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Review Article

Increasing grain zinc and yield of wheat for the developing world: A Review

Shahid Hussain*, Muhammad Aamer Maqsood and Rahmatullah

Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad-38040, Pakistan

Abstract: Hunger and zinc (Zn) malnutrition are major health risk factors in the developing countries. Wheat is a major staple food in the world but it is inherently low in grain Zn concentration especially when grown on Zn deficit calcareous soils. Therefore, producing Zn enriched wheat grains at the farmers' fields is the best solution against human Zn deficiency. Biofortification approaches include selection, improvement and management of cultivated wheat genotypes to ensure optimum grain Zn concentration for human consumption. Soil and foliar application of Zn to wheat grown on Zn deficient soils enhances both the grain yield and grain Zn concentration. Genotype screening for higher grain yield and grain Zn concentration is prerequisite to ensure adoptability of poor farmers to newly developed genotypes for Zn biofortification. Conclusively, simultaneous consideration of grain yield and grain Zn concentration of wheat is the sustainable and economical approach to achieve our food targets.

Keywords: biofortification, developing countries, grain yield, wheat, zinc deficiency

زيادة عنصر الزنك بالحبوب وإنتاج القمح للدول النامية – ورقة استعراضية

شهيد حسين* ، محمد عامر والمقصود و رحمة الله

معهد التربة وعلوم البيئة ، جامعة الزراعة ، فيصل آباد ، 38040 ، باكستان

الملخص: الجوع والزنك كسوء التغذية يشكلان أهم المخاطر الصحية التي تواجه البلدان النامية، يعتبر القمح الغذاء الرئيسي في كبرى دول العالم ولكن يتلازم ذلك مع الانخفاض في تركيز عنصر الزنك خاصة عندما يزرع في الأراضي ذات التربة الجيرية التي تعانى من انخفاض في عنصر الزنك ولذلك فإنتاج الزنك بمحصول القمح على مستوى حقول المزارعين، هي أفضل الحلول لمكافحة نقص عنصر الزنك عند الإنسان. ولضمان وجود عنصر الزنك في محصول القمح للاستهلاك البشرى يجب اختيار أفضل الوسائل الحيوية كالانتخاب وتحسين السلالات وإدارة محصول القمح المزروع. وجد أن الإضافات بواسطة الأوراق أو التربة لعنصر الزنك في القمح المزروع من التطبيقات الهامة خاصة التربة قليلة عنصر الزنك حيث وجدت أنها تعزز زيادة المحصول وزيادة عنصر الزنك في القمح. إن إجراء المسح الوراثي لسلالات محصول القمح والحبوب لأعلى تركيز ذلك هو شرط مهم لضمان تبنيها من قبل المزارعين الفقراء مقارنة بالحبوب المحسنة وراثيا بعنصر الزنك المحصن وراثيا في القمح وتوفير حبيبات عنصر الزنك لمحصول القمح تعتبر نهجا مستدام واقتصادي لتحقيق أهدافنا الغذائية.

* Corresponding Author, Email: id.hussain@yahoo.com

Introduction

Population of developing countries is rising more drastically than world's average population growth rate of 1.8% (Population Division, 2009). The increasing problem of food scarcity in the developing countries requires another food revolution (Huang et al., 2002). Currently, about 65% of world's total population is starving (Food Security Statistics, 2008). Malnutrition (improper diet and nutrition) and especially the under nutrition (inadequate nutrition) arises among the poor where food supply and diversification are lacking. The developing world is also under severe threat of micronutrient malnutrition as their major sources of daily calorie intake are from cereal grains low in essential nutrients.

World Health Organization reported deficiencies of Zn, iron and vitamin A in human population of developing countries. Human Zn deficiency is the fifth major cause of diseases and deaths in these countries (WHO, 2002). Around the world, 2.7 billion people are Zn deficient (WHO, 2002; Muller and Krawinkel, 2005). About 50% of world's population is under risk of Zn deficiency and prevalence is more in developing countries of Asia and Africa (Figure 1). Bhutta et al. (2007) reported that almost every third child and 40% of the mothers in Pakistan are suffering from Zn deficiency.

Required Zn intake depends on gender and growth stage. Generally, it is 10 mg Zn d^{-1} for adult women and 12 mg Zn d^{-1} for adult men. However, women during pregnancy and lactation require up to 14 mg Zn d^{-1}. These intake levels are generally not fulfilled in developing countries due to high reliance on Zn poor cereal grains for their daily calorie intake (Bouis and Welch, 2010). Supplementation, food diversification /modification and fortifications were previously suggested to solve Zn deficiency in humans. The recently devised approach to correct human Zn deficiency is biofortification. Genetic and agronomic approaches of biofortification are meant to increase bioavailable amounts of Zn in edible plant parts (White and Broadley, 2009). Molar ratio of phytate:zinc is an important parameter for evaluating Zn bioavailability as phytate-zinc complex is not available for human absorption.

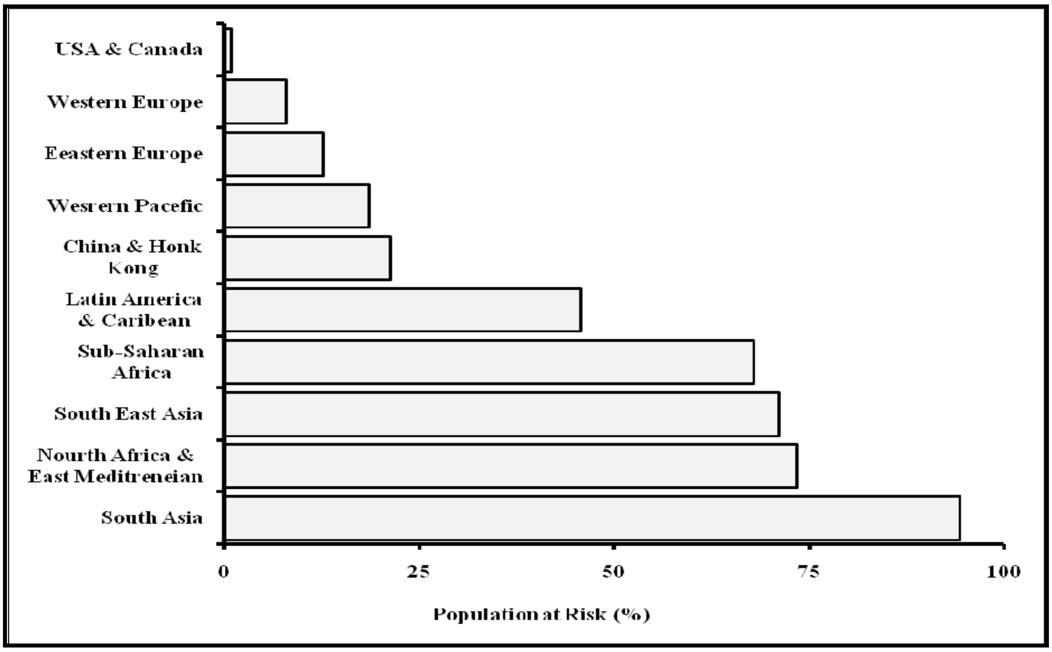


Figure 1. Population (%) at risk of zinc deficiency (modified from Brown et al., 2001).

The population with severe Zn deficiency is eating cereal grains produced on Zn-deficient soils (Figure 2), for example in India, Pakistan, China, Iran and Turkey (Alloway, 2008). Cereals, wheat and rice in particular, grown on these soils suffer from Zn deficiency. Grain-yield reduction > 50% along with reduced grain Zn concentrations have been observed under Zn deficiency (IZA, 2009). The soil conditions responsible for Zn deficiency in crops are low or high pH, high calcium carbonate contents, salinity, high phosphate status or application and prolonged water logging (Alloway, 2009). The extent of Zn deficiency in humans and staple food crops varies among regions. Soil types, resources, land holding, capital and many other factors have a strong influence on region specific approaches for biofortification.

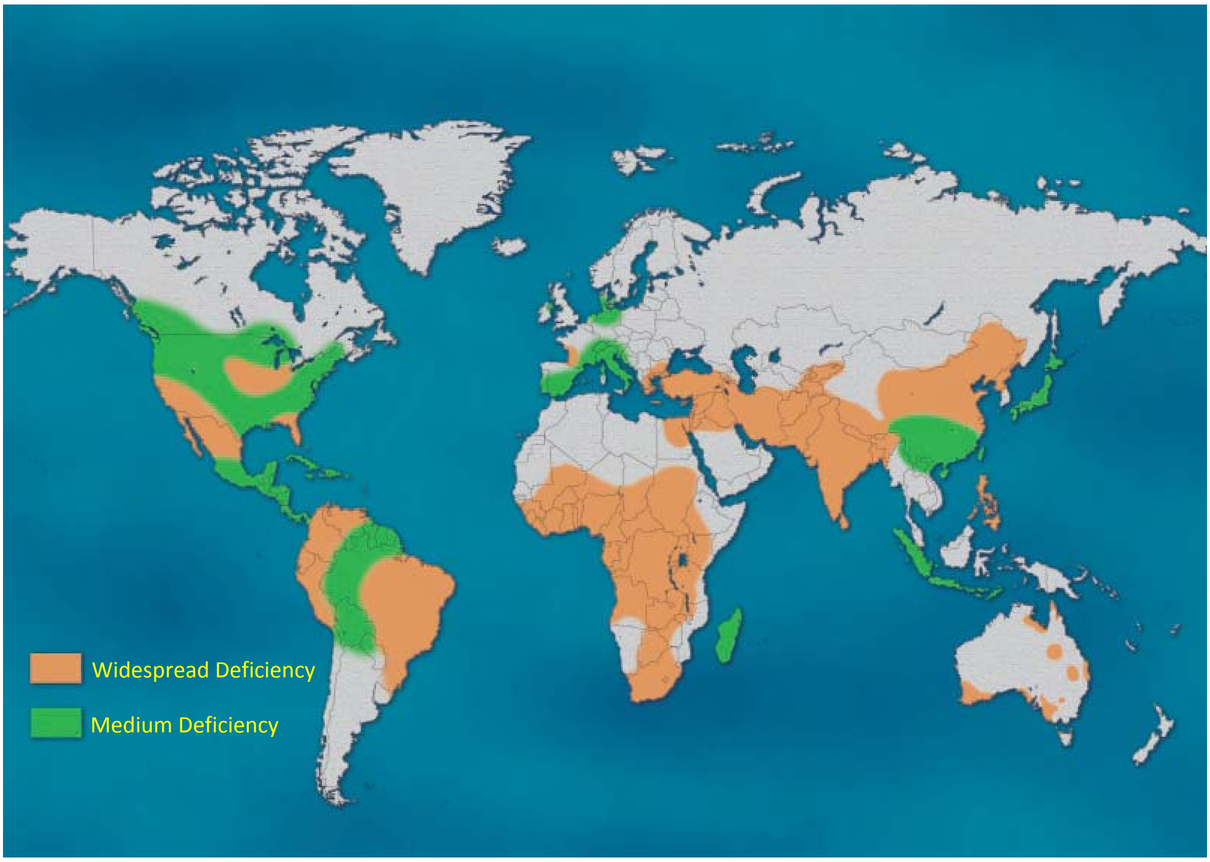


Figure 2. Soil zinc deficiency in the world (Alloway, 2008).

Wheat is consumed as a major staple food in the world and its demand is increasing with ever increasing population. Wheat breeders are developing genotypes for Zn biofortification, particularly under *Harvestplus* program of Consultative Group on International Agricultural Research. However, grain nutrient contents are often negatively correlated with grain yield. Developing countries are under high risk of hunger and hence cannot compromise on grain yield for Zn biofortification. To produce optimum grain yield of wheat with higher grain Zn concentration, application of Zn fertilizer seems mandatory. Despite significant wheat response of Zn application (Sillanpää, 1990), poor farmers are not applying this vital nutrient to their Zn deficient soils. Wheat genotypes are extensively sorted for Zn efficiency although, this does not ensure higher grain Zn concentration (Kalayci et al., 1999; Torun et al., 2000). Therefore, breeding for biofortification needs a new genotype screening criteria. It is proven fact that higher phytate:zinc molar ratio reduces Zn bioavailability to humans. Unfortunately, status of phytae:zinc molar ratios in grains of wheat genotypes and its relation with grain yield has not been established.

Considering food hunger and Zn malnutrition in the developing world, current review discusses Zn biofortification of wheat grain with grain yield. Fertilizer, rates and farmer friendly methods of Zn application for biofortification are conversed. Genotype screening for biofortification is suggested. Although similar approaches could also be recommended for other staple food cereals, only wheat is discussed in detail.

Biofortification of wheat grains with zinc

Hexaploid or bread wheat (*Triticum aestivum* L.) and tetraploid or durum wheat (*Triticum durum* L.) are the wheat genotypes that are currently grown on large scale to feed millions of people around the world (FAO Database, 2005; Seleiman et al., 2010). Wheat is a major source of calorie intake in central and western Asia (Figure 3). It is typically grown on alkaline calcareous soils of semi arid regions. These soil and climatic factors lead to decreased availability of soil Zn (IZA, 2009). Wheat is highly susceptible to Zn deficiency in such conditions and produces low grain yield with low levels of grain Zn concentration. Poor quality wheat grain is causing Zn deficiency in humans and need immediate attention. Wheat grains contain about 25–30 µg Zn g^{-1} dry weight, while for a measurable impact of Zn biofortification on human health, desired wheat grain Zn concentration should be > 50 µg g^{-1} dry weight (Cakmak, 2008).

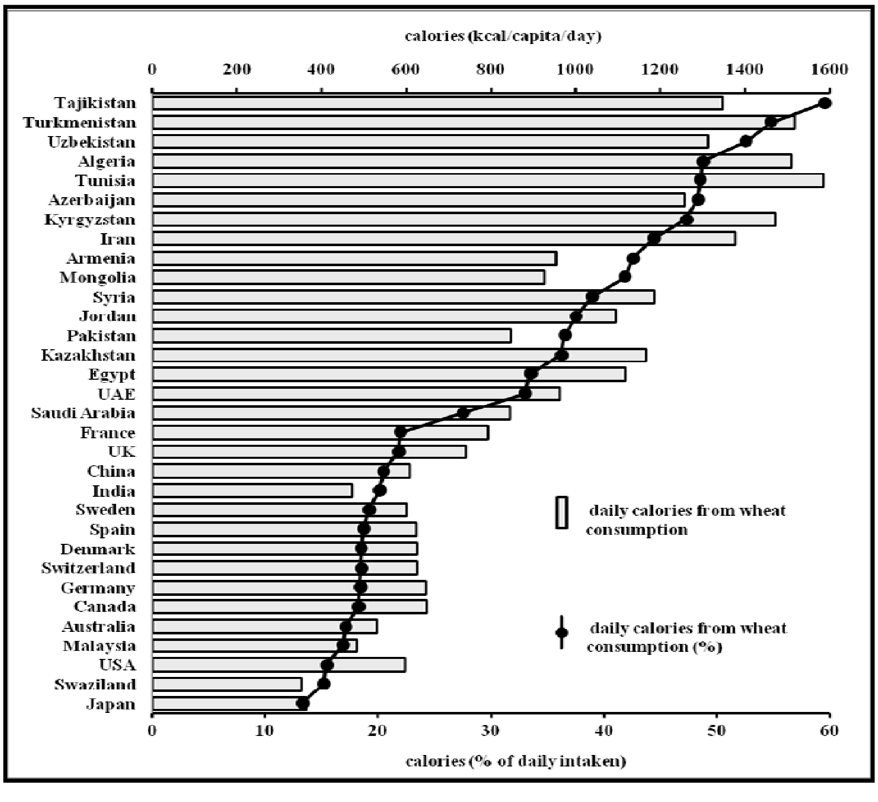


Figure 3. Daily calorie intake from wheat consumption in different countries of the world (FAO Database, 2005).

Traditional interventions tackled mineral malnutrition by supplementation, food fortification and dietary diversification. None of these have been universally successful on sustainable basis because they require safe delivery systems, stable political policies, appropriate social infrastructures and continued investment for longer periods (White and Broadley, 2005). For example, there is a possibility to fortify wheat flour for micronutrients as adopted by government of Pakistan for iron. Rural communities in Pakistan, about 65% of total population (Statistical Division, 2008), use locally milled flour and therefore will not be benefited by the scheme. The cost-effective and sustainable solution to human Zn deficiency is biofortification of staple food grains (Table 1). Genetic engineering, breeding and agronomic approaches are important tools of biofortification (Figure 4). Detailed comparison of genetic engineering and breeding approaches is given by Zimmermann and Hurrel (2002) and that of agronomic and breeding by Cakmak (2008). Till the break through in genetic engineering, agronomic and breeding approaches are fundamental means of biofortification in developing countries. Although biofortification is recognized as cost effective approach, it is not yet adopted in developing countries due to lack of indigenous studies.

Table 1. Possible solution to zinc deficiency in human population.

Intervention	Scope	Economics
Supplementation: giving mineral drugs as clinical treatment	It is generally recommended during pregnancy or in severe Zn deficiency for a shorter period.	It is costly and only recommended when a very quick response is required.
Fortification: addition of an ingredient to food to increase the concentration of a particular element	It is effective but limited to urban areas.	It is very uneconomical if carried out for longer period of times.
Food Diversification/modification: changes in food selection, processing and cooking for nutritional point of view	It is applicable only where alternative food products are available with high adoptability. These criteria are not fulfilled in rural areas of developing countries.	It is economically feasible and sustainable intervention.
Biofortification: increasing the bioavailable concentrations of micronutrients in edible portions of plants through crop management and genotype improvement	It is targeted (rural communities in devolving countries) and reachable (food fortification and supplementation cannot be extended to rural area by poor governments)	It is cost effective and sustainable approach. It has added benefit of yield increase on Zn deficient soils and seems permanent solution to the problem.

(Bouis and Welch, 2010; Stein et al., 2007; White and Broadley, 2005; FAO/WHO, 1998)

Transgenic approaches of biofortification rely on improving mobilization from the soil, uptake from the rhizosphere, translocation to the shoot and accumulation of mineral elements in bioavailable forms in edible tissues (Palmgren et al., 2008; Zimmermann and Hurrel, 2002; Hacisalihoglu and Kochian, 2003). Knocking out of enzymes in the phytate biosynthetic pathway and over expression of phytase (phytate-degrading enzyme) could also be a good strategy for increasing bioavailable grain Zn (White and Broadley, 2005). As compared to wild and primitive wheat, cultivated wheat is less favorable for breeding program due to narrow genetic variation for Zn concentration (Cakmak et al., 2004). Genotypes, developed for biofortification, should also produce higher grain yields and/or these should response to Zn application for yield and grain Zn concentration. Agronomic approach or Zn application is a rapid solution to enhance production and grain Zn concentration in cultivated genotypes. Despite significant response to Zn fertilization, farmers in most of the developing countries are not applying Zn to wheat. Fertilizer application strategy is an important complementary approach to the on-going breeding programs for biofortification (Cakmak, 2008). Rate, time, methods and sources of Zn application need optimization for agronomic biofortification (Rengel et al., 1999).

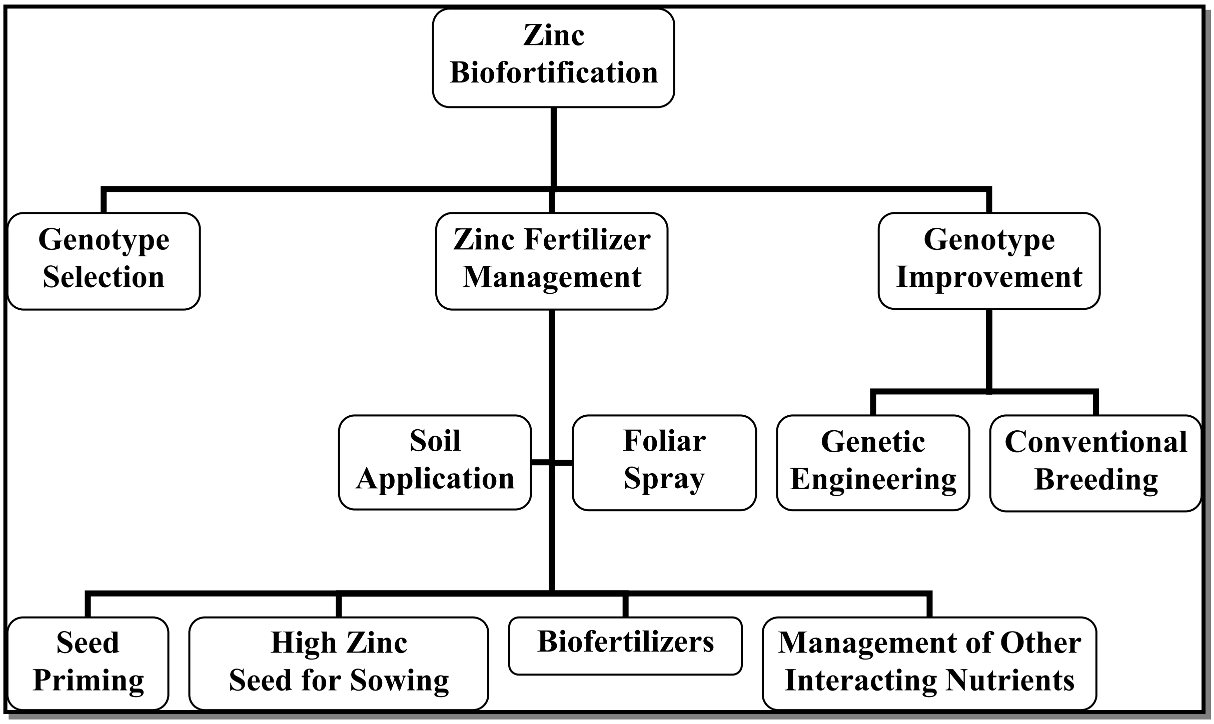


Figure 4. Approaches for zinc biofortification of staple food grains.

Grain quantity and biofortification

World total population will reach near 7 billion at the end of 2010 and it will cross 8 billion in 2025 (Population Division, 2009). Currently 963 million people across the world are facing hunger (Food Security Statistics, 2008). One-third of the world's total population is well-fed, one-third is under-fed and rest is starving. Approximately 80% of hunger affected people live in rural areas (Hunger Task Force, 2003). The Green Revolution has had a tremendous positive effect on wheat grain production through development of high yielding wheat genotypes. But for the first time since introduction of high yielding dwarf wheat genotypes, there are serious concerns about future wheat supply. The problem of food scarcity is increasing day by day and uprising in food production is mandatory (Huang et al., 2002). Global demand for wheat will rise about 40% by 2020 (Pingali and Rajaram, 1998). Conventional crop breeding (especially hybrid development), molecular biology, genetic engineering and resource management can greatly help in enhancing the crops to feed the poor. About 50% yield increase during 20th century can be attributed to application of inorganic fertilizers to nutrient depleted soils (Fageria, 2008). Balanced and integrated use of plant nutrients still has a large potential to increase the grain yield.

Nevertheless, quality of food carries same importance as the quantity. Increased grain Zn concentration is an important quality parameter of food. The biofortification approach relies on crop management and improvement strategies for higher grain Zn. The absorption of dietary Zn is mainly limited by high phytate in our food. Phytate:zinc molar ratio >15 reduces Zn absorbance to only 15% (Brown et al., 2001; White and Broadley, 2009). Genotypes differ in bioavailable Zn based on phytate:zinc molar ratios. In most countries, however, genotypes are not yet screened on the basis of bioavailable Zn.

Since the recognition of biofortification as a tool to combat mineral nutrient deficiencies in humans, breeder's criteria for genotype selection is changed from higher yield to higher mineral densities in grains. However, breeder has to answer both the nutritionists (increased bioavailable Zn) and farmers (increased grain yield) to fight food malnutrition (Morris and Sands, 2006). Breeding for higher grain Zn may affect concentration of essential organic and mineral compounds in grains. Neglecting grain yield and various food quality parameters for Zn biofortification is not justifiable. Therefore the biofortification could more precise be defined as "*producing food crops with increased bioavailable amounts of desired food element in edible plant parts to optimum levels while maintaining or improving yield and other food quality parameters.*"

Zinc application to wheat

Majority of world agricultural soils are deficient in Zn (Figure 2) and staple food crops grown on these soils suffer from Zn deficiency. Wheat grains produced without optimum soil Zn levels is resulting in human Zn deficiency (Alloway, 2008). Poor farmers in devolving countries do not apply Zn to wheat. Lack of awareness, economical constrains and product unavailability are the reasons for slow adoptability of small poor farmers to Zn application (Bell and Dell, 2008). Field demonstrations are valid programs to aware the farmers about beneficial effects of micronutrients on crop yield. Sillanpää (1990) reported universal wheat response to Zn application in most of the countries investigated under FAO field trails. Numerous studies has shown pronounced increase in shoot dry matter production (11–109%), grain yield (9–256%) and grain Zn concentration (9–912%) of wheat with application of Zn to these Zn deficient soils (Anonymous, 1998; Rengel et al., 1999; Rafique et al., 2006; IZA, 2009; Yilmaz et al., 1997). Zinc efficient wheat cultivars (genotypes that can grow and produce well on Zn deficient soils) also response to Zn application for grain yield and Zn concentration (Maqsood et al., 2009). Therefore, Zn application to Zn deficit soil is of great importance for increasing yield and grain Zn concentration.

The critical soil DTAP extractable Zn for wheat is 0.8 mg Zn kg^{-1} soil. However, genotypes differ significantly for optimum soil Zn levels. Soil Zn level required for optimum grain Zn concentration is higher than Zn required for optimum plant growth. In a pot study conducted at different soil DTPA Zn levels, yield reduction was not observed up to 7 mg Zn kg^{-1} soil but plant Zn concentration was greatly increased

(Takkar and Mann, 1978). With higher application rates, toxicity limit will gain importance and it should also be considered for the crops in rotation with wheat.

Most of the seed-Zn is located in the embryo and aleurone layer, whereas the endosperm is very low in Zn concentration. Zinc fertilizers may increase Zn concentration in grain, but it is mostly accumulated in pericarp (later to become a part of the seed coat). The Zn-rich parts of wheat grains are removed during milling, thus resulting in a marked reduction in flour Zn concentrations. Processing of grains need to be adjusted to allow maximum bran in flour (Slavin et al., 2000).

Zinc fertilizers

A comprehensive evaluation of Zn sources and methods of application at appropriate crop growth stage are required for increased grain yield and Zn concentration. Various fertilizers are available to correct Zn deficiency in crop plants. Chelated-Zn is relatively mobile in soil but expensive for poor farmers. Inorganic Zn fertilizers are available in oxides, sulphate and nitrates. For an effective Zn fertilizer, water soluble Zn must be > 40% (Slaton et al., 2005). Zinc sulfate ($ZnSO_4$) is the most widely applied inorganic source of Zn due to its high solubility and low cost. Zinc can also be applied to soils in form of ZnO, ZnEDTA and Zn-oxysulfate. The application of Zn as $ZnSO_4$ is most effective in increasing grain Zn compared to chelated Zn (ZnEDTA) and ZnO (Cakmak, 2008). There is also a possibility of developing biofertilizers that will help in increased grain Zn concentration. The integrated use of organic and inorganic fertilizers is more beneficial on sustainable basis (Alloway, 2008; Moyin-Jesu, 2008).

Micronutrients, such as Zn, are required in small quantities (< 10 kg ha^{-1}). Zinc enriched macronutrient fertilizers are best sources to avoid non-homogeneous placement and extra labor charges. Urea fertilizers containing Zn (e.g., zincated urea) improves both grain Zn and protein concentrations. With this approach, human Zn deficiency can also be handled on a large scale. Following the examples set in Turkey, government of devolving countries should provide the farmers with Zn enriched macronutrient fertilizers at low costs.

Methods of zinc application

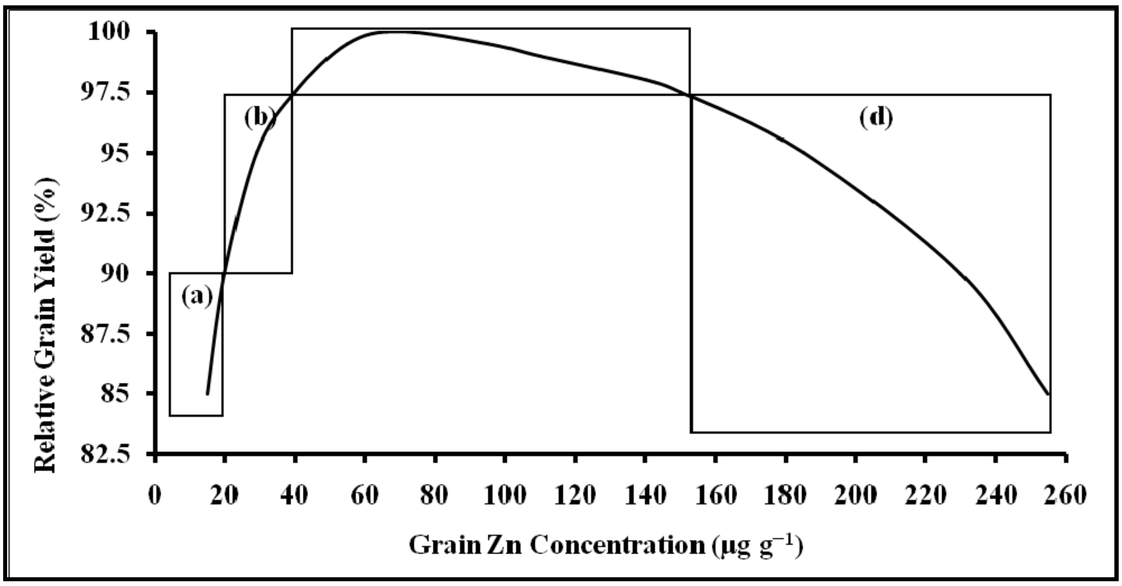
Methods of application may differentially influence yield and grain Zn concentration. Seed application can improve shoot growth but soil application is required for better grain yield. Zinc, required in trace amounts, is immobile in soil and plant environment. To overcome this problem, Zn fertilizers could also be directly sprayed to leaves of growing plants (Fageria et al., 2009). Due to toxicity and less mobility of Zn, more than one Zn sprays are recommended to fulfill the requirement of plants. Foliar application of Zn at grain filling directly relates with higher grain Zn concentration. Soil + foliar application of Zn can greatly enhance grain yield and grain Zn concentration (Yilmaz et al., 1997).

Farmer friendly application methods are more rapidly adopted by the poor farmers. For a method to be farmer friendly, it should save time, labor charges and non-homogeneous application with significant and observable increase in grain yield. Harris et al. (2008) found seed priming with $ZnSO_4$ a very cost-effective Zn application method that provided net benefit-to-cost ratio of 75 for wheat. Application of Zn with macronutrient fertilizers is also a farmer friendly method. Zinc addition may include incorporation, coating and bulk blending of Zn with granular NPK fertilizers. Zinc blending with NPK fertilizers was more effective in increasing plant Zn concentration and grain yield as compared to other methods (Mortvedt, 1991). Zinc application with herbicide spays also saves money and time of farmers (Fageria et al., 2009). However, interaction between herbicide and Zn need clear description.

Critical grain zinc concentrations

Green Revolution was possible due to introduction of fertilizer responsive-dwarf genotypes that produced high grain yield. Therefore, vigorous shoot growth does not ensure highest grain yield. Quality and quantity of wheat grain are the only attributes that can influence our inputs. Current food crises demands optimum Zn concentration in grain without any loss in yield. Although concentration in grain increases with Zn addition, recommendations are generally reported for 90–95% relative yield on marginal return basis (Rengel et al., 1999). Recommendations for 97.5–100% relative grain yield will ensure higher grain Zn concentration with optimum yield levels.

A typical relationship between grain yield and Zn concentration under increasing Zn application rates is presented in Figure 5. A concentration of Zn required for 90–97.5% relative gain yield is economical for farmers on marginal returns basis. Generally reported concentrations for these yield levels are 25–40 µg Zn g^{-1} dry weight of wheat grains (Cakmak, 2008). However, desirable concentration to combat human Zn deficiency might be 50–70 µg Zn g^{-1} dry weight. A range of 50–100 µg Zn g^{-1} dry weight can be achieved without any significant yield loss (for ≈ 100% relative grain yield). Such Zn rates are possible when government provide Zn enriched macronutrient fertilizers to farmers. However, researchers should carefully determine critical grain Zn concentrations for a specific genotype-environment combination and high rates of Zn should be recommended considering both human Zn requirements and plant Zn toxicity.



Range of grain Zn concentration in (a) and (d) are undesirable for plant and human health. The (b) covers a range of critical Zn concentration for optimum grain yield, while (c) is desirable for biofortification point of view.

Figure 5. Relationship between grain zinc (Zn) concentration and relative grain yield of wheat under increasing soil Zn application rates (generalized from Rafique et al., 2006; Takkar and Mann, 1978; Marschner, 1995).

Criteria for genotype selection

In search for higher yields and low farming costs, breeders have unconsciously selected for the genotypes reduced in nutritional quality. Therefore, selection criteria should be modified for nutritious food grains (Morris and Sands, 2006). Genotypes differ significantly for Zn efficiency and grain Zn concentration (Maqsood et al., 2009). Wheat genotypes are extensively sorted for Zn efficiency. Evaluating 164 bread wheat genotypes in a Zn-deficient calcareous soil, Torun et al. (2000) documented no relation between shoot Zn concentration and Zn efficiency. There is also no relation between Zn efficiency and Zn concentration in grain. Zinc-efficient genotypes absorb more Zn from soils, produce more dry matter and grain yield but do not necessarily have the highest Zn concentration in shoot or grain (Kalayci et al., 1999). High grain Zn concentration is not only an agronomic trait but it also appears to be under genetic control and should be selected independently. These findings advocate on reviewing genotype screening criteria.

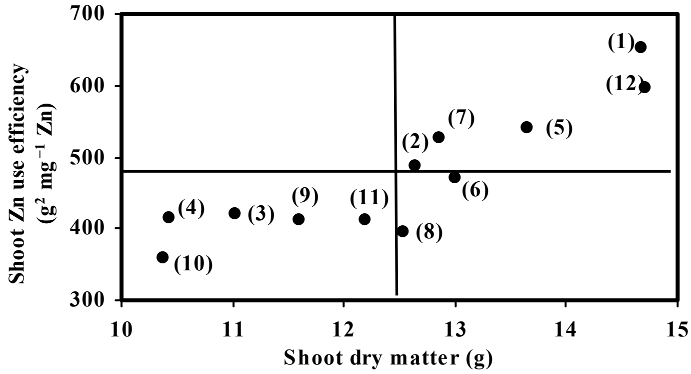
Concentration and uptake of Zn in grain seem feasible for biofortification. However, these do not account for grain yield to combat hunger. Giving equal weight to concentration and yield, indexing for grain yield and grain Zn concentration seems most feasible. Newly developed high yielding genotypes with higher bioavailable grain Zn will diffuse rapidly in farmers (Welch and Graham, 2004). A comparison of existing and devised categorization of genotypes is given in Figure 6 (unpublished data by authors). The suggested approach is a simple and direct way to identify genotypes for higher grain yield and Zn concentration. As yield is reduced at low Zn supply, genotypes that response best to Zn application for grain yield and grain Zn concentration should be recommended for breeding and cultivation.

Genotypes differ in Zn bioavailability based on Zn and phytate contents in food (Ficco et al., 2009). Scientists have presented mathematical model of Zn absorption as dependent on various dietary components, including Zn, phytate, and the phytate:zinc molar ratio. Trivariate model of Zn absorption as a function of dietary Zn and phytate is a simplistic expression (Hambidge et al., 2010) that the breeders can use. Therefore, genotypes can more precisely be screened for higher bioavailable grain Zn and higher grain yields. In most of the developing countries, little or no data is available about bioavailable amounts of Zn in the grains of cultivated wheat genotypes. There is a strong need to screen wheat genotypes for high bioavailable grain Zn before recommending for general cultivation.

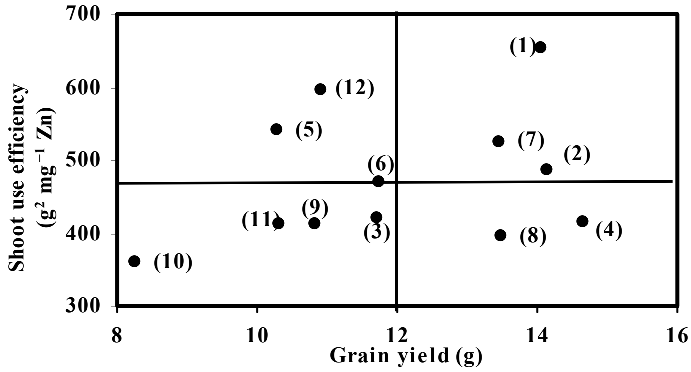
Conclusions

Combating human Zn malnutrition in developing countries is intricate especially under increasing hunger in the world. Biofortification approaches that also ensure high wheat grain yield will have high adoptability among farmers. Zinc fertilization with due consideration of yield and grain Zn concentration are important contemplation to be followed in Zn deficient soils. Application of Zn as $ZnSO_4$ to soil or foliar application is an effective way to increase grain Zn concentration with remarkable yield increase. Applying Zn with macronutrient fertilizers or at higher rates will give optimum yield and higher grain Zn concentration. Similarly, applying Zn for ≈ 100% relative grain yield will greatly increase grain Zn concentration.

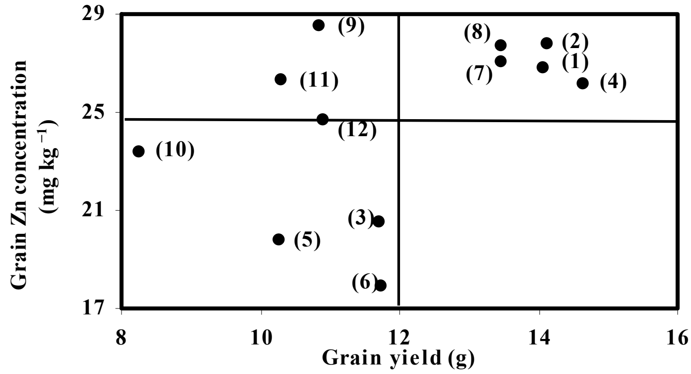
Future research need to be focused for farmer friendly Zn sources and application methods. Critical Zn concentrations in soil and plant need careful evaluation for biofortification. Selecting genotypes on the basis of higher grain yield and higher bioavailable grain Zn is required to simultaneously address hunger and Zn malnutrition in developing countries.



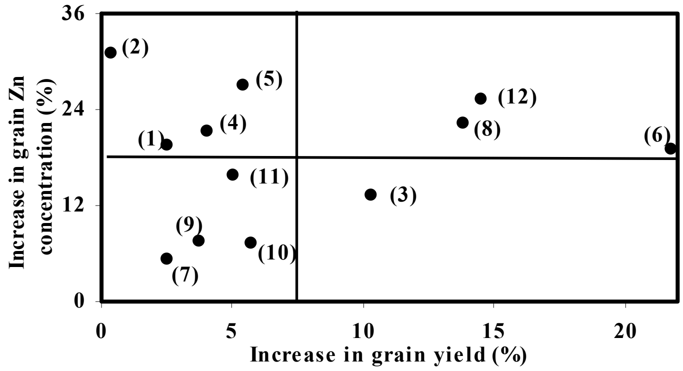
(a): Genotypes are generally screened for increased shoot growth and shoot Zn use efficiency. This approach sort out those genotypes that can produce higher shoot dry matter at Zn deficient environment. This screening method does not directly account for grain yield and Zn concentration.



(b): Screening for increased grain yield and shoot Zn use efficiency also does not encounter Zn concentration in grains. Although this approach screens genotypes that can producer higher grain yields at deficit Zn environment.



(c): Screening for biofortification should include grain yield and grain Zn concentration (or more precisely the bioavailable amount of Zn in grain). Efficient genotypes for biofortification will have higher grain Zn concentration and higher grain yields in the testing environments.



(d): Due to reasons discussed in text, application of Zn is requisite. Responsive genotypes will show pronounced increase in grain yield and Zn concentration with Zn application.

(1) Inqalab-91; (2) Bhakar-2000; (3) Pari-73; (4) Yaqora; (5) AS-2002; (6) Shafaq-2006; (7) Auqab-2000; (8) Sehar-2006; (9) Dirk; (10) Iqbal-2000; (11) Vatan; (12) SARC-1

Wheat genotypes were grown in pots at control (DTPA extractable Zn = 0.61 mg Zn kg^{-1} soil) or 6 mg Zn kg^{-1} soil. The (a), (b) and (c) are plant responses at control while (d) is increase (%) with Zn application over control. Sehar-2006, classified as zinc non-efficient (a, b), was efficient (c) and responsive (d) for biofortification.

Figure 6. Screening genotypes for zinc (Zn) biofortification of wheat grain (unpublished data by authors).

Acknowledgements

Soil Zn deficiency map is reproduced with permission. We gratefully acknowledge the author (Brain J. Alloway) and publishers (IZA and IFA) of *Zinc in Soils and Crop Nutrition, 2nd Edition* for this kind courtesy. Senior author gratefully acknowledges the financial support provided by Higher Education Commission (HEC) of Pakistan through Indigenous Ph.D. Fellowship Program.

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