Role of Agronomic Biofortification in Alleviating Malnutrition

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Article History

Article ID: IJEP61
Received in 7th August, 2015
Received in revised form 18th August, 2015
Accepted in final form 25th August, 2015

Abstract

Introduction of high yielding crop varieties in mid sixties brought a stirring 'Green Revolution' that remarkably enhanced the agricultural production and made country self sufficient in food grain production. But in the process, it caused a greater depletion of soil fertility and soon deficiency of micronutrients especially that of zinc (Zn) and iron (Fe) cropped up in many areas. This led to Zn and Fe deficiencies in human and animal health and also an important soil constraint to efficient crop production. Generally, there is a close geographical overlap between soil deficiency and human deficiency of Zn and Fe, indicating a high requirement for increasing concentrations of micronutrients in food crops. Breeding new plant genotypes for high grain concentrations of Fe and Zn (genetic biofortification) is the most cost-effective strategy to address the problem; but, this strategy is a long-term process. A rapid and complementary approach is therefore required for biofortification of food crops with Zn and Fe in the short-term. In this regard, a fertilizer strategy (agronomic biofortification) represents an effective way for biofortification of food crops. In this review paper, several examples are presented showing that application of Zn fertilizers greatly contribute to biofortification of cereal and pulse grains with Zn to alleviate this micronutrient deficiency from the human population.

Keywords: Agronomic biofortification, chickpea, corn, iron, oats, rice, wheat, zinc

1. Introduction

Good nutrition is fundamental to human health and wellbeing, yet according to the latest estimates from the UN Food and Agriculture Organization (FAO), about 805 million people—more than a tenth of the world's population—remains chronically undernourished. In 2013, globally 161 million children younger than 5 years were affected by stunting, and 51 million by wasting. Undernourishment is the main underlying cause of death in this age group, accounting for 45% of child deaths worldwide. Meanwhile, globally more than 2 billion people are affected by deficiencies of micronutrients such as iodine, vitamin A, zinc, and iron (Editorial 15 November 2014. The Lancet 384(9956):1721.). In countries with a high incidence of micronutrient deficiencies, cereal-based foods represent the largest proportion of the daily diet (Cakmak et al., 2010a; Bouis et al., 2011). The Harvest-Plus initiative of the CGIAR consortium is working with national and international partners to alleviate deficiencies of these mineral nutrients by biofortifying staple food crops with essential minerals and vitamins; an approach considered to be the most economical solution to human micronutrient deficiency (Welch and Graham, 2004; Bouis, 2007; Cakmak, 2008; Peleg et al., 2009).

Low dietary intake of Fe and Zn appears to be the major reason for the widespread prevalence of Fe and Zn deficiencies in human populations. In countries with a high incidence of micronutrient deficiencies, cereal-based foods represent the largest proportion of the daily diet (Cakmak, 2008). Cereal crops are inherently very low in grain Zn and Fe concentrations, and growing them on potentially Zn- and Fe-deficient soils further reduces Fe and Zn concentrations in grain (Cakmak et al., 2010a). Thus, biofortification of cereal crops with Zn and Fe is a high-priority global issue. Harvest-Plus (www.harvestplus.org) is the major international consortium to develop new plant genotypes with high concentrations of micronutrients by applying classical and modern breeding tools (i.e. genetic biofortification). The biofortification program is focusing on three micronutrients that are widely recognized by the World Health Organization (WHO) as limiting: iron, zinc, and vitamin A. Full-time breeding programs is under way for six staple food crops viz. rice, wheat, maize, cassava, sweet potatoes, and common beans. Pre-breeding feasibility studies are proposed for eleven additional staples: bananas, barley, cowpeas, groundnuts, lentils, millet, pigeon peas, plantains, potatoes, sorghum, and yams. Although plant breeding is the most sustainable solution to the problem, developing new micronutrient-rich plant genotypes is a protracted process and its effectiveness can be limited by the low amount of readily available pools of micronutrients in soil solution (Cakmak, 2008). Application of Zn- and Fe-containing fertilizers (i.e. agronomic biofortification) is a short-term solution and represents a complementary approach to breeding, which need to be taken on priority at the global level to overcome these two essential micronutrients nutrients deficiency in the food chain.

2. Agronomic Biofortification of Cereal and Pulse Grains

Essentiality of Fe in plants was reported by Sachs in 1860, while that of Zn was established by Maze' in 1916 (Bell and Dell, 2008). Zn deficiency was later reported in citrus in the United States (Chapman et al., 1940). A number of reviews on Zn in crop nutrition are available (Alloway, 2008). In India, Zn deficiency was first reported in rice by Nene (1966), and was followed by that in wheat in Punjab. Research on Zn in relation to crop production in India has been thoroughly reviewed (Katyal and Rattan, 2003; Prasad, 2006; Shukla et al., 2012). However, most work on Zn fertilization was done from the viewpoint of increasing crop yield. Work on agronomic bio-fortification of wheat was started in Turkey by Cakmak (2004), while in India it was initiated on rice by the author of this review (Shivay and Prasad, 2012; Shivay et al., 2007, 2008a,b,c). Most information on biofortification of cereal grains with Zn is available on rice, wheat, oats and corn which are briefly reviewed.

1.1. Rice

2.1.1. Method of application

Zn could be applied to soil or foliage. The seed priming with Zn fertilizers and dipping of rice seedlings in Zn fertilizer solutions have been tested and recommended for increased yield, but no data are available on their effect on biofortification of rice grains. Shivay and Prasad (2012) from New Delhi showed that on Zn-deficient soils, application of Zn (as zinc sulfate heptahydrate or ZSHH) significantly increased grain yield of rice as well as Zn concentration in rice grain. Soil application of Zn also increased Zn harvest index by 2%, although this was not statistically significant.

Shivay et al. (2010a, b) also reported that foliar application of only 1.2 kg Zn ha^{-1} as compared with 5.3 kg Zn ha^{-1} as soil application gave similar grain yield of rice but higher Zn concentration in grain. Zn harvest index for soil and foliar application was similar, but agronomic efficiency of Zn with foliar application was about four times of that for soil application; rate of Zn application was much lower when applied on foliage. Dhaliwal et al. (2010) from Ludhiana, India, showed that averaged on five rice cultivars foliar-applied Zn (three sprays of 0.5% ZSHH solution) recorded a Zn concentration of 47.0 mg kg^{-1} grain in brown rice when compared with 33.8 mg kg^{-1} grain in no Zn check. They also reported a Zn concentration of 29.1 mg kg^{-1} husk in Zn-sprayed crop as compared with 25.2 mg kg^{-1} husk in no Zn check.

In a multi-location study in China, India, Lao PDR, Thailand, and Turkey, Zn concentration in unhusked rice grain was about 69% higher with foliar application than with soil application; at some centers, it was almost twice that of with soil application (Phattarakul et al., 2012). This study also provided data on relative Zn concentration in unhusked (whole grain with husk, known as paddy in India; most of the data on biofortifcation of rice are on unhusked rice.), brown rice (whole caryopsis with husk removed by hand), and white rice (outer layer of pericarpsis including pericarp, testa, mucella, and part of aleurone layer along with embryo removed by polishing for 30 s in a standard laboratory mill). White rice is also known as polished rice (the form in which rice is mostly consumed). When Zn is foliar applied, only 53–54% of that in unhusked rice is found in polished or white rice as compared with 84.8%, when Zn is soil applied (Table 1). However, when Zn is soil applied, brown rice may contain a little more than in unhusked rice. Thus, a greater portion of foliar-applied Zn remained in husk. These data support the viewpoint of Jiang et al. (2007) that in rice Zn absorbed from the root plays a major role, while mobilization from the leaves plays a minor role. Using the data of Phattarakul et al. (2012) as the base, it worked out that although unhusked rice contained 52.6% Zn, the polished rice from it is likely to contain only 28.8% Zn, when Zn was foliar applied in the study of Shivay and Prasad (2012). As a contrast, when Zn was soil applied in sufficient quantity, Zn concentration in unhusked rice was 47.5%, while it was 40.3% in polished rice. Total Zn uptake by polished rice was also higher with soil-applied Zn; of course, much more Zn was applied to soil (25 kg ha^{-1}) as compared with that on foliage (1.2 kg ha^{-1}). Biofortification recovery (BRE_{Zn}), the term suggested by Impa and Johnson-Beebout (2012), with foliar

Table 1: Grain yield and relative zinc concentration in unhusked, brown and white (polished) rice (averaged over 9 site-years in China, India, Lao PDR, Thailand and Turkey)

Character-istic	Control (no Zn)	Soil Zn	Foliar Zn	Soil+ foliar Zn	Signifi-cance
Grain yield (t ha^{-1})	6.7	7.0	6.9	7.0	NS
Zn in un-husked rice (mg kg^{-1})	18.7	19.1	32.3	34.7	$p<0.01$
Zn in brown rice (mg kg^{-1})	19.1 (102.1)^{a}	20.8 (108.9)	24.4 (75.5)	25.5 (73.5)	$p<0.01$
Zinc in pol-ished rice (mg kg^{-1})	16.1 (18.1)^{b} (84.2)c	16.2 (84.8) (77.9)	17.7 (54.8) (72.5)	18.4 (53.0) (72.1)	$p<0.01$

aZn in brown rice expressed as percentage of unhusked rice; bZn in polished rice expressed as percentage of brown rice; cZn in polished rice expressed as percentage of unhusked rice; From Phattarakul et al. (2012).

application was about eight times of that obtained with soil application. Saenchai et al. (2012) from Thailand reported that the decrease in Zn concentration on milling of rice ranged from 16.2% to 48.2% in rice genotypes, being more in long and slender grain types. The range of Zn (mg kg^{-1}) in polished rice was 9.6–40.2 (mean 20.6) when compared with 17.3–59.2 (mean 28.7) in brown rice.

2.1.2. Sources of Zinc

Shivay et al. (2008a,c,d) and Shivay and Prasad (2010) from New Delhi reported that ZNSHH-coated urea was significantly superior to ZnO-coated urea in increasing Zn concentration in unhusked rice (also in polished rice when calculated on the basis of Phattarkul's data). The superiority of ZSHH was also recorded in succeeding wheat (Shivay et al., 2008a,c,d); Zn was applied to rice only. Water solubility of zinc sources is considered as an important criterion for Zn availability (Slaton et al., 2005). Westfall and Gangloff (2001) observed that the effectiveness of six granulated Zn fertilizers decreased as the percent of water-soluble Zn decreased in them, and calculated that at least 50% water-soluble Zn was considered desirable. In the United States, Zn fertilizer manufacturers are producing mixture of zinc sulfate and ZnO, which are known as Zn oxysulfates. However, from the manufacturer's viewpoint, ZnO is easier to coat, because it forms a good emulsion with an oil. Kiekens (1995) suggested that ZnO, $Zn(OH)_2$, and $ZnCO_3$ are about 105 times more soluble than soil Zn and these materials could be used as fertilizers.

Naik and Das (2008) compared ZNSHH and Zn–EDTA for rice at Pakyong, Sikkim. ZSHH was applied at 10 and 20 kg ha^{-1} as basal or in two equal splits (half basal and the rest half at grand tillering stage). Zn–EDTA was applied at 0.5 or 1.0 kg ha^{-1} in single application as basal; 1 kg ha^{-1} was also applied in two equal splits. Zn concentration in rice grain was significantly more (30.3 mg kg^{-1}) with 0.5 kg ha^{-1} Zn–EDTA than with 10 kg ha^{-1} ZSHH (25.5 mg kg^{-1}). Split application was better than a single application in ZSHH but not in Zn–EDTA. Zn-EDTA was better than ZNSHH, but more expensive.

1.2. Wheat

Soil Zn deficiency in major wheat growing areas leads to inherently low grain Zn concentration and is considered as a major factor in low human Zn intake (Alloway, 2009). Compared to the breeding approach, agronomic biofortification (e.g. application of Zn fertilizers) represents a short-term solution to the problem (Cakmak, 2008). Soil Zn applications are, however, less effective in increasing grain Zn, while foliar Zn applications result in remarkable increases in grain Zn concentration in wheat (Cakmak et al., 2010a,b). By optimizing the timing and the solute concentration of foliar Zn application, wheat grain Zn concentration could be further increased, not only in whole grains but also in the endosperm (Cakmak et al., 2010b; Zhang et al., 2010). Most Zn fertilization studies have focused on increasing grain yield, though grain Zn concentration is also starting to be addressed (Cakmak, 2009). The various methods of Zn application may differentially influence yield and grain Zn concentration. Knowledge of the different forms of Zn fertilizer and timing of foliar Zn application is crucial for enhancing grain Zn. The most effective method for increasing grain Zn is the soil+foliar application method, which may result in an about 3-fold increase in grain Zn concentration (Cakmak et al., 2010a). When a high concentration of grain Zn is targeted, in addition to a high grain yield, combined soil and foliar application is recommended. Alternatively, using seeds with high Zn concentrations, together with foliar application of Zn, is also an effective way to improve both grain yield and grain Zn concentration. Applying Zn during the grain development stage contributes to increased grain Zn concentration (Zhang et al., 2010) as foliarly-applied Zn can be absorbed by the leaf epidermis and then transported to other plant parts via the xylem and phloem (Haslett et al., 2001). McGarth et al. (2012) reported from Rothamsted, UK, that sewage sludge application to soil can increase Zn concentration in wheat grain in non-calcareous soils, but not on a calcareous soil for at least 2–8 years after application and was similar in effectiveness to zinc carbonate.

The timing of foliar Zn application is an important factor determining its effectiveness in increasing grain Zn concentration; large grain Zn increases are most likely when foliar Zn fertilizers are applied to plants at a late growth stage. Ozturk et al. (2006) studied changes in grain Zn concentration in wheat during the reproductive stage and found that the highest concentration of grain Zn occurs during the milk stage of grain development. Foliar application of Zn during reproductive growth seems to be more effective in increasing grain Zn concentration than spraying of Zn at earlier growth stage. In addition to increasing the concentration of Zn in the whole grain, foliar application also increased the concentration in the starchy endosperm. The increased Zn in the starchy endosperm resulting from foliar application should also be highly bioavailable due to the low phytate content.

Among the different forms of Zn fertilizer that were tested, the application of Zn as $ZnSO_4$ was most effective in increasing grain Zn, compared to other forms of Zn. The HarvestZinc (www.harvestzinc.org) initiative has been investigating different fertilizer strategies and the most efficient Zn application method for promoting Zn uptake and maximizing grain Zn accumulation. Increasing grain Zn by soil and/or foliar applications also provides additional positive impacts in terms of seed vitality and seedling vigor. Priming seeds in Zn-containing solutions is an alternative way to increase seed Zn prior to sowing. High seed Zn concentrations ensure good root growth and contribute to better protection against soil borne pathogens (Cakmak, 2012).

1.3. Corn

Not much information is available on agronomic biofortification in corn. Small holder farmers in South Africa, Zimbabwe, and other African countries use very little amounts of chemical fertilizers and use of Zn fertilizers is a far cry. A study in Zimbabwe showed that the application of cattle manure (supplying 113 g Zn ha^{-1})+NPK and leaf litter (supplying 430 g Zn ha^{-1})+NPK significantly increased Zn concentration in corn grain over NPK (Manzeke et al., 2012). Shivay and Prasad (2014) reported that combined application of zinc as 5 kg Zn to soil + 1 kg Zn as foliar recorded the highest Zn concentration in corn grain as well as in stover. The different treatments studied in this experiment were in the following order: combined>foliar>soil through Zn-coated urea>soil to increase the zinc concentration in the corn.

1.4. *Oats*

In a recent study, Shivay et al. (2013) reported that coating Zn as ZnO or zinc sulfate onto oats grains at 2 kg per 100 kg (required for sowing 1 ha) recorded zinc concentration of about 32 mg kg^{-1} as compared with about 25 mg kg^{-1} obtained with soil application at the same rate of application. For soil application, zinc sulfate was better than ZnO.

1.5. *Chickpea*

In a recent study, Shivay et al. (2014) reported that application of Zn as soil or foliar through ZSHH or Zn-EDTA increased Zn concentration in grain and straw of chickpea. In the case of grain, 3 sprays of ZSHH recorded significantly more Zn in grain than soil application or 1 or 2 sprays. As regards, Zn-EDTA in both the years of study, application of 3 sprays recorded the highest Zn concentration (72.3%), significantly more than 2 sprays, which in turn recorded significantly more than a single spray or soil application (Table 2). The two sources of Zn differed significantly, when 2 or 3 sprays were made; Zn-EDTA recorded significantly higher Zn concentration in grain than ZSHH in both the years of study. With both the sources of Zn different methods of application were in the following order: 3 foliar sprays> 2 foliar prays>one foliar sprays or soil application; 3 foliar applications recording the highest Zn concentration in straw. When soil applied or a single foliar application was made, Zn-EDTA recorded significantly more Zn in chickpea straw than ZSHH, straw.

Table 2: Effect of sources, time and method of Zn application on Zn concentrations in grain, and straw of chickpea

Treatment	Zn concentration (mg kg grain^{-1})		Zn concentration (mg kg straw^{-1})	
	2011–12	2012–13	2011–12	2012–13
Control	37.5	36.3	14.8	13.5
NPK	42.6	41.4	18.3	17.1
NPK+ZSHH soil @ 5 kg Zn ha^{-1}	51.9	50.7	22.6	21.3
NPK+ZSHH, one spray	49.8	48.5	22.8	21.5
NPK+ZSHH, two sprays	54.7	53.4	27.1	25.8
NPK+ZSHH, three sprays	58.4	57.1	32.5	31.2
NPK+Zn-EDTA @ 2.5 kg Zn ha^{-1}	52.6	51.3	24.6	23.4
NPK+Zn-EDTA, one spray	51.2	50.1	25.1	24.0
NPK+Zn-EDTA, two sprays	58.1	56.7	28.3	27.1
NPK+Zn-EDTA, three sprays	72.3	63.5	33.9	32.6
SEm±	1.11	1.12	1.18	0.61
CD (p=0.05)	3.31	3.33	3.51	1.81

2. Conclusion

Agronomic biofortification is the easiest and fastest way for biofortification of cereals and pulses grains with Fe, Zn, or other micro mineral nutrients in developing Asian and African countries, where cereals are the staple food. From the biofortification viewpoint, foliar application is better and requires lesser amount of Fe and Zn fertilizers than their soil application. Agronomic biofortification will certainly help to overcome the malnutrition from the rural populace in India.

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