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REVIEW

Zinc Fertilization of Cereals for Increased Production and Alleviation of Zinc Malnutrition in India

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Abstract Zinc deficiency has emerged as the fourth important micronutrient deficiency in humans. Zn deficiency is responsible for diarrhoea in infants, dwarfism in adolescents and loss of disability adjusted life years (DALYs) in adults. The loss of DALYs in India is estimated at 2.8 million. Since cereals are staple food in India and other Asian countries, fortification of their grains with Zn is a simple way to overcome Zn deficiency in humans in these areas. Efforts are underway to breed cereal cultivars with grains higher in zinc, but this requires considerable time. Fertilization of cereals with Zn is a faster, quicker and certain way to increase zinc content in cereals and this practice needs to be put in place without any delay.

Keywords Foliar application of Zn · Phytate · Phytate:Zn molar ratio · Zn fertilization · Zn malnutrition · Zn deficiency in soil

Abbreviations
BMPs: Best management practices; DALY: Disability adjusted life years; PDS: Public Distribution System; DTPA: Diethylene triamine pentaacetic acid; DW: Dry weight; IRRI: International Rice Research Institute; Mt: Million tonnes; PZMR: Phytate:Zn molar ratio; RWCS: Rice–wheat cropping system; Zn: Zinc; ZnO: Zinc oxide;

Introduction

Globally, three major micronutrient deficiencies have been recognised in humans [2]. The deficiencies are: (i) vitamin A deficiency leading to blindness; about 57 % of pre-school children in India have sub-clinical vitamin A deficiency; (ii) iron deficiency leading to anaemia; about 79 % of the kids between 6 and 35 months of age and 56 % of women between 15 and 49 years of age are anaemic in India and (iii) iodine deficiency leading to goitre and cretinism is endemic in 85 % districts in India [19]. The fourth micronutrient deficiency of Zn has recently received global attention. Some data on global mortality in children under 5 years of age due to different micronutrient deficiencies in 2004 are given in Table 1. Zn deficiency was next only to vitamin A deficiency and was responsible for over 453 thousand deaths. Zinc deficiency leads to diarrhoea and pneumonia in children [3, 7, 9]. Childhood dwarfism is considered as indication of Zn deficiency and about 61 million children under the age of 15 years are reported to be dwarf [13]. Zn plays an important role in production of proteins and thus helps in wound healing, blood formation and growth and maintenance of tissue [2]. Stein et al. [32] using DALYs (disability adjusted life years) showed that Zn deficiency in India is a highly relevant health problem and is responsible for a loss of 2.8 million DALYs per

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annum. They observed that biofortification of cereals (rice and wheat) may reduce this burden by 20–51 % and save 0.6–1.4 million DALYs each year. Importance of Zn in human nutrition and health has received some attention in India in recent years [18, 19, 33].

Cereals are the staple food in India and meet 60 % of the energy and protein needs of humans in the country (Table 2). As a contrast in developing countries such as the USA, cereals meet only a little over 20 % of the energy and protein needs of humans [6, 17]. Of the cereals rice and wheat make up a little over 80 % of the total cereals production in the country and are distributed through Public Distribution System (PDS) of the Govt. of India. Although un-hulled rice (paddy) contains 27–42 mg Zn kg^{-1} grain [25], the polished rice contains only 13–15 mg Zn kg^{-1} grain [36], while wheat grains contain 38–47 mg Zn kg^{-1} [26]. A diet of 300–400 g cereals day^{-1} will supply only 4–6 mg Zn day^{-1} in the case of rice and 11–18 mg Zn day^{-1} in the case of wheat. However, only a part of the Zn present in cereals is bio-available due to the presence of phytates. The phytate content varies from 0.14 to 0.60 % in rice and 0.39–1.35 % in wheat (Wikipedia Int.). Animal proteins contain higher amounts of Zn and also do not contain phytates and are therefore a better source of Zn. Animal proteins, however, form a very small part of Indian diet. Gibson [8] reported that a PZMR (phytate:Zn molar ratio) above 15 in foods is associated with reduced Zn bioavailability. The recommended dietary allowance for humans is 15 mg Zn day^{-1} for adult males and 12 mg Zn day^{-1} for adult females (16–19 mg Zn day^{-1} for breast feeding women) [35]. Fortification of cereal grains with Zn either by Zn fertilization of these crops or development of Zn efficient cultivars of these crops is therefore important from the viewpoint of food security as well as nutritional security.

Area, Production and Productivity of Cereals in India

Over the past 60 years (1950–2010), the total area under cereals has increased from 78.2 million hectares (M ha) in 1950–1951 to 98 M ha in 2009–2010 (Table 2). The increase was most in wheat (193 %), followed by that in maize (159 %) (Fig. 1). The area under rice during this period increased by 36 %, while that under pearl millet was negligible (1.1 %). On the contrary, the area under sorghum declined by 50 %. As regards production of cereals during the same period, it increased by 380 % (Fig. 2). The largest increase was in wheat (1,143 %), followed by maize (882 %) and rice (201 %). The increase in the production of sorghum, despite 50 % reduction in area was 4 %, while that in pearl millet was 2.5 %. This is why India's Green Revolution is mainly considered as wheat revolution. As compared to 1950–1951, the productivity in 2009–2010 increased four-fold in wheat, 3.7-fold in maize, 3-fold in rice and about 2.5-fold in pearl millet and sorghum (Fig. 3). This enormous increase in productivity and production was possible due to a massive programme in developing high yielding hybrids and varieties of crops and a matching research in crop agronomy resulting in the development of best management practices (BMPs) for different cereals for the different regions of the country.

However, in conventional breeding the emphasis has been on grain yield and not much attention was attached to the concentration of nutrients including micronutrients, which, in general, decline as the yield increases [37]. Also there have been efforts to breed cultivars capable of growing on Zn stress soils. This all led to the development of crop cultivars with lower concentration of Zn in grain as well as straw.

Table 1 Global mortality in children under 5 years of age in 2004

Deficiency	Deaths
Vitamin A	666,771
Zinc	453,207
Iron	20,854
Iodine	3,619

Source Black et al. [3]

Zinc Deficiency in Indian Soils

Zinc malnutrition achieves great significance in India because nearly half of the Indian soils are poor in available Zn. Percentage of soil samples deficient in DTPA-extractable available Zn varies from 8 % in Puducherry to 78 % in Maharashtra (Table 3). Zn deficiency is less prevalent in the western states of Rajasthan and Gujarat. Zn deficiency was first detected in rice at Pantnagar, Uttarakhand in 1965 by Nene [15]. There has been great emphasis on Zn fertilization in rice and wheat in northwestern India and as a result now the soils in the northern states of Punjab, Haryana and western Uttar Pradesh have a low percentage of Zn deficient soils. More than 90 % of Zn in soils occurs as insoluble Zn and is unavailable to plants, while exchangeable Zn ranges from 0.1 to 2 mg kg^{-1} soil [28]. Soluble Zn in bulk soil solution generally varies from 4×10^{-10} M to 4×10^{-6} M [1]. In calcareous soils such as those found in the rice–wheat cropping system (RWCS) belt in India, soluble Zn concentration may be as low as 10×10^{-9} M and can limit plant growth [11]. The soil factor most affecting the availability of Zn is pH. In a study at Bhopal desorption of adsorbed Zn decreased with increasing pH and stopped abruptly at pH 7.5 [23]. Alternate flooding and drying as obtained under irrigated rice culture also results in increased desorption of Zn [24].

Table 2 Area, production and productivity of cereals in India

Year	Rice	Wheat	Sorghum	Pearl millet	Maize	Total cereals*	Rice + wheat (% of total cereals)
Area (million hectares)							
1950–1951	30.8	9.7	15.6	9.0	3.2	78.2	51.8
1970–1971	37.6	18.2	17.4	12.9	5.8	101.8	54.8
1990–1991	42.7	24.2	14.4	10.5	5.9	103.2	64.8
2009–2010	41.9	28.4	7.8	8.9	8.3	98.0	71.7
Production (million tonnes)							
1950–1951	29.6	6.5	5.5	2.6	1.7	42.4	85.1
1970–1971	42.2	23.8	8.1	8.0	7.5	96.6	63.3
1990–1991	74.3	55.1	11.7	6.9	9.0	162.1	79.8
2009–2010	89.1	80.8	6.7	6.5	16.7	203.4	83.5
Productivity (kg/ha)							
1950–1951	668	663	353	288	547	542	–
1970–1971	1,123	1,307	466	622	1,279	949	–
1990–1991	1,740	2,281	814	658	1,518	1,571	–
2009–2010	2,125	2,839	860	731	2,024	2,075	–

* Total for cereals includes minor millets such as ragi etc

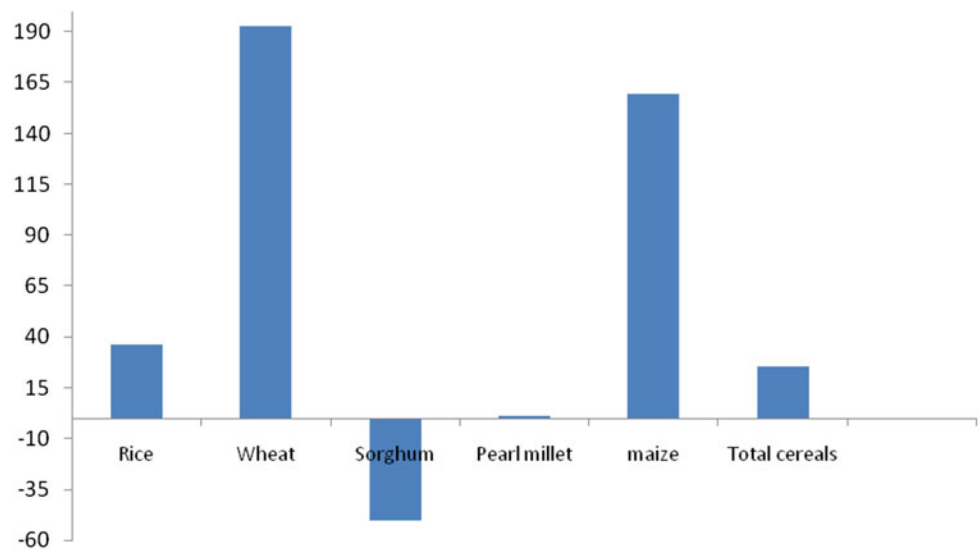

Fig. 1 Percentage increase/decrease in area of cereal crops during 2009–2010 over 1950–1951

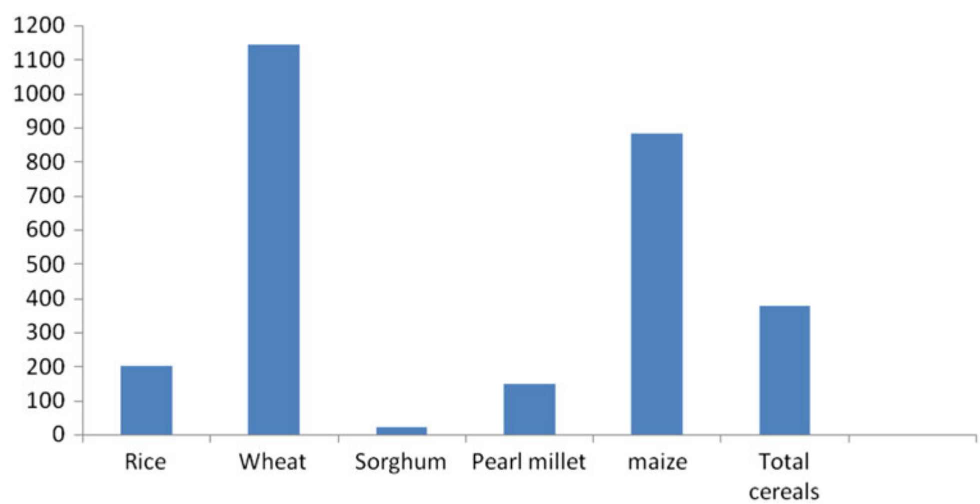

Fig. 2 Percentage increase/decrease in production of cereal crops during 2009–2010 over 1950–1951

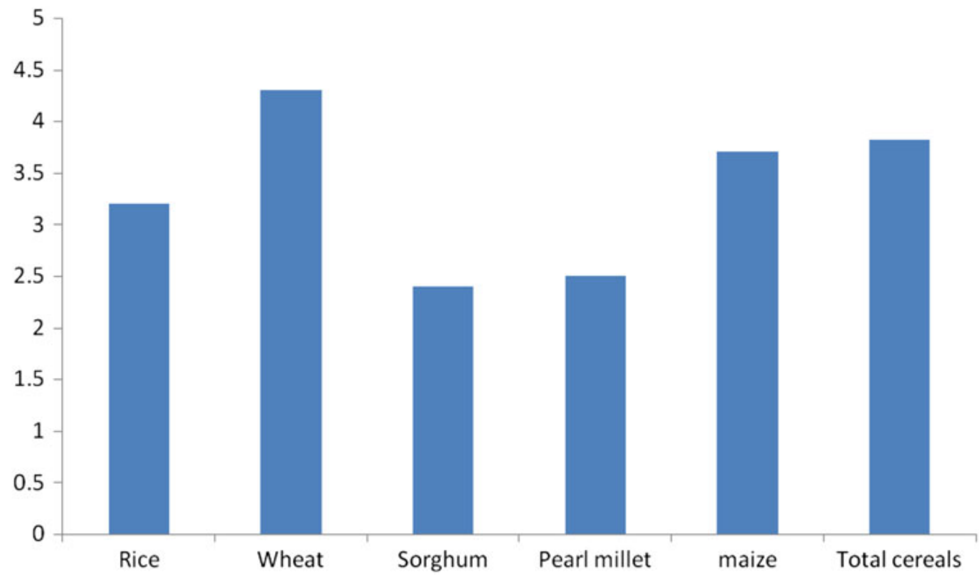

Fig. 3 Times increase in the productivity of cereal crops during 2009–2010 over 1950–1951

Table 3 Extent of Zn deficiency in soils of different states of India

Region	State (% of samples deficient in available Zn)
Eastern	Assam (34.0), Bihar & Jharkhand (65.3), Orissa (51.0), West Bengal (36.0), Chhattisgarh (63.0)
Northern	Punjab (24.6), Haryana (26.4), Uttar Pradesh (38.9), Uttarakhand (28.0), Himachal Pradesh (42.0), J&K (12.0)
Western and Central	Madhya Pradesh (65.8), Maharashtra (78.0), Rajasthan (21.0), Gujarat (19.9)
Southern	Andhra Pradesh (46.7), Tamil Nadu (71.4), Karnataka (72.8), Kerala (34.0 %)

Table 4 Critical limits of DTPA extractable Zn (mg kg^{-1} soil) for cereals for different major soils

Soil	Rice	Wheat	Maize	Sorghum
Alluvial	0.38–0.90	0.40–0.80	0.54–1.00	–
Black	0.84–1.34	0.54	–	–
Red and Black	0.45–2.00	0.46–0.60	1.00–2.00	1.00–2.00
Red	0.60–1.00	–	0.65–0.80	–

Table 5 Zn recommendations for corn in Minnesota (USA)

DTPA extractable Zn (mg kg^{-1} soil)	Starter (kg ha^{-1})	Broadcast (kg ha^{-1})
0.00–0.25	2	10
0.25–0.50	2	10
0.51–0.75	1	5
0.75–1.00	0	0
1.01	0	0

The critical limits of DTPA extractable Zn vary from 0.38 to 2 mg kg^{-1} for different soils and crops (Table 4) [34]. Zn application is recommended when soils have available Zn level below the critical level. In this context Zn fertilizer recommendations for corn and some other crops in the state of Minnesota (USA) are worth taking note of (Table 5), because the Zn application recommendations are staggered on the basis of soil test and are not made simply on the basis of critical level.

Zn Deficiency Symptoms in Plants

Since Zn is associated with several enzymes, its deficiency leads to several disorders in plants. Also since Zn is relatively immobile in plants, its deficiency symptoms generally appear on the growing young tissue. The essentiality of Zn was first shown by Maze [14] in maize, where it is known as 'white bud'. As already pointed out, its deficiency in rice was first reported by Nene [15] at the G. B. Pant University of Agriculture and Technology, Pantnagar. In rice the characteristic symptoms are bronzing

Table 6 Relative tolerance of rice genotypes to Zn stress

Class	% Response to applied Zn	Genotypes
Highly susceptible	103–237	Sita, IR 36, Pankaj, Radha, Saket 4
Susceptible	40–78	Prabhat, SBR 3025
Moderately tolerant	12–20	Rajshree, RAU 1326-29-3-1, Kanka, Mashuri
Tolerant	5–10	TCA 177, Vaidehi

Table 7 Zn deficiency scores of some common IRRI rice cultivars at IRRI

Cultivar	Observations (Nos.)	Minimum score	Maximum score	SD
IR 42	159	1	9	1.78
IR 36	152	1	9	1.74
IR 20	47	3	9	1.82
IR 8	45	3	9	1.49
IR 54	35	3	9	1.16

Table 8 Relative tolerance of wheat genotypes to Zn stress

Class	% Response to applied Zn	Genotypes
Triticum aestivum		
Highly susceptible	27–29	PBW 343, WH 747
Moderately susceptible	11–28	WH 542, HD 2009, HD 2329, HP 1731
Less susceptible	7–10	UP 2338, WH 157
Triticum durum		
Highly susceptible	36–46	WH 912, PDW 215
Moderately susceptible	17–36	WH 896, PDW 233, HD 4502, MACS 2846
Less susceptible	13–17	Raj 1555, PBW 34

starting with young leaves and then spreading to other plant parts. The disease was given the name *Khaira* due to dark brown colour similar to *Khair*. In severe Zn deficiency, dark brown patches of stunted rice plants appear in the field. In wheat, bronzing is not so evident and necrosis in leaves and stunting are more obvious symptoms.

Critical Levels in Rice and Wheat Tissue

Yoshida et al. [41] established the following criteria (mg Zn kg^{-1} whole plant tissue DM) for Zn deficiency in rice: <10 definite deficiency, 10–15 very likely deficiency, 15–20 likely deficiency and >20 unlikely deficiencies. In India, Srivastava et al. [30] reported a critical limit of 23.6 mg kg^{-1} DW of the 3rd fully open leaf from the top at 60 days after transplanting for the rice cultivar Jaya, while it was 23 mg kg^{-1} DW for the rice cultivar PD-4. Thus, rice cultivars differ in their tolerance to Zn deficiency and a list of highly deficient to tolerant ones at Pantnagar are given in Table 6. Even intra-cultivar variations exist and IRRI has prepared a data base for this. Some data on popular IRRI rice cultivars are given in Table 7. The reasons for intra-cultivar include variation in the magnitude of the stress over space and time, genotype × environment variation, involvement of a large number of genes and low heritability of genes [20]. Wissuwa et al. [39] observed that native soil Zn status was an important factor in determining Zn concentration in rice grains and depending upon soil Zn status, grain Zn concentration could vary from 8 to 47 mg kg^{-1} grain in a single genotype.

As in rice, wheat cultivars also differ in their effectiveness in utilizing native soil Zn [4, 22, 29]. Some data from Pantnagar are in Table 8. In India Takkar et al. [34] gave a critical limit of 8–12 mg Zn kg^{-1} DW in whole tissue of wheat, while Srivastava et al. [30] reported a value of 18.4 mg Zn kg^{-1} DW in flag leaf at 60 days after sowing.

Response of Cereals to Zn Fertilization

Reviewing the data from several research centres in India, Rattan et al. [21] reported an average response (kg ha^{-1}) of 760 in rice, 670 in maize, 380 in wheat, 480 in sorghum and 210 in pearl millet. Similar but slightly lesser response of cereals to Zn fertilization was reported by Patel [16]. Based on these average responses of cereals to Zn Shukla and Behera [27] predicted that additional production due to Zn fertilization could be 11.86, 3.53, 1.3 Mt in rice, 0.28 Mt in sorghum and 0.19 Mt in pearl millet. Thus, total increase in cereal production in India due to Zn fertilization could be about 17 Mt, which is 7.6 % of the total cereal production in 2010–2011. Thus, adequate Zn fertilization can certainly help in increasing cereal production in the country.

Biofortification of Cereals with Zn

In view of the emergence of Zn as an important nutritional problem, especially in the developed countries, the need for genetic biofortification of cereals by developing cultivars with higher Zn (and other micronutrients) contents in

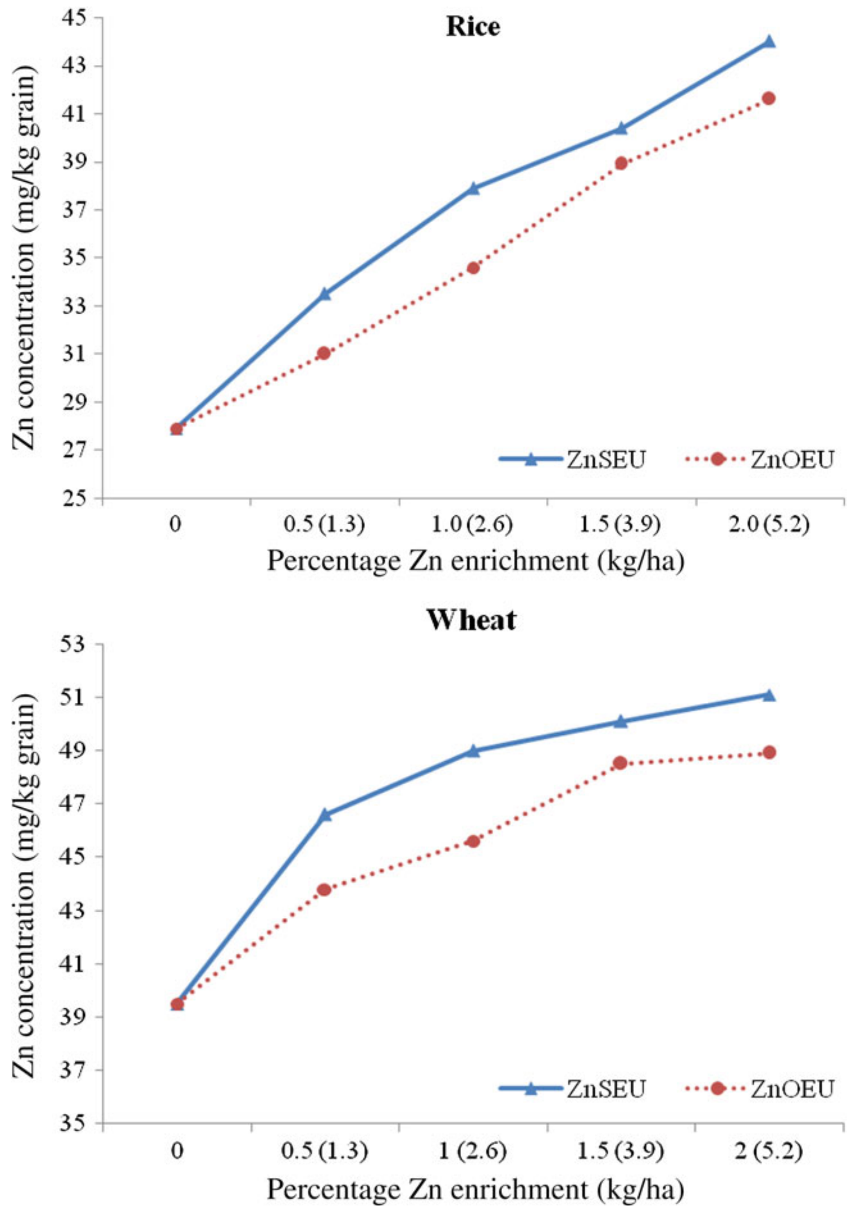

Fig. 4 Grain Zn concentration in rice and wheat due to degree of Zn enrichment of urea. *Solid lines* for Zn sulphate (ZnSEU) and *dotted lines* for Zn oxide enriched urea (ZnOEU)

grains was mooted by Graham [10]. Their findings led to the development of programmes such as HarvestPlus, Golden Rice and African Biofortified Sorghum Project focusing on the development of crop varieties capable of producing grains higher in Zn and other micronutrients contents [31]. Such programmes require fairly long time and so far no Zn rich cultivar in any cereal has become available. Further such cultivars may not be high yielding. Combining high grain yield and high Zn concentration in grain needs still more time. Also the produce from newly developed cultivars may not be acceptable to consumers, who have their own preferences.

On the contrary agronomic biofortification through Zn fertilization (also referred to as ferti-fortification) results in increased grain production as well as higher Zn concentration in grains at the same time [19]. Even cultivars developed by genetic biofortification will need Zn fertilization.

Work on agronomic biofortification of cereals (rice and wheat) in India was started by our group at the Indian Agricultural Research Institute, New Delhi with the availability of zinc enriched urea using zinc sulphate or ZnO from a fertilizers company. Grain yield of rice as well as wheat increased as the degree of Zn enrichment of urea was increased from 0.5 to 2.0 % (equivalent to an application of 1.3–5.2 kg Zn ha^{-1}). Zn enrichment of urea @2 % Zn as zinc sulphate increased the grain yield of rice by 29.4 % and that of wheat by 19.1 %. As compared to the grain yield the increase in grain Zn concentration was much more. Zn enrichment of urea @2 % Zn as zinc sulphate increased the grain Zn concentration by 61.8 % in rice and by 51.1 % in wheat; the actual value (mg Zn kg^{-1} grain) was 47.4 % with Zn fertilization and 29.3 % without Zn in rice (Fig. 4). The corresponding value (mg Zn kg^{-1} grain) in wheat was 51.1 with Zn fertilization and 39.5 without Zn. Zn sulphate was better than ZnO for Zn enrichment of urea, both in respect of grain yield as well as grain Zn concentration. This was mainly due to zinc sulphate being water soluble, while ZnO is not water soluble. Westfall and Gangloff [38] reported that the effectiveness of six granulated Zn fertilizers decreased as the per cent water soluble Zn decreased in them and they observed that at least 50 % water soluble Zn was desirable. To achieve this Zn fertilizer manufacturers in USA are using a mixture of ZnO and zinc sulphate for enriching fertilizers with Zn. Such fertilizers are referred to as Zn oxysulphates.

Hossain et al. [12] from Jessore (Bangladesh) reported that Zn application increased grain Zn concentration in maize by 73 % and in rice by 141 %. The actual values (mg Zn kg^{-1} grain) for maize were 28.4 for Zn fertilized (@4 kg ha^{-1}) crop as against 16.5 for no Zn control. Similarly, the grain Zn concentration (mg Zn kg^{-1} grain) in rice was 50.0 for Zn fertilized (@2 kg Zn ha^{-1}) crop as against 20.7 for no Zn control.

Yang et al. [40] from Yangling (China), reported that soil Zn application had mixed effect in increasing grain Zn concentration in wheat; it increased by 21 % in some cultivars, while it decreased it in other cultivars. However, foliar application of Zn increased grain Zn concentration in all wheat cultivars ranging from 26 to 115 %. Grain Zn concentration in wheat ranged from 33.3 to 59.7 %. Dhaliwal et al. [5] from Ludhiana also reported a significant increase in grain Zn concentration due to foliar application of 0.5 % zinc sulphate solution. The cultivars, however, differed in their response to foliar Zn application; the increase was 44.8 % in PR 116, 42.4 % in PR 115, 40.6 % in PR 114, 39.3 % in PASU 201 and 30.8 % in PR 113. The Zn concentration in rice grain was 47 % in Zn fertilized crop as against 33.8 % in no Zn control.

Yang et al. [40] also reported that application of Zn reduced phytate concentration and phytate:Zn molar ratio in wheat grain. The actual values for phytic acid were 8.13 g kg^{-1} grain as against 7.01 in unfertilized crop. Zn fertilization reduced phytate:Zn molar ratio from 23.38 in unfertilized crop to 13.74 and this brought the phytate:Zn molar ratio in Zn fertilized wheat below the level of 15, above which the bioavailability of Zn is reduced [9].

Conclusions

- This review brings out that agronomic biofortification is an effective and faster method for increasing grain Zn concentration in cereals.
- Since cereals are staple food in most developing countries in Asia including India, Zn fortification of cereal grains benefits all including the poorest of the poor.
- Zinc fertilization has great relevance to India, because about half of its soils are deficient in available Zn.

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