Role of Zinc Nutrition in Crop Production and Human Nutrition

Ismail Cakmak
Sabanci University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey

Introduction

Zinc Deficiency: A Global Nutritional Problem in Human Populations

Zinc (Zn) has particular physiological functions in all living systems, such as i) maintenance of structural and functional integrity of biological membranes, ii) detoxification of highly toxic oxygen free radicals and iii) contribution to protein synthesis and gene expression. Among all metals, Zn is needed by the largest number of proteins. Zinc-binding proteins make up nearly 10 % of the proteomes in eukaryotic cells, indicating that at least 2800 proteins are zinc dependent. About 36% of the eukaryotic Zn-proteins are involved in gene expression (Andreini et al., 2006). Its deficiency, therefore, results in diverse impairments in biological systems.

Zinc deficiency represents a common micronutrient deficiency problem in human populations, resulting in severe impairments in human health. Major health complications caused by Zn deficiency include impairments in brain function, weakness in immune system to deadly infectious disease and alterations in physical development. Zinc deficiency is known to be responsible for deaths of nearly 450,000 children under 5 years old annually (Black et al., 2008). Analyses made by a panel of 8 top-*economists* **(***including 5 Nobel Laureates) under the Copenhagen Consensus in 2008 (www.copenhagenconsensus.com) identified Zn deficiency, together with vitamin A deficiency, as the top priority global issue. Copenhagen Consensus concluded that elimination of the Zn deficiency problem in human populations will result in immediate impacts and high returns for humanity in the developing world.*

It is estimated that Zn deficiency affects, on average, one-third of the world's population, ranging from 4 to 73 % in different countries (Hotz and Brown, 2004). Low dietary intake is known to be the major reason for high incidence of Zn deficiency in human populations, particularly in the countries/regions where soils are low in available Zn, and cereal grains with low Zn concentration are the major source of calorie intake. Increasing Zn concentration of food crops is, therefore, an important challenge.

Soil Zinc Deficiency Represents an Important Constraint to Crop Production and Nutritional Quality of Grains

Nearly the half of the cultivated soils are affected from low levels of plant available Zn, especially calcareous soils of arid and semi-arid regions. Major soil factors *resulting in adverse impacts on solubility of Zn in soils include high pH, low organic matter, low soil moisture and high metal oxides with large fixing capacity for Zn (Fig. 1).*

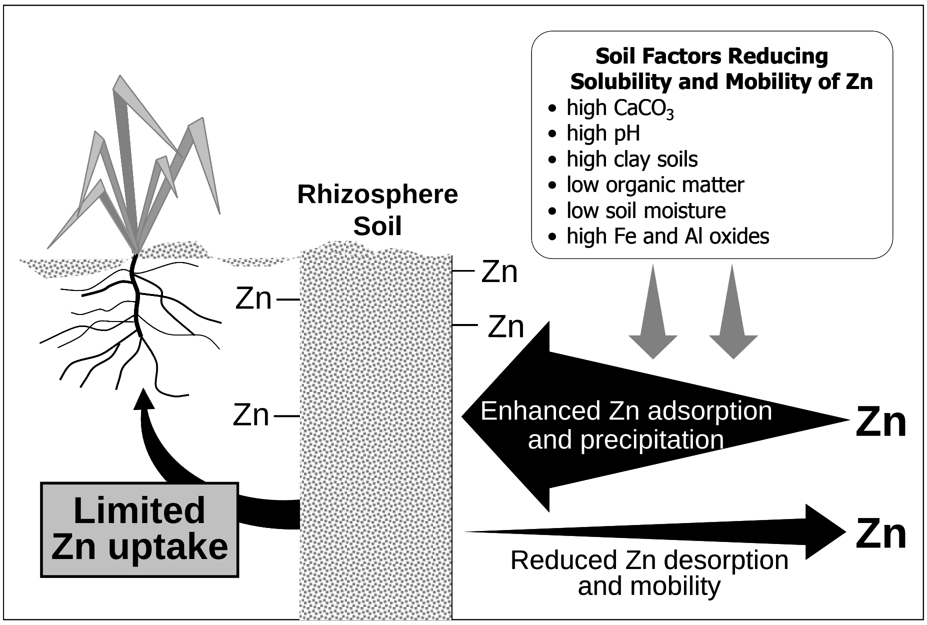

Fig. 1: Main soil factors affecting solubility and root uptake of Zn in soils (from Cakmak, 2008)

Since food crops, particularly cereal crops, are inherently low in grain Zn concentration, growing them on potentially Zn-deficient soils further reduces Zn concentration of food crops and thus dietary intake of Zn of human populations. Based on a range of reports and survey studies, the average concentration of Zn in whole grain of wheat in various countries range between 20 to 35 mg kg^{-1} (Rengel et al., 1999; Cakmak et al., 2004) which are not adequate for human nutrition with Zn. Same situation is also known for rice and maize which even contain much less Zn than wheat. In the case of Zn-deficient soils, the reported Zn concentrations for wheat are much lower and range between 5 to 15 mg kg^{-1} (Erdal et al 2002; Kalayci et al., 1999).

Soil Zn deficiency (i.e., low plant availability of Zn) has severe impacts on crop production. In certain regions with very low plant available Zn in soils (DTPA-Zn: around 0.1 mg kg^{-1}) cereal production is not economic with grain yields of 250 kg ha^{-1} and Zn fertilization is necessary to obtain a proper yield. As shown in Central Anatolia, application of Zn fertilizers in such soils enhances grain yield by a factor of 6 to 8 to around 2 000 kg ha^{-1}. In general, soils containing less than 0.5 mg DTPA-extractable Zn are considered potentially Zn deficient that may respond well to Zn fertilizers (Lindsay and Norvell, 1978). Low concentration of Zn in seeds has also *negative impacts on growth of plants in Zn deficient soils. Evidence is available showing that seedlings derived from seeds with low concentrations of Zn are highly susceptible to biotic and abiotic stress conditions during seed germination and early growth stages.*

These results indicate that improving Zn concentration of seeds/grains is also important for better agronomic performance of seedlings. Seeds with high nutrient density, especially with micronutrients, contribute greatly to better agronomic performance of seedlings besides its positive impacts on human nutrition. In future, a particular attention should be, therefore, paid to routine seed analyses for composition of mineral nutrients. Harvesting seeds with high nutrient density represent an important challenge.

Solutions to the Zinc Deficiency Problem

Currently, various strategies are being discussed to alleviate Zn deficiency related problems in human nutrition. Giving Zn supplements to the target populations or fortification of foods with Zn are considered as useful interventions against the problem. Although these approaches are very effective in reducing the extend of the problem, these interventions seem to be, however, not affordable long-term and not easily accessible by the target populations living in the rural parts of the developing countries. For example, 25 million USD is needed annually to eliminate micronutrient deficiencies in a nation with 50 million affected people by using food fortification program (Bouis et al., 2000).

Alternatively, agriculture offers simple and cost-effective solutions to the problem. Plant breeding and agronomy represent cost effective strategies to alleviate micronutrient malnutrition problem by increasing grain concentrations of micronutrients and their daily intake through diets (Pfeiffer and McClafferty, 2007; Cakmak et al., 2010a). It is well-documented that plant genotypes are highly different in utilization of poorly-soluble sources of micronutrients in soils and translocation of micronutrients into grain (Cakmak, 2002; White and Broadley, 2009). For example in case of Zn, genotypes of a given food crop species show impressive genetic variation for Zn accumulation in grain, especially wild and primitive forms of food crops. Such large natural variations in seed concentrations of Zn can be exploited under breeding programs to improve modern cultivars with high concentrations of Zn (e.g., genetic biofortification). The genetic biofortification strategy is a highly promising, cost-effective and long-term solution to Zn deficiency problem in human populations. Currently, impressive progress is being made under different breeding programs in improving stable food crops with high concentrations of micronutrients, especially under HarvestPlus program (www.harvestplus.org), which is established under the Consultative Group on International Agricultural Research. Harvest Plus program uses plant breeding tools to improve stable food crops with Zn, Fe and vitamin A and *to contribute to human health globally. The main sponsor of this global program is Bill and Melinda Gates Foundation.*

Agronomy and Plant Mineral Nutrition

Developing new Zn-dense genotypes by using plant breeding approach takes, however, a long time, and the impact and success of a breeding program depend on sufficient amount of readily available pools of Zn in soil solution (Cakmak, 2008). High Zn deficiency incidence in human populations are observed mainly in the regions where soils are very low in plant available (chemically soluble) Zn. Majority of cereal-cultivated soils globally have number of adverse soil chemical factors (i.e., high pH values, low soil moisture and low organic matter) that can potentially diminish the expression of high grain Zn trait and limit the capacity of newly developed (biofortified) cultivars to absorb adequate amount of Zn from soils and accumulate in grain. For example, among the soil chemical factors, soil pH plays a decisive role in chemical solubility and root uptake of Zn. In a pH range between 5.5 and 7.0, Zn concentration in soil solution is decreased up to 45-fold for each unit increase in soil pH. This increases risk for inducing Zn deficiency problem in plants and leading to low yield and simultaneously low Zn concentrations in grain (Marschner, 1993).

Increasing cultivation of high-yielding cultivars may further contribute to the extent of Zn deficiency in soils by progressively depleting available soil-Zn pools. This depletion of available Zn pools by large off-take in agricultural produce may occur to a greater extent in soils with low Zn solubility. Intensification of farming by introducing high-yielding cultivars contributes not only to Zn depletion in the soil but also to dilution of Zn in the harvested parts of plants such as in seeds/grains (Cakmak, 2008). Increasing evidence is available showing that selection of modern cultivars with high yield capacity over more than 100 years caused clear decline in grain concentrations of minerals, especially micronutrients (Garvin et al., 2006; Fan et al., 2008)

Zinc Fertilizer Strategy for Improving Yield and Grain Zn Concentrations

A short-term and complementary solution is, therefore, required to alleviate Zn deficiency related problems in human populations. In this regard, agronomy (e.g., fertilizer strategy) offer quick and effective practices to biofortify food crops with Zn at desirable levels. Fertilizer strategy simultaneously also contributes to better yield depending on the secerity of soil Zn deficiency.

Increasing chemical solubility of Zn in the rhizosphere by adding different organic amendments into soils, shifting from monocropping into intercropping systems, and applications of Zn fertilizers to soil and foliar are well-documented agricultural strategies which can significantly contribute to root uptake and grain density of Zn (Cakmak, 2008; Zuo and Zhang, 2009). It has been well-documented that addition of different organic materials into soils as compost or farmyard manures greatly contributes to solubility and spatial availability of Zn and also the total amount of plant-available Zn concentrations (e.g., DTPA-extractable Zn) in soils (Srivastava and Sethi, 1981; Arnesen and Singh, 1998; Asada et al., 2010). Existence of a strong positive relationship between soil organic matter and soluble Zn concentrations in rhizosphere soil was reported in a study of 18 different soils collected in Colorado (Catlett et al., 2002), indicating importance of organic matter in improving spatial availability of Zn to plant roots (Marschner, 1993). In the case of biofortification of dicots with micronutrients, intercropping dicots together with cereal species is a very useful practice as presented in Fig. 2. Iron concentration in different parts of peanut plants is significantly increased by intercropping with maize plants, possibly due to the root-induced changes in solubility of micronutrients and/or increases in biological activity in the rhizosphere (Zuo and Zhang, 2009).

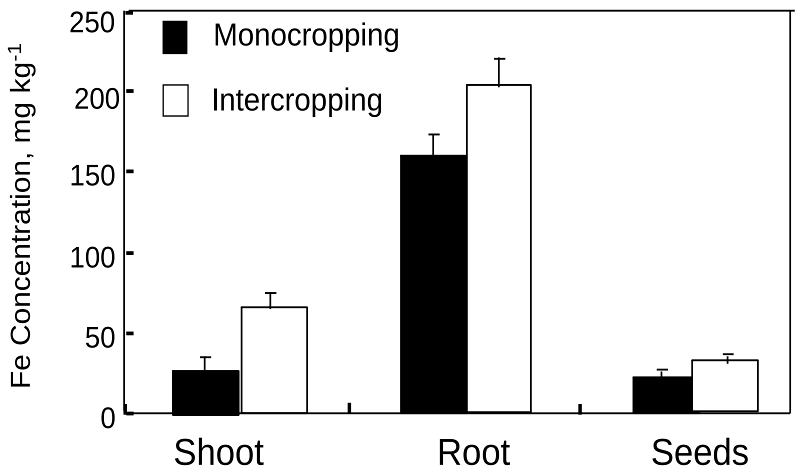

Fig. 2: Effect of intercropping peanut with maize plants on Fe concentration of shoot, roots and seeds of peanut plants grown on a calcareous soil (Zuo and Zhang, 2009).

Application of Zn fertilizers or the NPK fertilizers containing Zn represent a useful and quick approach to improving concentrations of Zn in food crops. Zinc can be directly applied to soil as both organic and inorganic compounds. Zinc sulfate ($ZnSO_4$) is the most commonly applied inorganic source of Zn due to its higher solubility and lower cost. Zinc can also be applied to soils in form of ZnO and Zn-oxysulfate (Mordvedt, 1991; Martens and Westermann, 1991). A factor affecting the selection of the source of Zn fertilizers is how uniformly they can be applied to soil. To ensure uniform application of Zn into soil, Zn can be incorporated into, or coated on, the granular N-P-K fertilizers. In India, urea is most commonly applied N fertilizer, and suggested to be good option for the enrichment with Zn. In various field tests conducted with wheat and rice in India it has been demonstrated that enrichment urea fertilizer with Zn up *to 3 % improved significantly both grain yield and grain Zn concentration (Table 1). In these experiments, ZnO and ZnSO4 have been used to enrich urea with Zn, and both Zn sources were similarly effective in improving grain Zn concentrations, although ZnSO4 always tended to be better than ZnO in increasing grain Zn and improving yield (Shiway et al., 2008).*

Table 1: Effect of Zn-enriched urea (ZEU) on grain yield and grain Zn concentrations of aromatic rice grown under field conditions in India (Shivay et al., 2008)

Treatments	Zn Added	Grain Yield	Grain Zn Concentration
	kg ha^{-1}	ton ha^{-1}	mg kg^{-1}
Prilled Urea	-	3.87	27
0.5% ZEU	1.3	4.23	29
1.0% ZEU	2.6	4.39	33
2.0% ZEU	5.2	4.60	39
3.0% ZEU	7.8	4.76	42

In the Central Anatolia, where Zn deficiency is a well-documented problem in Turkey, soil application of Zn fertilizers significantly increased both grain yield and grain concentrations of Zn (Fig. 3). Combined application of soil and foliar Zn fertilizers are more effective in enhancing grain Zn concentration, and causes increases in grain Zn concentration up to 3-fold (Cakmak et al., 2010a,b).

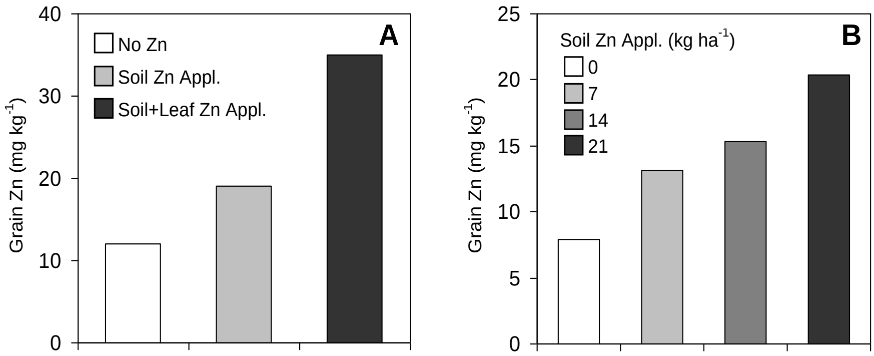

Fig. 3: Grain Zn concentrations of durum wheat treated by soil and foliar application of $ZnSO_4$ (A) and increasing amount of Zn fertilization into soil (B) grown on a highly Zn-deficient calcareous soil under field conditions in Central Anatolia (Cakmak et al., 2010a)

The effect of soil-applied Zn fertilizers on grain Zn concentration is not sufficiently high in soils with adequate amount of plant available Zn. Under such conditions, foliar application of Zn fertilizers is an essential practice in order to improve grain Zn concentration of cereal crops at adequate amounts for a better human nutrition. Martens and Westermann (1991) reported 0.5 to 1.0 kg Zn ha^{-1} as the most commonly used rates of Zn in foliar applications to correct Zn deficiency in plants. . Foliar application of Zn fertilizers can be performed by using either $ZnSO_4$ or chelated forms of Zn (e.g., Zn-EDTA). Our recent results show that ZnSO4 is a better Zn source in increasing grain Zn concentration when compared to ZnEDTA and ZnO when sprayed to foliar in wheat (unpublished results; see also Cakmak, 2008).

Timing of Zn spray on foliage plays an important role in effectiveness of the foliarly applied Zn fertilizers in increasing grain Zn concentration (Cakmak et al., 2010b). As discussed by Cakmak (2008) particular increases in Zn deposition into grain can be achieved when foliar Zn fertilizers are applied to plants at a late growth stage. Ozturk et al. (2006) monitored changes in Zn concentration in wheat grain during the grain development and found that the highest accumulation of Zn in grain takes place during the milk stage of the grain development. In a recently published study it has been shown that foliar spray of Zn late in the growing season in wheat (e.g., at milk and dough stage) resulted in much larger enhancement in grain Zn concentration when compared to the applications of Zn at earlier growth stages (Table 2).

Table 2: Zinc concentrations of the whole grain and the bran, embryo and endosperm fractions of the wheat grown under field conditions with foliar Spray of 0.5% $ZnSO_4.7H_2O$ at different growth stages in the Konya (a Zn-deficient location) and Samsun locations in Turkey (from Cakmak et al. 2010b)

	Zn concentration (mg kg^{-1})							
	Konya				Adana			
Foliar Zn Treatment Stages	Whole Grain	Bran	Embryo	Endosperm	Whole Grain	Bran	Embryo	Endosperm
Control (No Zn appl.)	12	20	38	8	32	42	70	11
Stem + Booting	19	28	47	10	51	72	96	15
Milk + Dough	25	41	63	15	57	88	98	16

Increases in concentration of whole grain Zn associated with late foliar Zn applications were also well reflected in various grain fractions such as embryo, aleurone and endosperm. The increases found in concentration of endosperm Zn through Zn spray during the reproductive growth stage were particularly impressive

(Fig. 4). These increases in endosperm Zn concentration may have important impacts on human nutrition, because the endosperm part is the most commonly eaten part of wheat in number of countries where Zn deficiency incidence in human populations is very high.

Nitrogen nutritional status of plants has also positive impacts on grain concentration of Zn. Increase in grain Zn concentration by applying soil and/or foliar Zn fertilizers is maximized when the N nutritional status of plants is improved either by soil or foliar application of N fertilizers (e.g., urea) (Kutman et al., 2010, 2011). It seems that N and Zn act synergistically in improving grain Zn concentration in wheat when Zn and N are sufficiently high in growth media or plant tissues. Most probably, improving N nutritional status of plants contribute to better root Zn uptake and/or Zn accumulation in grain by affecting at least one of the following processes: i) root exudation of compounds contributing to solubility and uptake of Zn (e.g., phytosiderophores), ii) root growth and morphology, iii) abundance and expression of transporter proteins mediating uptake and transport of Zn in root cells, iii) nitrogenous compounds contributing to mobility and transport (and retranslocation) of Fe and Zn by chelation (e.g., nicotianamine, amino acids) and iv) increasing amount of seed proteins which bind/store Zn. The positive impacts of N nutrition on grain Zn indicate that an increasing attention should be paid to N management in cultivation of food crops and in establishing breeding programs for an effective biofortification of grains with Zn.

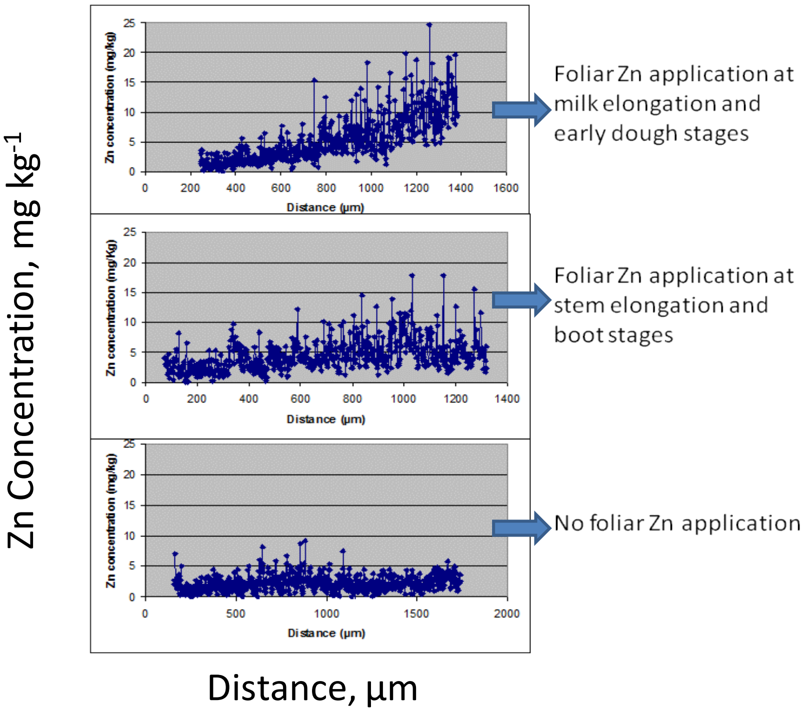

Fig. 4: Changes in Zn concentrations of endosperm part of bread wheat grains harvested at the Adana locations in Turkey. Grains subjected to laser ablaited-ICP-MS analysis were from plants which were either not treated (no foliar Zn application) or treated with foliar spray of $ZnSO_4$. $7H_2O$ at the stem elongation and booting or at the milk and dough stages. For further details see Cakmak et al. 2010b.

Agronomic Benefits Resulted from Zn Fertilization

Increasing seed concentration of micronutrients by soil and/or foliar applications of Zn also provides additional positive impacts in terms of seed vitality and seedling vigour. As reviewed by Welch (1999) when seeds with low concentration of Zn are sown, the ability of the new crop to withstand environmental stresses at the early growth stages is greatly impaired. Plants emerging from seeds with low Zn have poor seedling vigor and field establishment on Zn-deficient soils. Under rainfed conditions, wheat plants derived from seeds containing 1.5 µg Zn per seed had better seedling establishment and 2-fold higher grain yields than the wheat plants that emerged from seeds containing only 0.4 µg Zn per seed (Yilmaz et al., 1998). Similarly, Rengel and Graham (1995) showed that increasing seed-Zn contents from 0.25 µg per seed to 0.70 µg per seed significantly improved root and shoot growth of wheat plants under Zn deficiency. Priming seeds in Zn-containing solutions is an alternative way to increase seed Zn prior to sowing (Harris et al., 2007). High Zn concentrations in seeds ensure good root growth and contribute to better protection against soil-borne pathogens.

Conclusions

Improving Zn nutritional status of food crops by applying soil and/or foliar Zn fertilizers offers a practical and rapid solution to the well-documented Zn deficiency problem in human populations. In the target countries with high incidence of Zn deficiency, new fertilizer policies should be developed to promote application of Zn containing fertilizers to soil and/or foliar for a quick biofortification of food crops with Zn. The returns associated with Zn fertilization of food crops are expected to be very high with significant impacts on humanity and also crop production.