Biofortification of food crops: a novel strategy for reducing micronutrient malnutrition

M Jahiruddin

Department of Soil Science, Bangladesh Agricultural University, Mymensingh 2202, Bangladesh

ARTICLE INFORMATION

Article History
Submitted: 31 Mar 2020
Accepted: 12 Apr 2020
First online: 16 Apr 2020

Academic Editor
Jiban Shrestha
jibshrestha@gmail.com

*Corresponding Author
M Jahiruddin
m_jahiruddin@yahoo.com

OPEN ACCESS

Cite this article: Jahiruddin M. 2020. Biofortification of food crops: a novel strategy for reducing micronutrient malnutrition. Fundamental and Applied Agriculture 5(2): 133–146. doi: 10.5455/faa.96078

1 Introduction

Micronutrient malnutrition is a great concern in the present day world. Access to food is not enough, access to nutritious food is important for a healthy nation. Humans require 10–15 mg Fe and 12-15 mg Zn daily (Welch and Graham, 2004). The FAO has five objectives, of which objective 1 is to ‘help eliminate hunger, food insecurity and malnutrition’ (FAO, 2019). Biofortification means biological fortification. Thus, it is a biological process of adding micronutrients to food crops through breeding or agronomic approach. It is recognized as a good means of dietary improvement of malnourished rural population (Bouis, 2013; Garg et al., 2018). The agricultural system that produces foods in the developing world usually does not provide enough micronutrients (trace elements and vitamins) to meet the human needs, although the production of carbohydrates via cereal crops is adequate to feed the world (Welch et al., 1997). In devel-
oping countries, the staple cereals (rice, wheat, maize) are largely grown in micronutrient, particularly Zn deficient soils and the farmers do not regularly use micronutrient fertilizers, thus the grains contain low amount of micronutrients. Furthermore, minimum attention is given to the production of micronutrient-rich non-staples, such as pulses, vegetables and fruits. Again, the increased prices of vegetables and pulses have made it difficult for the poor to afford quality diet (Bouis et al., 2011a). Inadequate intake of micronutrients in diets can affect the normal functions of brain, immunity and reproductive systems (World Bank, 1994).

A number of studies have been done and are in progress regarding biofortification of cereals as in rice (Behura et al., 2011; Mubarak et al., 2015), wheat (Cakmak et al., 2010; Guzmán et al., 2014) and maize (Qin et al., 2012; Simić et al., 2011). It is now well agreed that adoption of two strategies (agronomic and breeding) can increase the micronutrient concentrations of food crops and thus consumption of these foods can reduce the malnutrition of humans. Agronomic technique through fertilizer management can rapidly increase the micronutrient concentration of crop foods (Zuo and Zhang, 2011; Cakmak and Kutman, 2018) and breeding technique (conventional and transgenic) through developing new varieties can enhance the capacity of plant roots to take up nutrients from soil and accumulate them in edible parts (White and Broadley, 2009).

This article aims at reviewing the progress of biofortification research and identifying sustainable strategy to enhance micronutrient concentration in staple foods and thereby reducing the malnutrition of world poor. It is hypothesized that the breeding approach alone cannot adequately address micronutrients enrichment of food grains, agronomic approach via fertilizer application can effectively complement the breeding strategy.

2 Micronutrient malnutrition

2.1 Concept

Malnutrition can arise in three forms (Ritchie and Roser, 2020): (a) hunger and undernourishment, (b) obesity or overnourishment, and (c) micronutrient deficiencies. In this article, human malnutrition in the form of micronutrient deficiency has been addressed. Micronutrient refers to a substance that is essential in trace amounts for the growth and metabolism of a living organism. To a human nutritionist micronutrient could be a vitamin or a mineral, while plant scientists mean it only minerals. So, nutritionally micronutrient malnutrition is a dietary deficiency of minerals and vitamins.

2.2 Essential micronutrients

Humans need 11 trace elements (minerals) and 14 vitamins for their normal growth and health. Both animals and plants require eight essential trace elements, but not all the same. A list of minerals required for humans, livestock and crops is shown in Table 1 and the amount of requirement for humans is presented in Table 2. Each mineral nutrient has a definite role in human, animal and plant metabolisms. Of the essential micronutrients, the most frequently reported deficiencies for human health are Fe, Zn, I and vitamin A (Welch and Graham, 2004), the reason can be attributed to the smaller amount of micronutrients in cereal grains (Garg et al., 2018) and the higher amount of antinutrient substances e.g. phytic acid (White and Broadley, 2009), a substance that inhibits the absorption of mineral elements by the gut. The levels of trace elements like Cu, Zn, Mn, Fe and Mo in crops can be sufficient for optimum yields, but they may be suboptimal to meet the needs of livestock (Shukla et al., 2018). Cobalt is essential for livestock and legume (pulse) crops. Humans need 14 vitamins which include water-soluble vitamins viz. ascorbic acid, biotin, cobalamin, folic acid, niacin, pantothenic acid, pyri-doxyine, riboflavin and thiamin and fat-soluble vitamins viz. retinoic acid, calciferol, tocopherol, phylloquinone, and menoquinone (Graham et al., 2001).

2.3 Hidden hunger

Unlike energy-protein undernourishment, the health impact of micronutrient deficiency is not always visible; it is therefore also called ‘hidden hunger’. Swaminathan (2014) states, ‘Hidden hunger is one vibrant of hunger which arises from lack of micronutrients’. Pregnant women and children are at greater risk of micronutrient deficiencies. This is due to higher physiological requirements; pregnancy and child development often create demand for specific vitamins and minerals. Based on the global burden of disease estimates there are 26 major risk factors of human health, of them Fe deficiency ranks 9th, Zn deficiency 11th, and vitamin A deficiency 13th (Ezzati et al., 2002).

Poor diet is a major cause of hidden hunger. Cereal based diets, the largest source of energies (calories) for the rural people, are relatively low in vitamins and minerals which results in hidden hunger. In addition, poverty is a major factor that limits the access to nutritious foods e.g. meat, milk, fish, fruits, vegetables (Bouis et al., 2011a). About 800 million people in the world are chronically hunger (calorie deficiencies) (FAO et al., 2017) and more than 2 billion people are affected by hidden hunger (micronutrient deficiencies), the vast majority from developing countries (WHO, 2006; McGuire, 2015; Hodge, 2016). Based on the Disability-Adjusted Life Years (DALYs) data, Gödecke et al. (2018) have observed
Table 1. Essential micronutrients required for humans, livestock and crops †

| Micronutrient       | Humans | Livestock | Crops |
|---------------------|--------|-----------|-------|
| Boron (B)           | No     | No        | Yes   |
| Cobalt (Co)         | Yes    | Yes       | No    |
| Copper (Cu)         | Yes    | Yes       | Yes   |
| Iron (Fe)           | Yes    | Yes       | Yes   |
| Manganese (Mn)      | Yes    | Yes       | Yes   |
| Molybdenum (Mo)     | Yes    | No        | Yes   |
| Zinc (Zn)           | Yes    | Yes       | Yes   |
| Fluorine (F)        | Yes    | No        | No    |
| Iodine (I)          | Yes    | Yes       | No    |
| Selenium (Se)       | Yes    | Yes       | No    |
| Chlorine (Cl)       | No     | No        | Yes   |
| Chromium (Cr)       | Yes    | No        | No    |
| Silicon (Si)        | Yes    | Yes       | No    |
| Nickel (Ni)         | No     | No        | Yes   |

† Source: Bell and Dell (2008);

Table 2. Amount of essential micronutrients required for humans †

| Element | RDA          | RNI | UL  | SUL |
|---------|--------------|-----|-----|-----|
| Fe (mg) | 8.0-18.0     | 11.4| 45.0| 17.0|
| Zn (mg) | 8.0-11.0     | 9.5 | 40.0| 25.0|
| Mn (mg) | 1.8-2.3      | >1.4| 11.0| 4.0 |
| Cu (mg) | 0.9          | 1.2 | 10.0| 10.0|
| I (µg)  | 150          | 140 | 1100| 500 |
| Se (µg) | 55           | 75  | 400 | 450 |
| Mo (µg) | 45           | 50-400| 2000| NS  |
| Cr (µg) | 25-35        | >25 | NS  | NS  |
| F (mg)  | 3-4          | NS  | 10.0| NS  |
| Si (mg) | NS           | NS  | NS  | 1500|

† Source: White and Broadley (2005); NS = Non specified; RDA = Recommended daily allowance (US recommendation); RNI = Reference nutrient intake (UK recommendation) (Amount enough for at least 97% in a group); UL = Upper intake level (US recommendation); SUL= Safe upper level (UK recommendation)

that all country-level determinants have larger effects on the burden of chronic hunger (calorie deficiencies) than on the burden of hidden hunger (micronutrient deficiencies), and complementary micro-level interventions are required to end hidden hunger. Hidden Hunger Index (HHI) of different countries of south Asia and south-east Asia are shown in Table 3.

2.4 Micronutrient malnutrition in south Asia

The situation of Fe and Zn deficiency is worse in south and south-east Asia where high proportion of cereal crops, such as rice and wheat, is consumed as a staple food (Cakmak, 2008; Stein, 2009). Cereals contribute about 60% for Zn and 55% for Fe to the daily intake of these minerals by Bangladeshi people (Islam et al., 2014). Ahmed et al. (2016) has reviewed the micronutrient deficiencies among children and women in Bangladesh. The review states that as per National Micronutrients Status Survey report (2011-12), among the preschool-age children 20.5% are deficient in vitamin A, 44.5% in Zn and 10.7% in Fe. About 57% non-pregnant and non-lactating women are Zn deficient, and 25% women Fe deficient, and nearly 50% pregnant and lactating women are anaemic, induced by Fe deficiency. WHO (2007) estimates that in India about 27% population is suffering from Zn deficiency induced disorders which include poor immune system, diarrhea, poor physical and mental growth. Children are vulnerable to Zn deficiency which is the reason for 4.4% of the total child deaths in the world (Black, 2003).
Table 3. Hidden Hunger Index (HHI) and micronutrient deficiencies in south Asia and south-east Asia †

| Region          | Country     | Deficiency prevalence (%) |                      |                      |                      |
|-----------------|-------------|---------------------------|----------------------|----------------------|----------------------|
|                 |             | HHI score | Zn ‡ | Fe § | Vitamin A ¶ |
| South Asia      | Afghanistan | 47.7      | 59.3 | 19   | 64.5      |
|                 | India       | 48.3      | 47.9 | 34.7 | 62       |
|                 | Pakistan    | 26.7      | 42   | 25.5 | 12.5     |
|                 | Bangladesh  | 29.3      | 43   | 23.5 | 21.7     |
|                 | Sri Lanka   | 22.3      | 19.2 | 12.6 | 35.3     |
|                 | Nepal       | 35.3      | 49.3 | 24.2 | 32.3     |
|                 | Bhutan      | 33.3      | 37.5 | 40.3 | 22       |
|                 | Maldives    | 30        | 31.9 | 48.9 | 9.4      |
| South-East Asia | Indonesia   | 27.3      | 40.1 | 22.3 | 19.6     |
|                 | Thailand    | 14.7      | 15.7 | 12.6 | 15.7     |
|                 | Philippines | 30.7      | 33.8 | 18.2 | 40.1     |
|                 | Malaysia    | 11.7      | 15.6 | 16.2 | 3.5      |
|                 | Singapore   | NA        | 4.4  | 11.3 | NA       |
|                 | Vietnam     | 24        | 43.3 | 17.1 | 12       |
|                 | Myanmar     | 36.3      | 40.6 | 31.6 | 36.7     |
|                 | Cambodia    | 31        | 39.5 | 31   | 22.3     |
|                 | Laos        | 38.7      | 47.6 | 24.1 | 44.7     |
|                 | Brunei      | NA        | 11.6 | 14.5 | NA       |
|                 | Timor-Leste | 39        | 55.7 | 15.8 | 45.8     |

† Source: Muthayya et al. (2013); NA = Data not available, HHI score = \([\text{Stunting} (%) + \text{Anemia} (%) + \text{Low serum retinol} (%) \] / 3, three components equally weighted; ‡ Stunting as proxy for Zn; § Anemia as proxy for Fe; ¶ Low serum retinol, <0.7 µmol L\(^{-1}\)

Among the developing countries, Pakistan is recognized as one of the highest levels of child malnutrition country (Asim and Nawaz, 2018). In Asia, there are almost half of the total stunned children and two-thirds of all wasted children under the age of 5 years (UNICEF, 2015). Abeywickrama et al. (2018) from Sri Lanka reported an abundance of Fe, Zn, Ca, folate, and vitamin A deficiencies, with females being more vulnerable than males. Despite recent successes in economic growth, agricultural output and health care, the prevalence of micronutrient deficiencies is high in south Asia. Harding et al. (2017) have reviewed the situation using the metric of stunting (indicator of Zn deficiency). Pakistan has the highest national prevalence (44%) (AKU, 2011), followed by Afghanistan (41%) (Ministry of Public Health and UNICEF and Aga Khan University, 2014) and Nepal (41%) (MoHP, 2012), India (39%) (Raykar et al., 2015), Bangladesh (36%) (ICDDR,B, 2013) and Sri Lanka (13%) (Jayatissa et al., 2014). In Bangladesh 57% non-pregnant women and in Pakistan 41% women are Zn deficient. In south Asia, excepting Sri Lanka, about 40% children under 5 years are anemic, in Sri Lanka, this level is 20.0–39.9% (UNICEF et al., 2001). In India, Bangladesh and Nepal, the anaemia problem prevails more in rural areas than in urban. Iron deficiency causes about half of anemic populations in south Asia (Kassebaum et al., 2014).

2.5 Ways to address micronutrient malnutrition

Human micronutrient malnutrition can be addressed in four possible ways (Ritchie and Roser, 2020):

(a) Supplementation: Use of concentrated micronutrients in pill, powder or liquid form;

(b) Food fortification: Addition of micronutrients to food products during processing such as rice milling, wheat flours;

(c) Biofortification: Addition of micronutrients to food crops by breeding or agronomic method.

(d) Diet diversification: Consumption of micronutrient rich diet, e.g. fruits, vegetables, pulses etc.

In the past, nutrient supplementation, food fortification and diet diversification were largely used as means of reducing micronutrient deficiency (Mayer, 2005; Brown et al., 2007; Casey et al., 2009; Eneroth et al., 2010; Ritchie and Roser, 2020). However, these approaches had limited success (Ssemakula and Pfeiffer, 2011). Child mortality from diarrhoea and pneumonia reduced much in Bangladesh for use of ‘baby zinc’ tablet developed by ICDDR,B (Baqui, 2002; Brooks et al., 2005). However, fortification and supplementation programs can complement biofortification for better use by urban people, not by rural people.
3 Biofortification

There are two broad approaches of micronutrient biofortification in crops: breeding and agronomic. Breeding approach includes conventional breeding and genetic engineering (transgenic). Agronomic approach covers fertilizer management, variety screening and crop diversification.

3.1 Breeding method

Both conventional breeding and genetic engineering (transgenic) can play a good role to increase the Fe and Zn concentrations of edible parts of crops (Ghandilyan et al., 2006).

3.1.1 Conventional breeding method

The breeders generally give more attention to the development of crop varieties for yield improvement (Belford and Sedgley, 1991; Peng et al., 1999) and resistance to biotic (Datta, 2002; Pasalu et al., 2008) and abiotic stresses (Ashraf et al., 2012). Recently many crop scientists have paid considerable attention to the improvement of micronutrient density in the food crops (Zhang et al., 2012). For successful breeding for higher mineral content, exploration of genetic variability is essential and also knowledge about the genetics of the observed variation and genotype × environment interaction is important (Welch and Graham, 2004). As stated by Nair et al. (2013), the variation in mineral concentrations (0.03–0.06 g kg\(^{-1}\) for Fe, and 0.02–0.04 g kg\(^{-1}\) for Zn) among the mungbean genotypes renders the scope for mineral enrichment in the newly developed varieties. Reports are available about variation in Fe and Zn concentrations of wheat grain due to genetic variability (Rengel et al., 1999; Cakmak et al., 2002; Velu et al., 2011; Pant et al., 2020). The genetic variation in grain Fe and Zn concentrations among the cultivated varieties of cereals (e.g. wheat) is found generally low, but greater variation is often found in the wild relatives (Welch et al., 2005; Chhuneja et al., 2006; Pfeiffer and McClafferty, 2007; Cakmak, 2008; Tiwari et al., 2008). Wild accessions might have 2-fold higher grain Fe and Zn concentrations than the widely grown varieties for many cereals (White and Broadley, 2005). The CIMMYT breeding program has developed high-yielding bread wheat lines through hybridization and selection that contained 10-90% higher grain Zn and Fe concentrations than popular commercial varieties (Guzmán et al., 2014).

3.1.2 Transgenic (genetic engineering) method

Transgenic approach deals with improvement of mineral uptake from root zone, translocation to the shoot and accumulation in edible tissues, and also reducing the concentration of antinutrients and increasing the concentration of promoter substances (White and Broadley, 2005; Davies, 2007; Zhu et al., 2007). Limited works have been done on vegetable crops with respect to micronutrient biofortification. Modern biology technique (genetic engineering) can help vegetable breeders to incorporate candidate genes into elite cultivars for higher mineral content and thereby improving the mineral value (Gomathi et al., 2017). Bt brinjal (Solamun melongena) is the first genetically engineered crop in Bangladesh (Shelton et al., 2018).

During rice milling, more than 50% of the Zn could be lost and the remaining portion of Zn might not be fully available for intestinal absorption due to presence of antinutrient compounds e.g. phytates (Das et al., 2018). Thus it is suggested that biofortification programme should also aim at Zn partitioning more to seed endosperm. Garg et al. (2018) has given a good analysis about transgenic approach. When genetic diversity is not available, genetic transformation could be a better option. In this approach, once a useful gene is discovered, that can be utilized in multiple crops. Various genes from different sources have been utilized to enhance the level of vitamins, minerals, essential amino acids, and essential fatty acids in the food crops. Examples are phytoene synthase (PSY), carotene desaturase, and lycopene \(\Delta_6\)-cyclase for vitamins, ferritin and nicotinamine synthase for minerals, albumin for essential amino acids, and \(\Delta_6\) desaturase for essential fatty acids.

3.1.3 The ‘HarvestPlus’ programme

The HarvestPlus Challenge Programme on ‘Biofortified Crops for Improved Human Nutrition’ has been initiated in 2004 with the objective to develop cultivars of staple food crops with rich in Fe, Zn, and vitamin A (\(\beta\)-carotene). The Consultative Group on International Agricultural Research (CGIAR) has started this programme with financial support from the Bill and Melinda Gates Foundation, the World Bank, and USAID. It is an interdisciplinary alliance of research institutions and implementing agencies. The target crops include 7 food crops such as rice (Oryza sativa L.), wheat (Triticum aestivum L.), maize (Zea mays L.), cassava (Manihot esculenta Crantz), pearl millet (Pennisetum americanum Leek), beans (Phaseolus vulgaris L.) and sweet potato (Ipomoea batatas L.). Those crops have been chosen based on the observation that those foods are consumed as staple foods by the world’s poor. The HarvestPlus programme is going on in south Asia for rice Zn (target 28 mg g\(^{-1}\)) in Bangladesh and India, for wheat Zn (target 28 mg g\(^{-1}\)) & Fe secondary) in India and Pakistan, and for lentil Fe (target 70 mg g\(^{-1}\)) & Zn secondary) in Bangladesh, Nepal and India (HarvestPlus, 2014).

Success of biofortification programme depends on three factors, as outlined by Bouis et al. (2011b). The factors are: (i) the biofortified crop must be high
yielding and profitable to the farmer, (ii) the biofortified crop must show as efficacious and effective in reducing micronutrient malnutrition of humans, and (iii) the biofortified crop must be acceptable to both farmers and consumers in the regions where people are afflicted by micronutrient deficiency. All these points are well taken in the HarvestPlus program (Hotz and McClafferty, 2007). Thus, the biofortified crop variety should be high yielding with high minerals content and acceptable to the people suffering from micronutrient malnutrition. For example, BRRI dhan62 (Zn enriched rice variety) has not been popularized among the farmers in Bangladeshi due to low yield potential (4.0-4.5 t ha\(^{-1}\)). However, the later varieties (BRRI dhan64, 72, 74 and 84) have addressed this problem.

3.1.4 Bioavailability of micronutrients

Micronutrient bioavailability refers to the proportion of a nutrient that is absorbed from the diet and used for normal body functions (Aggett, 2010). Bioavailability of a nutrient is regulated by some external and internal factors. External factors include food matrix and chemical form of the nutrient and internal factors are gender, age, life stage (e.g. pregnancy), etc. Not the whole amount of minerals present in plant foods is bioavailable to humans due to presence of antinutritional compounds that interfere with the absorption or utilization of the nutrients in humans (Welch and Graham, 1999). In general, seeds and grains of staple food crops contain very low bioavailable levels of Fe and Zn (i.e., about 5% of the total Fe and about 25% of the total Zn present in the seed is bioavailable). So far, phytic acid (myo-inositol-1,2,3,4,5,6-hexakisphosphate), fibres (e.g. cellulose), polyphenols (e.g. tannins), haemagglutinins (e.g. lectins) and heavy metals (e.g. Cd) are recognized as antinutritional compounds (Graham et al., 2001; Hurrell, 2004; Welch and Graham, 2004). Phytic acid or phytate can strongly bind divalent cations (e.g. Zn\(^{2+}\)) and thus limit the cation bioavailability, even in the digestive tract. On the contrary, phytate has a positive function since it is a major storage form of seed phosphorus that needed for germination.

3.1.5 Mechanisms of Fe and Zn absorption

Plants possess two mechanisms for Fe acquisition from soil. In Strategy I (dicots and non-graminaceous monocots), the roots acidify the rhizosphere and release organic acids and phenolic compounds to increase Fe\(^{3+}\) concentrations in the soil solution. These compounds chelate Fe\(^{3+}\), which is subsequently reduced to Fe\(^{2+}\) by ferric reductase enzymes in the plasma membrane of root epidermal cells (Wu et al., 2005; Mukherjee et al., 2005). In Strategy II (graminaceous monocots such as rice, corn and wheat), phytosiderophores (structural derivatives of mugineic acid) are released into the rhizosphere to chelate Fe\(^{3+}\), and the Fe\(^{3+}\)–phytosiderophore complex is taken up by root cells (Roberts et al., 2004; Ishimaru et al., 2006). Concerning Zn acquisition, it is assumed that the most Zn is transported symplastically across the root to the xylem via the apoplast (White et al., 2002; Broadley et al., 2007). Zinc is taken up across the plasma membrane of root cells as Zn\(^{2+}\) or as a Zn–phytosiderophore complex (Suzuki et al., 2006; Broadley et al., 2007; Ismail et al., 2007). A number of 48 putative genes regulate the transport of Fe and Zn for accumulation in kernels (maize) which indicates that mineral accumulation in cereal grains is a complex polygenic process (Sharma and Chauhan, 2008; Maqbool and Beshir, 2018). The Zn and Fe concentrations in cereals is reported to be positively correlated (Jahiruddin and Islam, 2018). Chakrabarti et al. (2009) has explained the correlation between kernel (maize) Zn and kernel Fe in terms of pleiotropic effects or linkage among the genes regulating these elements concentration.

3.2 Agronomic approach

Agronomic biofortification greatly concerns with fertilizer management to elevate the mineral concentrations in edible portions of crops (White and Broadley, 2009). For increasing the fertilizer use efficiency the 4R nutrient stewardship (right source, right rate, right time and right place) of fertilizer application is important (Johnston and Bruulsema, 2014). Zinc deficiency is pronounced in calcareous and wetland soils, and as crop maize and wetland rice are the most responsive to zinc fertilization (Jahiruddin, 2015). In situation, when availability of a nutrient in soil is low for fixation or any other reason and when mobility of a mineral within plant body is low, foliar spray of soluble inorganic fertilizers would be very helpful. It is reported that soil application combined with foliar spray is more effective in increasing micronutrient concentration in grains (Guo et al., 2016; Maqbool and Beshir, 2018). Foliar application of Fe in rice (Yuan et al., 2012) and wheat (Aciakoz et al., 2011), and foliar Zn in rice (Wei et al., 2012) and wheat (wen Yang et al., 2011) are reported to increase their concentration in grains. Foliar Zn application during early milk stage of rice could be the most effective way to elevate grain Zn concentration (Mabesa et al., 2013).

Besides fertilizer management, use of soil microbes, especially mycorrhizal fungi and plant growth promoting rhizobacteria (PGPR) such as Bacillus, Pseudomonas can play a good role for acquisition of im mobile mineral elements from the root zones (Rengel et al., 1999; Mishra et al., 2011; Sharma et al., 2013). Thus, micronutrient fertilizers, organic manures and microbial biofertilizers need to be added to soil in an integrated way. Liming is also important for acid
soils (pH<5.5) to reduce the toxicity of Al and some micronutrients (Fe, Zn and Mn). Crop varieties such as rice varieties may vary in yield potential and micronutrient density in their edible parts. They may differ in their capacity to absorb Fe and Zn from soil (Shivay et al., 2010; Jahiruddin and Islam, 2018). Thus, selection of a genotype which is high yielding and possesses comparatively higher efficiency to absorb and translocate micronutrients from roots to grains can be regarded as a good agronomic practice. Joy et al. (2015) in Africa reported 23, 7 and 19% increased Zn concentration in maize, rice and wheat grains due to soil application, and 30, 25 and 63% Zn increase for foliar spray in these crops, respectively.

Erosion and leaching loss of nutrients, liming of acid soils, and minimum use of micronutrient fertilizers and organic manure are the good reasons for micronutrient deficiencies in agricultural soils (Fageria et al., 2002). Positive influence of Zn fertilization is reported on Zn concentration of rice and maize grains, mungbean seeds, tuber (potato), curd (cauliflower) grown in alluvial soils of Bangladesh (Hossain et al., 2008; Sarker et al., 2019a,b). An increment of 4-8 µg g⁻¹ Zn in wheat grain and 2-4 µg g⁻¹ Zn in rice grain is possible through Zn fertilization (Jahiruddin and Islam, 2018). Farmers of south Asian countries commonly use N, P and K fertilizers; use of micronutrient fertilizers is limited (Jahiruddin, 2019). Positive information is also reported. Shukla et al. (2018) demonstrates that the extent of Zn deficiency in Indian soils is in declining trend and currently it is 36.5% Zn deficiency which shows farmers’ awareness to apply Zn fertilizers.

Efficient management of N and Zn fertilizers would help enhance the grain Fe and Zn concentrations, as evidenced by positive correlation of seed Fe and Zn with N contents in several crops (Zhang et al., 2008; Cakmak et al., 2010; Kutman et al., 2010). In many cases, there is found inverse relationship between grain yield and grain Zn concentration (Garvin et al., 2006; McDonald et al., 2008). Information is also available that grain yield increases, along with a considerable increase in grain Zn concentration, as reported from Pakistan (Zou et al., 2012), China (Karim et al., 2012) and Turkey (Yilmaz et al., 1997). Siddika (2019) observed a synergistic relationship between N and Zn concentrations of rice.

3.3 Benefits and limitations of biofortification

There is an added benefit of agronomic biofortification that the micronutrient rich seeds of biofortified varieties would produce viable and vigorous seedlings and thus would improve disease resistance and growth characteristics, with giving yield benefits (Rengel and Graham, 1995; Graham and Welch, 1996; Cakmak, 2008). A great disadvantage is that agronomic biofortification gives short-term benefits and therefore, every time fertilizer application is necessary that would add an extra cost. Furthermore, fixation of Zn and Fe may occur in high pH soils that limit the capacity of biofortified crops to absorb them from soil. Low yield, interactions between genotype and environment, lack of sufficient genetic diversity for breeding program, consumer resistance and safety of genetically modified (GM) crops are the main weaknesses of genetic biofortification (Falk et al., 2002; Cakmak, 2008; Palmgren et al., 2008; Joshi et al., 2010). Moreover, adoption of biofortified varieties depends on the factors that they should perform higher yield, with higher stress tolerance and other qualities such as taste, color, and flavor (Wolson, 2007). Crops fortified with β-carotene (vitamin A) exhibit a deep yellow to orange color as seen in golden rice, orange-fleshed sweet potato, and yellow cassava (Pray et al., 2007; Ramaswami, 2007). On the contrary, Zn or Fe enriched varieties does not have such visible characteristics and this limits their acceptance by the consumers.

Breeding approach is a long-term process and needs tremendous efforts and time, requiring number of crossing and backcrossing activities over a number of years, and its success depends on the stability of the targeted micronutrient trait under various environmental conditions. Besides, the potential benefits of biofortification depend on the groups of people (men, women, children and elderly), amount of staple food(s) consumed, the prevalence of existing micronutrient deficiencies, and special needs for processes such as growth, pregnancy, and lactation (Hotz and McClafferty, 2007). Presently we are looking many successes of transgenic biofortification, e.g. lysine and tryptophan rich quality protein maize, vitamin A (β-carotene) rich orange sweet potato and vitamin A rich golden rice (Garg et al., 2018). However, the success rate and acceptability of genetic engineering technique (transgenic) appears to be much lower compared to conventional breeding. Furthermore, globally introduction of GMO food crops is a subject of debate and truly its consumption is very low. In breeding programs, interrupting the negative relationship between grain yield with Zn or Fe concentration is a challenging task for enhanced micronutrient density in cereal grains (Zhao and McGrath, 2009; Bouis and Welch, 2010; Waters and Sankaran, 2011). Research to develop a variety combining the qualities of high yield with high micronutrient concentration in grains would take fairly a long time. Processing of food grain is also important in the context of biofortification strategy. Minerals such as iron, zinc, and copper that are highest in the rice bran are lost during milling and polishing. This is not a problem for Se and S since they exist as maximum in the embryo (Gregorio et al., 2000). However, the extent of the loss is genotype dependent (Waters and Sankaran, 2011).
4 Sustainable strategies for micronutrient enrichment

When a soil is critically deficient in micronutrients, the benefits of biofortified varieties cannot be achieved. Thus, biofortification should be considered as an integrated approach in which both breeding and agronomic approaches are equally important for question of sustainability (Mubarak et al., 2015). In cultivation of micronutrient biofortified varieties, application of micronutrient fertilizers can be regarded as a sustainable strategy to boost the crop yield with higher mineral concentrations in edible parts (Bouis et al., 2003; Genc et al., 2005; White and Broadley, 2005; Graham et al., 2007; Pfeiffer and McClafferty, 2007). Concurrently, it is also needed to enhance the concentrations of ‘promoter’ substances such as ascorbate (vitamin C) which stimulates the absorption of mineral elements by the gut, and to lower the concentrations of ‘antinutrients’, such as phytate, which interferes with their absorption (White and Broadley, 2009). Agronomic biofortification is complementary to breeding approach. When the genotypes having higher grain minerals are developed, their cultivation should be properly fertilized with Fe and Zn (Prasad et al., 2014). Thus, neither breeding nor agronomic approach alone can solve the problem of micronutrient malnutrition adequately and sustainably. For an effective and sustainable strategy, agronomic biofortification needs to be complemented with breeding strategy for micronutrient enrichment of food crops.

5 Conclusions

A good progress has been made in research concerning mineral biofortification of food crops with a view to addressing micronutrient malnutrition in humans. The main tune of this effort is breeding strategy with transgenic approach supported by the HarvestPlus programme. Still there is a big challenge to clearly explain the molecular mechanisms and genetic behaviour of crops regarding Zn and Fe accumulation in grains. Development of farmers’ acceptable varieties with high yield potential and high micronutrient characteristics still remains a great challenge. When a soil is highly deficient in Zn or Fe, the yield as well as nutrient concentration of the biofortified crops grown in that soil would not be satisfactory. Thus, integration of agronomic (fertilizer management) with breeding approach is required to achieve the goal of reducing micronutrient malnutrition.

Conflict of Interest

The author declares that there is no conflict of interests regarding the publication of this paper.

References

Abeywickrama H, Koyama Y, Uchiyama M, Shimizu U, Iwasa Y, Yamada E, Ohashi K, Mitobe Y. 2018. Micronutrient status in Sri Lanka: A review. Nutrients 10:1583. doi: 10.3390/nu10111583.

Aciksoz SB, Yazici A, Ozturk L, Cakmak I. 2011. Biofortification of wheat with iron through soil and foliar application of nitrogen and iron fertilizers. Plant and Soil 349:215–225. doi: 10.1007/s11104-011-0863-2.

Aggett PJ. 2010. Population reference intakes and micronutrient bioavailability: A European perspective. The American Journal of Clinical Nutrition 91:1433S–1437S. doi: 10.3945/ajcn.2010.28674c.

Ahmed F, Prendiville N, Narayan A. 2016. Micronutrient deficiencies among children and women in Bangladesh: progress and challenges. Journal of Nutritional Science 5:e46. doi: 10.1017/jns.2016.39.

AKU. 2011. Pakistan Medical Research Council & Government of Pakistan. Aga Khan University, Karachi and Islamabad, Pakistan.

Ashraf MY, Mahmood K, Ashraf M, Akhtar J, Hussain F. 2012. Optimal Supply of Micronutrients Improves Drought Tolerance in Legumes. In: Ashraf M, Öztürk M, Ahmad M, Aksoy A. (Eds), Crop Production for Agricultural Improvement. Springer, Dordrecht, Netherlands. doi: 10.1007/978-94-007-4116-4_25.

Asim M, Nawaz Y. 2018. Child malnutrition in Pakistan: Evidence from literature. Children 5:60. doi: 10.3390/children5050060.

Baqui AH. 2002. Effect of zinc supplementation started during diarrhoea on morbidity and mortality in Bangladeshi children: community randomised trial. BMJ 325:1059–1059. doi: 10.1136/bmj.325.7372.1059.

Behura N, Sen P, Kar MK. 2011. Introgression of yellow stem borer (Scirpophaga incertulas) resistance genes into cultivated rice (Oryza sp.) from wild species. Indian Journal of Agricultural Sciences 81:359–362.

Belford RK, Sedgley RH. 1991. Conclusions: Ideotypes and physiology: Tailoring plants for increased production. Field Crops Research 26:221–226. doi: 10.1016/0378-4290(91)90037-v.

Bell R, Dell B. 2008. Micronutrients for Sustainable Food, Feed, Fibre and Bioenergy Production. IFA, Paris, France.
Zinc deficiency, infectious disease and mortality in the developing world. The Journal of Nutrition 133:1485S–1489S. doi: 10.1093/jn/133.5.1485s.

Black RE. 2003. Zinc deficiency, infectious disease and mortality in the developing world. The Journal of Nutrition 133:1485S–1489S. doi: 10.1093/jn/133.5.1485s.

Bouis H. 2013. Biofortification: A new tool to reduce micronutrient malnutrition. Proceedings XVII. International Plant Nutrition Colloquium.

Bouis HE, Chassy BM, Ochanda JO. 2003. Genetically modified food crops and their contribution to human nutrition and food quality. Trends in Food Science & Technology 14:191–209. doi: 10.1016/s0924-2244(03)00073-6.

Bouis HE, Eozenou P, Rahman A. 2011a. Food prices, household income, and resource allocation: Socioeconomic perspectives on their effects on dietary quality and nutritional status. Food and Nutrition Bulletin 32:S14–S23. doi: 10.1177/15648265110321s103.

Bouis HE, Hotz C, McClafferty B, Meenakshi JV, Pfeiffer WH. 2011b. Biofortification: A new tool to reduce micronutrient malnutrition. Food and Nutrition Bulletin 32:S31–S40. doi: 10.1177/15648265110321s105.

Bouis HE, Welch RM. 2010. Biofortification – A sustainable agricultural strategy for reducing micronutrient malnutrition in the global south. Crop Science 50:S20–S32. doi: 10.2135/crop-sci2009.09.0531.

Brown, Wessells, Hess. 2007. Zinc bioavailability from zinc-fortified foods. International Journal for Vitamin and Nutrition Research 77:174–181. doi: 10.1024/0300-9831.77.3.174.

Cakmak I. 2008. Enrichment of cereal grains with zinc: Agronomic or genetic biofortification? Plant and Soil 302:1–17. doi: 10.1007/s11104-007-9466-3.

Cakmak I, Kutman UB. 2018. Agronomic biofortification of cereals with zinc: A review. European Journal of Soil Science 69:172–180. doi: 10.1111/ejss.12437.

Cakmak I, Pfeiffer WH, McClafferty B. 2010. Biofortification of durum wheat with zinc and iron. Cereal Chemistry 87:10–20. doi: 10.1094/cchem-87-1-0010.

Casey GJ, Phuc TQ, MacGregor L, Montresor A, Mihrshahi S, Thach TD, Tien NT, Biggs BA. 2009. A free weekly iron-folic acid supplementation and regular deworming program is associated with improved hemoglobin and iron status indicators in Vietnamese women. BMC Public Health 9:261. doi: 10.1186/1471-2458-9-261.

Chakraborti M, Prasanna BM, Hossain F, Singh AM, Guleria SK. 2009. Genetic evaluation of kernel Fe and Zn concentrations and yield performance of selected maize (Zea mays L.) genotypes. Range Management and Agroforestry 30:109–114.

Das A, Singh SK, Kumar M, Kumar O, and. 2018. Zinc biofortification: a novel strategy for improving human health. Journal of Experimental Biology and Agricultural Sciences 6:751–762. doi: 10.18006/2018.6(5).751.762.

Datta SK. 2002. Bioengineered rice for plant protection. Biotechnology and Genetic Engineering Reviews 19:339–356. doi: 10.1080/02648725.2002.10648033.

Davies KM. 2007. Genetic modification of plant metabolism for human health benefits. Mutation Research/Fundamental and Molecular Mechanisms of Mutagenesis 622:122–137. doi: 10.1016/j.mrfmmm.2007.02.003.

Eneroth H, el Arifeen S, Persson LA, Lonnerdal B, Hossain MB, Stephensen CB, Ekstrom EC. 2010. Maternal multiple micronutrient supplementation has limited impact on micronutrient status of Bangladeshi infants compared with standard iron and folic acid supplementation. The Journal of Nutrition 140:618–624. doi: 10.3945/jn.109.111740.

Ezzati M, Lopez AD, Rodgers A, Hoorn SV, Murray CJL. 2002. Selected major risk factors and global and regional burden of disease. The Lancet 360:1347–1360. doi: 10.1016/s0140-6736(02)11403-6.
Fageria NK, Baligar VC, Clark RB. 2002. Micronutrients in crop production. Advances in Agronomy :185–268. doi: 10.1016/s0065-2113(02)77015-6.

Falk MC, Chassy BM, Harlander SK, Hoban TJ, McGloughlin MN, Akhlaghi AR. 2002. Food biotechnology: Benefits and concerns. The Journal of Nutrition 132:1384–1390. doi: 10.1093/jn/132.6.1384.

FAO. 2019. Our priorities – The Strategic Objectives of FAO. Food and Agriculture Organization, Rome, Italy.

FAO, IFAD, UNICEF, WFP, WHO. 2017. The State of Food Security and Nutrition in the World: Building Resilience for Peace and Food Security. World Food Programme, FAO, Rome, Italy.

Garg M, Sharma N, Sharma S, Kapoor P, Kumar A, Chunduri V, Arora P. 2018. Biofortified crops generated by breeding, agronomy, and transgenic approaches are improving lives of millions of people around the world. Frontiers in Nutrition 5:12. doi: 10.3389/fnut.2018.00012.

Garvin DF, Welch RM, Finley JW. 2006. Historical shifts in the seed mineral micronutrient concentration of us hard red winter wheat germplasm. Journal of the Science of Food and Agriculture 86:2213–2220. doi: 10.1002/jsfa.2601.

Genc Y, Humphries JM, Lyons GH, Graham RD. 2005. Exploiting genotypic variation in plant nutrient accumulation to alleviate micronutrient deficiency in populations. Journal of Trace Elements in Medicine and Biology 18:319–324. doi: 10.1016/j.jtemb.2005.02.005.

Ghandilyan A, Vreugdenhil D, Aarts MGM. 2006. Progress in the genetic understanding of plant iron and zinc nutrition. Physiologia Plantarum 126:407–417. doi: 10.1111/j.1399-3054.2006.00646.x.

Gomathi M, Vethamoni P, Gopinath P. 2017. Biofortification in vegetable crops – A review. Chemical Science and Review Letters 6:1227–1237.

Graham R, Welch R. 1996. Breeding for staple food crops with high micronutrient density. Working papers on agricultural strategies for micronutrients. International Food Policy Research Institute, Washington DC, USA.

HarvestPlus. 2014. Better Crop · Better Nutrition. HarvestPlus, Washington, DC, USA. https://www.harvestplus.org/. Accessed on 15 April 2020.

Hodge J. 2016. Hidden hunger: approaches to tackling micronutrient deficiencies. In: Gillespie S, Hodge J, Yosef S, Pandya-Lorch R (Eds), Nourishing Millions: Stories of Change in Nutrition. International Food Policy Research Institute (IFPRI), Washington DC, USA.

Gödecke T, Stein AJ, Qaim M. 2018. The global burden of chronic and hidden hunger: Trends and determinants. Global Food Security 17:21–29. doi: 10.1016/j.gfs.2018.03.004.

Harding KL, Aguayo VM, Webb P. 2017. Hidden hunger in south asia: a review of recent trends and persistent challenges. Public Health Nutrition 21:785–795. doi: 10.1017/s1368980017003202.

Hossain MA, Jahiruddin M, Islam MR, Mian MH. 2008. The requirement of zinc for improvement of crop yield and mineral nutrition in the maize – mungbean – rice system. Plant and Soil 306:13–22. doi: 10.1007/s11104-007-9529-5.

Hotz C, McClafferty B. 2007. From harvest to health: Challenges for developing biofortified staple foods and determining their impact on micronutrient status. Food and Nutrition Bulletin 28:S271–S279. doi: 10.1177/15648265070282s206.
Hurrell. 2004. Phytic acid degradation as a means of improving iron absorption. International Journal for Vitamin and Nutrition Research 74:445–452. doi: 10.1024/0300-9831.74.6.445.

ICDDR,B. 2013. UNICEF Bangladesh, Global Alliance for Improved Nutrition. National Micronutrient Status Survey (Bangladesh) 2011–2012, Dhaka, Bangladesh.

Ishimaru Y, Suzuki M, Tsukamoto T, Suzuki K, Nakazono M, Kobayashi T, Wada Y, Watanabe S, Matsuhashi S, Takahashi M, Nakanishi H, Mori S, Nishizawa NK. 2006. Rice plants take up iron as an $\text{Fe}^{3+}$-phytosiderophore and as $\text{Fe}^{2+}$. The Plant Journal 45:335–346. doi: 10.1111/j.1365-313x.2005.02624.x.

Islam M, Jahiruddin M, Islam M, Alim M, Akhtaruzzaman M. 2014. Consumption of unsafe foods: evidence from heavy metal, mineral and trace element contamination. FAO Project Completion Report, Department of Soil Science, Bangladesh Agricultural University, Mymensingh, Bangladesh.

Ismail AM, Heuer S, Thomson MJ, Wissuwa M. 2007. Genetic and genomic approaches to develop rice germplasm for problem soils. Plant Molecular Biology 65:547–570. doi: 10.1007/s11103-007-9215-2.

Jahiruddin M. 2015. Zinc and Boron Deficiency in Crops and Their Management in Bangladesh .

Jahiruddin M. 2019. Research and development on natural resource management in south Asia. In: Shrestha RB, Bokhtiar SM, Khetarpal R, Thapa YB (Eds), Agricultural Policy and Program Framework: Priority Areas for research & Development in South Asia. SAC, Dhaka, Bangladesh.

Jahiruddin M, Islam R. 2018. Biofortification of zinc and iron in cereals by fertilizer use and variety selection. Project Completion Report (BAS-USDA PALS BAU-CR-10), Department of Soil Science, Bangladesh Agricultural University, Mymensingh, Bangladesh.

Jayatissa R, Gunathilaka M, Fernando D. 2014. National Nutrition and Micronutrient Survey 2012. Part I: Anaemia Among Children Aged 6–59 Months and Nutritional Status of Children and Adults. Ministry of Health, Colombo.

Johnston A, Brouhsema T. 2014. 4R nutrient stewardship for improved nutrient use efficiency. Procedia Engineering 83:365–370. doi: 10.1016/j.proeng.2014.09.029.

Joshi A, Crossa J, Arun B, Chand R, Trethewan R, Vargas M, Ortiz-Monasterio I. 2010. Genotype × environment interaction for zinc and iron concentration of wheat grain in eastern Gangetic plains of India. Field Crops Research 116:268–277. doi: 10.1016/j.fcr.2010.01.004.

Joy EJM, Stein AJ, Young SD, Ander EL, Watts MJ, Broadley MR. 2015. Zinc-enriched fertilisers as a potential public health intervention in Africa. Plant and Soil 389:1–24. doi: 10.1007/s11104-015-2430-8.

Karim MR, Zhang YQ, Zhao RR, Chen XP, Zhang FS, Zou CQ. 2012. Alleviation of drought stress in winter wheat by late foliar application of zinc, boron, and manganese. Journal of Plant Nutrition and Soil Science 175:142–151. doi: 10.1002/j.pln.201100141.

Kassebaum NJ, Jasrasaria R, Naghavi M, Wulf SK, Johns N, Lozano R, Regan M, Weatherall D, Chou DP, Eisele TP, Flaxman SR, Pullan RL, Brooker SJ, Murray CJL. 2014. A systematic analysis of global anemia burden from 1990 to 2010. Blood 123:615–624. doi: 10.1182/blood-2013-06-508325.

Kutman UB, Yildiz B, Ozturk L, Cakmak I. 2010. Biofortification of durum wheat with zinc through soil and foliar applications of nitrogen. Cereal Chemistry Journal 87:1–9. doi: 10.1094/cchm-87-1-0001.

Mabesa R, Impa S, Grewal D, Johnson-Beebout S. 2013. Contrasting grain-zn response of biofortification rice ($Oryza sativa$ L.) breeding lines to foliar Zn application. Field Crops Research 149:223–233. doi: 10.1016/j.fcr.2013.05.012.

Maqbool MA, Beshir A. 2018. Zinc biofortification of maize ($Zea mays$ L.): Status and challenges. Plant Breeding 138:1–28. doi: 10.1111/pbr.12658.

Mayer JE. 2005. The golden rice controversy: Useless science or unfounded criticism? BioScience 55:726–727. doi: 10.1641/0006-3568(2005)055[0726:tgrcus]2.0.co;2.

McDonald GK, Genc Y, Graham RD. 2008. A simple method to evaluate genetic variation in grain zinc concentration by correcting for differences in grain yield. Plant and Soil 306:49–55. doi: 10.1007/s11104-008-9555-y.

McGuire S. 2015. FAO, IFAD, and WFP. the state of food insecurity in the world 2015: Meeting the 2015 international hunger targets: Taking stock of uneven progress. rome: FAO, 2015. Advances in Nutrition 6:623–624. doi: 10.3945/an.115.009936.
Ministry of Public Health and UNICEF and Aga Khan University. 2014. National Nutrition Survey Afghanistan 2013. AKU, Kabul, Afghanistan.

Mishra PK, Bisht SC, Ruwari P, Joshi GK, Singh G, Bisht JK, Bhatt J. 2011. Bioassociative effect of cold tolerant Pseudomonas spp. and Rhizobium leguminosarum-PR1 on iron acquisition, nutrient uptake and growth of lentil (Lens culinaris L.). European Journal of Soil Biology 47:35–43. doi: 10.1016/j.ejsobi.2010.11.005.

MoHP. 2012. Nepal Demographic and Health Survey 2011. Ministry of Health and Population, New ERA and ICF International, Kathmandu and Calverton, MD.

Mubarak T, Sheikh FA, Bangroo SA. 2015. Role of rice in tackling hidden hunger: The biofortification approach. Research Journal of Agricultural Sciences 6:1–7.

Mukherjee I, Campbell NH, Ash JS, Connolly EL. 2005. Expression profiling of the Arabidopsis ferric chelate reductase (FRO) gene family reveals differential regulation by iron and copper. Planta 223:1178–1190. doi: 10.1007/s00425-005-0165-0.

Muthayya S, Rah JH, Sugimoto JD, Roos FF, Kraemer K, Black RE. 2013. The global hidden hunger indices and maps: An advocacy tool for action. PLoS ONE 8:e67860. doi: 10.1371/journal.pone.0067860.

Nair RM, Yang RY, Easdown WJ, Thavarajah D, Thavarajah P, d’A Hughes J, Keatinge JDHD. 2013. Biofortification of mungbean (Vigna radiata) as a whole food to enhance human health. Journal of the Science of Food and Agriculture 93:1805–1813. doi: 10.1002/jsfa.6110.

Palmgren MG, Clemens S, Williams LE, Krämer U, Borg S, Schjerring JK, Sanders D. 2008. Zinc biofortification of cereals: problems and solutions. Trends in Plant Science 13:464–473. doi: 10.1016/j.tplants.2008.06.005.

Pant K, Ojha B, Thapa D, Kharel R, Gautam N, Shrestha J. 2020. Evaluation of biofortified spring wheat genotypes for yield and micronutrient contents. Fundamental and Applied Agriculture 5:78–87. doi: 10.5455/faa.79404.

Pasalu I, Prakash A, Mohanty S, Krishnamurthy P, Katti G, Tewari S, Prasad J, Krishnaiah N. 2008. Bio-intensive integrated pest management in rice. In: Rice research priorities and strategies for second green revolution. Central Rice Research Institute, Cuttack, Orissa, India.

Peng S, Cassman KG, Virmani SS, Sheehy J, Khush GS. 1999. Yield potential trends of tropical rice since the release of IR8 and the challenge of increasing rice yield potential. Crop Science 39:1552–1559. doi: 10.2135/cropsci1999.3961552x.

Pfeiffer WH, McClafferty B. 2007. HarvestPlus: Breeding crops for better nutrition. Crop Science 47:S88–S105. doi: 10.2135/cropsci2007.09.0020pbs.

Prasad R, Shivay VS, Kumar D. 2014. Agronomic biofortification of cereal grains with iron and zinc. In: Advances in Agronomy. Elsevier. p. 55–91. doi: 10.1016/b978-0-12-800137-0.00002-9.

Pray C, Paarlberg R, Unnevehr L. 2007. Patterns of political response to biofortified varieties of crops produced with different breeding techniques and agronomic traits. AgBioForum 10:135–143.

Qin H, Cai Y, Liu Z, Wang G, Wang J, Guo Y, Wang H. 2012. Identification of QTL for zinc and iron concentration in maize kernel and cob. Euphytica 187:345–358. doi: 10.1007/s10681-012-0692-2.

Ramaswami B. 2007. Biofortified crops and biotechnology: A political economy landscape for India. AgBioForum 10:170–177.

Raykar N, Majumder M, Laxminarayan R. 2015. India Health Report: Nutrition 2015. Public Health Foundation of India, New Delhi, India.

Rengel Z, Batten G, Crowley D. 1999. Agronomic approaches for improving the micronutrient density in edible portions of field crops. Field Crops Research 60:27–40. doi: 10.1016/s0378-4290(98)00131-2.

Ritchie H, Roser M. 2020. Micronutrient Deficiency. Our World in Data. https://ourworldindata.org/micronutrient-deficiency. Accessed on 13 April 2020.

Roberts LA, Pierson AJ, Panaviene Z, Walker EL. 2004. Yellow stripe1. Expanded roles for the maize iron-phytosiderophore transporter. Plant Physiology 135:112–120. doi: 10.1104/pp.103.037572.

Sarker MMH, Jahiruddin M, Moslehiuddin AZM, Islam MR. 2019a. Optimization of zinc and boron doses for cauliflower–maize–rice pattern in floodplain soil. Communications in Soil Science and Plant Analysis 50:1425–1438. doi: 10.1080/00103624.2019.1621332.

Sarker MMH, Moslehiuddin AZM, Jahiruddin M, Islam MR. 2019b. Direct and residual effects
of micronutrients on crops in a pattern in floodplain soil. Communications in Soil Science and Plant Analysis 50:2245–2262. doi: 10.1080/00103624.2019.1659295.

Sharma A, Chauhan RS. 2008. Identification of candidate gene-based markers (SNPs and SSRs) in the zinc and iron transporter sequences of maize (Zea mays L.). Current Science :1051–1059.

Sharma A, Shankhdhar D, SC S. 2013. Enhancing grain iron content of rice by the application of plant growth promoting rhizobacteria. Plant, Soil and Environment 59:89–94. doi: 10.17221/683/2012-pse.

Shelton AM, Hossain MJ, Paranjape V, Azad AK, Rahman ML, Khan ASMMR, Prodhon MZH, Rashid MA, Majumder R, Hossain MA, Hussain SS, Husening JE, McCandless L. 2018. Bt eggplant project in Bangladesh: History, present status, and future direction. Frontiers in Bioengineering and Biotechnology 6:106. doi: 10.3389/fbioe.2018.00106.

Shivay Y, Prasad R, Rahal A. 2010. Studies on some nutritional quality parameters of organically or conventionally grown wheat. Cereal Research Communications 38:345–352. doi: 10.1556/crc.38.2010.3.5.

Shukla AK, Behera SK, Pakhre A, Chaudhari SK. 2018. Micronutrients in soils, plants, animals and humans. Indian Journal of Fertilisers 14:30–54.

Siddika A. 2019. Biofortification of zinc in rice grain through nitrogen and zinc fertilizer application. MS Thesis, Department of Soil Science, Bangladesh Agricultural University, Mymensingh.

Šimić D, Drinić SM, Zdunić Z, Jambrović A, Ledenčan T, Brkić J, Brkić A, Brkić I. 2011. Quantitative trait loci for biofortification traits in maize grain. Journal of Heredity 103:47–54. doi: 10.1093/jhered/esr122.

Ssemakula G, Pfeiffer W. 2011. Considerations for implementation of biofortification in developing countries: The case of Sub-Saharan Africa. Symposia Brief: Progress, Challenges, and the Way Forward in Breeding and Gene Discovery: Vitamin A. First Global Conference on Biofortification. November 9-11, 2011. Washington DC, USA.

Stein AJ. 2009. Global impacts of human mineral malnutrition. Plant and Soil 335:133–154. doi: 10.1007/s11104-009-0228-2.

Suzuki M, Takahashi M, Tsukamoto T, Watanabe S, Matsuhashi S, Yazaki J, Kishimoto N, Kikuchi S, Nakanishi H, Mori S, Nishizawa NK. 2006. Biosynthesis and secretion of mugineic acid family phytosiderophores in zinc-deficient barley. The Plant Journal 48:85–97. doi: 10.1111/j.1365-313x.2006.02853.x.

Swaminathan M. 2014. Bring More Women Farmers on Board to Eliminate Hunger. Times of India, India.

Tiwari VK, Rawat N, Neelam K, Randhawa GS, Singh K, Chhuneja P, Dhalwal HS. 2008. Development of Triticum turgidum subsp. durum – Aegilops longissima amphiploids with high iron and zinc content through unreduced gamete formation in F1 hybrids. Genome 51:757–766. doi: 10.1139/g08-057.

UNICEF. 2015. Levels and Trends in Child Malnutrition. The United Nations Children’s Fund, New York, USA http://www.unicef.org/media/files/Levels_and_Trends_in_Child_Mortality.

UNICEF, University UN, WHO. 2001. Iron Deficiency Anaemia: Assessment, Prevention, and Control. A Guide for Programme Managers. World Health Organization, Geneva, Switzerland.

Velu G, Singh R, Huerta-Espino J, Peña J, Ortiz-Monasterio I. 2011. Breeding for enhanced zinc and iron concentration in CIMMYT spring wheat germplasm. Czech Journal of Genetics and Plant Breeding 47:S174–S177. doi: 10.17221/3275-cjgpb.

Waters BM, Sankaran RP. 2011. Moving micronutrients from the soil to the seeds: Genes and physiological processes from a biofortification perspective. Plant Science 180:562–574. doi: 10.1016/j.plantsci.2010.12.003.

Wei Y, Shohag MJL, Yang X. 2012. Biofortification and bioavailability of rice grain zinc as affected by different forms of foliar zinc fertilization. PLoS ONE 7:e45428. doi: 10.1371/journal.pone.0045428.

Welch RM, Combs GF, Duxbury JM. 1997. Toward a ‘Greener’ Revolution. Issues in Science and Technology 14:50–58.

Welch RM, Graham RD. 1999. A new paradigm for world agriculture: meeting human needs. Field Crops Research 60:1–10. doi: 10.1016/s0378-4290(98)00129-4.

Welch RM, Graham RD. 2004. Breeding for micronutrients in staple food crops from a human nutrition perspective. Journal of Experimental Botany 55:353–364. doi: 10.1093/jxb/erh064.
Welch RM, House WA, Ortiz-Monasterio I, Cheng Z. 2005. Potential for improving bioavailable zinc in wheat grain (triticum species) through plant breeding. Journal of Agricultural and Food Chemistry 53:2176–2180. doi: 10.1021/jf040238x.

Wen Yang X, hong Tian X, chun Lu X, xian Cao Y, hui Chen Z. 2011. Impacts of phosphorus and zinc levels on phosphorus and zinc nutrition and phytic acid concentration in wheat (Triticum aestivum L.). Journal of the Science of Food and Agriculture 91:2322–2328. doi: 10.1002/jsfa.4459.

White P, Broadley M. 2005. Biofortifying crops with essential mineral elements. Trends in Plant Science 10:586–593. doi: 10.1016/j.tplants.2005.10.001.

White PJ, Broadley MR. 2009. Biofortification of crops with seven mineral elements often lacking in human diets - iron, zinc, copper, calcium, magnesium, selenium and iodine. New Phytologist 182:49–84. doi: 10.1111/j.1469-8137.2008.02738.x.

WHO. 2006. Guidelines on Food Fortification with Micronutrients. World Health Organization, Geneva, Switzerland.

WHO. 2007. UNICEF India, Children and Malnutrition. Global Database on Child Growth and Malnutrition in United Nations Administrative Committee on Coordination/Sub-Committee on Nutrition, Low Birth Weight, Nutrition Policy, Paper 18. World Health Organization, Geneva, Switzerland.

Wolson R. 2007. Assessing the prospects for the adoption of biofortified crops in south africa. AgBioForum 10:184–191.

World Bank. 1994. The challenge of dietary deficiencies of vitamins and minerals. In: Enriching Lives: Overcoming Vitamin and Mineral Malnutrition in Developing Countries. World Bank, Washington DC, USA.

Welch RM, House WA, Ortiz-Monasterio I, Cheng Z. 2005. Potential for improving bioavailable zinc in wheat grain (triticum species) through plant breeding. Journal of Agricultural and Food Chemistry 53:2176–2180. doi: 10.1021/jf040238x.

Wen Yang X, hong Tian X, chun Lu X, xian Cao Y, hui Chen Z. 2011. Impacts of phosphorus and zinc levels on phosphorus and zinc nutrition and phytic acid concentration in wheat (Triticum aestivum L.). Journal of the Science of Food and Agriculture 91:2322–2328. doi: 10.1002/jsfa.4459.

White P, Broadley M. 2005. Biofortifying crops with essential mineral elements. Trends in Plant Science 10:586–593. doi: 10.1016/j.tplants.2005.10.001.

White PJ, Broadley MR. 2009. Biofortification of crops with seven mineral elements often lacking in human diets - iron, zinc, copper, calcium, magnesium, selenium and iodine. New Phytologist 182:49–84. doi: 10.1111/j.1469-8137.2008.02738.x.

WHO. 2006. Guidelines on Food Fortification with Micronutrients. World Health Organization, Geneva, Switzerland.

WHO. 2007. UNICEF India, Children and Malnutrition. Global Database on Child Growth and Malnutrition in United Nations Administrative Committee on Coordination/Sub-Committee on Nutrition, Low Birth Weight, Nutrition Policy, Paper 18. World Health Organization, Geneva, Switzerland.

Wolson R. 2007. Assessing the prospects for the adoption of biofortified crops in south africa. AgBioForum 10:184–191.

World Bank. 1994. The challenge of dietary deficiencies of vitamins and minerals. In: Enriching Lives: Overcoming Vitamin and Mineral Malnutrition in Developing Countries. World Bank, Washington DC, USA.