nutrition. 2005; 135:2823-2830.
18. Hussain ST. Agronomic Biofortification of Rice (*Oryza sativa* L.) with Zinc Fertilization. Division of Agronomy, Sher-e-Kashmir University of Agricultural Sciences & Technology of Kashmir, 2015.
19. International Zinc association (IZA) database, 2014.
20. Ishimaru Y, Bashir K, Nishizawa N. Zn uptake and translocation in rice plants. Rice book, 2011; 4:21-27.
21. Jat SL, Shivay YS, Parihar CM. Dual purpose summer legumes and zinc fertilization for improving productivity and zinc utilization in aromatic hybrid rice (*Oryza sativa*). Indian Journal of Agronomy. 2011; 56(4):328-333

22. Jena J, Sethy P, Jena T, Mishra SR, Sahoo SK, Dash GK, *et al*. Rice biofortification: A brief review. Journal of Pharmacognosy and Phytochemistry. 2017; 7(1, 2):644-2647.
23. Jiang W, Struik PC, Lingna J, van-Keulen H, Ming Z, Stomph TJ. Uptake and distribution of root applied or foliar applied Zn after flowering in aerobic rice. Annals of Applied Biology, 2007; 150:383-391.
24. Kandoi A, Bhatia BD, Oandey S, Sen PC, Satya K. Cellular immunity status in anaemia in pregnancy. Indian Journal of Medical Research. 1991; 94:11-15.
25. Katyal JC, Rattan RK. Secondary and micronutrients research: Gaps and future needs. Fertiliser News. 2003; 48(4):9-20
26. Kausar MA, Ali S, Iqbal MM. Zinc nutrition of three rice varieties in alkaline soils. Pakistan Journal of Soil Science. 2001; 20:9-14.
27. Khaliq W, Saifur R, Kashif R. Effect of different Zinc sources and methods of application on rice yield and nutrients concentration in rice grain and straw. Journal of Env. and Agri. Sci. 2014; 5(2):23-27
28. Khattak SG, Dominy PJ, Ahmad W. Effect of Zn as soil addition and foliar application on yield and protein content of wheat in alkaline soil. J Natn. Sci. Foundation Sri Lanka. 2015; 43(4):303-312.
29. Khattak SG, Dominy PJ, Ahmad W. Effect of Zn as soil addition and foliar application on yield and protein content of wheat in alkaline soil. J Natn. Sci. Foundation Sri Lanka. 2015; 43(4):303-312
30. Kulhare PS, Tagore GS, Sharma GD. Effect of foliar spray and sources of zinc on yield, zinc content and uptake by rice grown in a vertisol of central India. International Journal of Chemical Studies. 2017; 5(2):35-38
31. Kumar D, Kumar R, Singh P, Kumar P. Effect of different zinc management practices on growth, yield, protein content, nutrient uptake and economics on rice under partially reclaimed salt affected soil. Journal of Pharmacognosy and Phytochemistry. 2017; 6(5):638-640.
32. Kumar R, Kumar M, Sharma R, Singh PK, Yadav KG, Kumar A *et al*. Effect of sources and methods of zinc application on growth and yield of Basmati rice (*Oryza sativa* L.). Journal of Pharmacognosy and Phytochemistry SP. 2019; (2):1048-1051.
33. Liu H, Gan W, Rengel Z, Zhao P. Effects of zinc fertilizer rate and application method on photosynthetic characteristics and grain yield of summer maize. Journal of Soil Science and Plant Nutrition. 2016; 16:550-562.
34. Maqsood MM, Irshad S, Wajid A, Hussain A. Growth and yield response of Basmati-385 (*Oryza sativa* L.) to $ZnSO_4$ application. Pakistan Journal of Biological Science. 1999; 2(4):1632-1633.
35. McClain, Craig J, Edward J, Kasarskis Jr, Allen JJ. Functional consequences of zinc deficiency. Progress in Food and Nutrition Science. 1985; 9:185-226.
36. Mehla DS, Singh KS, Sekhon D, Bhardwaj KK. Long term effect of inorganic and organic inputs on yield and soil fertility in rice- wheat cropping system in India. 18th World. Cong. Of Soil. Sci. (WCSS) held on 9-15 July 2006, Pennsyl Philadephia, 2006, 163-32,
37. Mustafa G, Ehsanullah AN, Qaisrani SA, Iqbal A, Khan HZ, Jabran K *et al*. Effect of zinc application on growth and yield of rice (*Oryza sativa* L.). Int. J Agro Vet. Med. Sci., 2011; 5:530- 535.
38. Mustafa G, Ehsanullah, Akbar N, Qaisrani SA, Iqbal A, Khan HZ *et al*. Effect of Zinc Application on Growth and Yield of Rice (*Oryza sativa* L.). IJAVMS. 2011; 5(6):530-535
39. Mustafa G, Ehsanullah, Akbar N, Qaisrani SA, Iqbal A, Khan HZ *et al*. Effect of Zinc Application on Growth and Yield of Rice (*Oryza sativa* L.). IJAVMS. 2011; 5(6):530-535
40. Naik SK, Das DK. Evaluation of various zinc extractants in low land rice soil under the influence of zinc sulphate and chealated zinc. Communi. Soil. Sci. and Pl.Anal., 2010; 41:122-134.
41. Naik SK, Das DK. Effect of split application of zinc on yield of rice (*Oryza sativa* L.) in an inceptisol. Arch. Agron. Soil Sci., 2007; 53:305-313.
42. Nattinee P, Cakmak I, Panomwan B, Jumniun W, Benjavan R. Role of Zn fertilizers in increasing grain Zn concentration and improving grain yield of rice. The Proceedings of the International Plant Nutrition Colloquium XVI, Department of Plant Sciences, UC Davis USA, 2009.
43. Nestel P, Bouis HE, Meenakshi JV, Pfeiffer W. Biofortification of staple food crops. The Journal of nutrition. 2006; 136(4):1064-1067.
44. Nilson A, Piza J. Food fortification: A tool for fighting hidden hunger Food and Nutrition Buletin. 1998; 19:49-60.
45. Peda Babu P, Shanti M, Rajendra Prasad B, Minhas PS. Effect of zinc on rice in rice –black gram cropping system in saline soils. Andhra Agricultural Journal. 2007; 54(1, 2):47-50.
46. Pooniya V, Shivay YS. Effect of green manuring and zinc fertilization on productivity and nutrient uptake in Basmati rice (*Oryza sativa*)-wheat (*Triticum aestivum*) cropping system. Indian Journal of Agronomy, 2011; 56(1):29-35.
47. Pooniya V, Shivay YS. Enrichment of Basmati rice grain and straw with zinc and nitrogen through ferti-fortification and summer green manuring under Indo-Gangetic plains of India. Journal of Plant Nutrition. 2013; 36(1):91-117.
48. Rhodes D, Klug A. Zinc fingers. Scientific American, 1993; 268:56-65
49. Sandstead HH. Requirements of zinc in human subjects. Journal of the American College of Nutrition. 1985; 4:73-82.
50. Scholl TO, Hediger ML, Fischer RL, Shearer JW. Anemia vs. iron deficiency: increased risk of preterm delivery in a prospective study. American Journal of Clinical Nutrition. 1992; 55:985-988.
51. Singh AK, Thakur SK, Singh SS. Effect of N with and without FYM and Zn on Yield, uptake and economics of rice. Journal of Agriculture Issues. 1996; 8:175-176.
52. Singh AK, Singh NP, Nongkyarih P. Response of rice to Zn in the soils of Meghalaya. Fertilizer News. 2014; 47(8):53-54
53. Singh UN, Tripathi BN. Response of rice cultivars to zinc in soidic soil. Ann Pl. Soil Res. 2008; 10(1):75-77
54. Slaton NA, Norman RJ, Wilson CE. Effect of zinc source and application time on zinc uptake and grain yield of flooded-irrigated rice. Agronomy Journal. 2005; 97:272-278.
55. Sudha S, Stalin P. Effect of zinc on yield, quality and grain zinc content of rice genotypes. International Journal of Farm Sciences. 2015; 5(3):17-27.

56. Suzuki M, Bashir K, Inoue H, Takahashi M, Nakanishi H, Nishizawa N. Accumulation of starch in Zn-deficient rice. Rice book, 2012; 5:9.
57. Vallee BL, Falchuk KH. The biochemical basis of zinc physiology. Physiological Review. 1993; 73:79-118.
58. Varshney P, Singh SK, Shrivastava PC. Frequency and rate of zinc application under hybrid rice wheat sequence in Mollisols of Uttarakhand. J Indian Soc. Soil Sc. 2008; 56:92-98
59. Velu G, Ortiz-Monasterio I, Cakmak I, Hao Y, Singh RP. Biofortification strategies to increase grain zinc and iron concentrations in wheat. Journal of Cereal Sciences. 2014; 59:365-372.
60. Wang YY, Wei YY, Dong LX, Lu LL, Feng Y, Zhang J, *et al*. Improved yield and Zn accumulation for rice grain by Zn fertilization and optimized water management. J Zhejiang Univ. Sci. B. 2014; 15(4):365-374
61. Wingerd J, Christianson R, Lovitt WV, Schoen EJ. Placental ratio in white and black women: relation to smoking and anemia. American Journal of Obstetrics & Gynecology. 1976; 124:671-675.
62. Zaman QU, Aslam Z, Yaseen M, Ihsan MZ, Khaliq A, Fahad S *et al*. Zinc biofortification in rice: leveraging agriculture to moderate hidden hunger in developing countries. Archives of Agronomy and Soil Science, 2017. 10.1080/03650340.2017.1338343.