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Biofortified Crops Generated by Breeding, Agronomy, and Transgenic Approaches Are Improving Lives of Millions of People around the World

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Biofortification is an upcoming, promising, cost-effective, and sustainable technique of delivering micronutrients to a population that has limited access to diverse diets and other micronutrient interventions. Unfortunately, major food crops are poor sources of micronutrients required for normal human growth. The manuscript deals in all aspects of crop biofortification which includes—breeding, agronomy, and genetic modification. It tries to summarize all the biofortification research that has been conducted on different crops. Success stories of biofortification include lysine and tryptophan rich quality protein maize (World food prize 2000), Vitamin A rich orange sweet potato (World food prize 2016); generated by crop breeding, oleic acid, and stearidonic acid soybean enrichment; through genetic transformation and selenium, iodine, and zinc supplementation. The biofortified food crops, especially cereals, legumes, vegetables, and fruits, are providing sufficient levels of micronutrients to targeted populations. Although a greater emphasis is being laid on transgenic research, the success rate and acceptability of breeding is much higher. Besides the challenges biofortified crops hold a bright future to address the malnutrition challenge.

Keywords: malnutrition, biofortification, transgenic, agronomic, breeding

INTRODUCTION

"Biofortification" or "biological fortification" refers to nutritionally enhanced food crops with increased bioavailability to the human population that are developed and grown using modern biotechnology techniques, conventional plant breeding, and agronomic practices. The United Nations Food and Agriculture Organization has estimated that around 792.5 million people across the world are malnourished, out of which 780 million people live in developing countries (1). Apart from this, around two billion people across the world suffer from another type of hunger known as "hidden hunger," which is caused by an inadequate intake of essential micronutrients in the daily diet (2, 3) despite increased food crop production (4). Besides this overnutrition is growing matter of concern.

So far, our agricultural system has not been designed to promote human health; instead, it only focuses on increasing grain yield and crop productivity. This approach has resulted in a rapid rise in micronutrient deficiency in food grains, thereby increasing micronutrient malnutrition among consumers. Now agriculture is undergoing a shift from producing more quantity of food crops to producing nutrient-rich food crops in sufficient quantities. This will help in fighting "hidden hunger" or "micronutrient malnutrition" especially in poor and developing countries, where diets are dominated by micronutrient-poor staple food crops (5).

TRANSGENIC FODDER

Transgenic alfalfa (*Medicago sativa*)

Alfalfa is as an important feed legume crop in many countries. Attempts have been made to improve its nutritional status through enhancement of isoflavonoids, essential amino acids, and improve its digestibility. Isoflavonoids are a predominantly legume-specific subclass of flavonoid secondary metabolites. Transgenic alfalfa has been generated by constitutively expressing IFS that is correlated with its increased isoflavonid composition (186). Alfalfa suffers from a limited level of the sulfur-containing amino acids, methionine, and cysteine. Its methionine content has been increased by the expression of cystathionine γ-synthase [*AtCgS* (187)]. Improvement in the digestibility of forages has also been an area of interest as it correlates with animal performance. By targeting three specific cytochrome P450 enzymes for antisense downregulation, transgenic alfalfa lines have been generated with low lignin content (188). Alfalfa has also been engineered to increase phytase activity, and thereby enabling its use in animal feeds, including livestock, poultry, and fish feed (189).

BIOFORTIFICATION THROUGH AGRONOMIC APPROACHES

Biofortification through agronomic methods requires physical application of nutrients to temporarily improve the nutritional and health status of crops and consumption of such crops improves the human nutritional status (202). In comparison with inorganic forms of minerals, the organic ones are more available for a man, as they can be absorbed more easily; and are less excreted (203) and their toxicity symptoms are less intensive (DRI 2000). It generally relies on the application of mineral fertilizers and/or increase in their solubilization and/or mobilization from the soil in the edible parts of plants. Macrominerals like nitrogen, phosphorus, and potassium (NPK) make an important contribution to the attainment of higher crop yields (204). Through the application of NPK-containing fertilizers, agricultural productivity increased in many countries of the world in the late 1960s and resulted in Green Revolution and saved them from starvation. In the current scenario, these fertilizers are important and necessary to improve crop yield and save the human population from starvation as low-input agriculture cannot feed the current seven billion world population (205). Microminerals iron, zinc, copper, manganese, I, Se, Mo, Co, and Ni are found in varying degrees in the edible portion of certain plants and are usually absorbed from the soil. Improvement of the soil micronutrient status by their application as fertilizers can contribute to decrease in micronutrient deficiency in humans (206). When crops are grown in soils, where mineral elements become immediately unavailable in the soil and/or not readily translocated to edible tissues targeted application of soluble inorganic fertilizers to the roots or to the leaves are practiced. Agronomic biofortification is simple and inexpensive, but needs special attention in terms of source of nutrient, application method and effects on the environment. These should be applied regularly in every crop season and thus are less cost-effective in some cases. Use of mineral fertilizers is evidently feasible in the developed world, as exemplified by the success of Se fertilization of crops in Finland (207), zinc fertilization in Turkey (208), and I fertilization in irrigation water in China (209).

In addition to fertilizers, plant growth-promoting soil microorganisms can be used to enhance the nutrient mobility from soil to edible parts of plants and improve their nutritional status. Soil microorganisms like different species of genera *Bacillus*, *Pseudomonas*, *Rhizobium*, *Azotobacter*, etc. can also be utilized to increase the phytoavailability of mineral elements (210, 211). The N_2-fixing bacteria play important role in increasing crop productivity in nitrogen limited conditions (212). Many crops are associated with mycorrhizal fungi that can release organic acids, siderophores, and enzymes capable of degrading organic compounds and increasing mineral concentrations in edible produce (210, 213). Different crops have been targeted through agronomical biofortification to improve the human nutritional status (**Table 3**).

CEREALS

Rice Agronomic Biofortification

Micronutrient biofortification through agronomical practices is an alternative strategy to reduce the iron and zinc deficiency in rice grain. Biofortification of rice plants by foliar spray of iron was an effective way to promote iron concentration in rice grains (214–216). Similarly, fortifying germinating rice plantlets with ferrous sulfate lead to increase iron concentration in germinated brown rice [up to 15.6 times the control (215)]. Foliar application of zinc has been reported as an effective agronomic practice to promote rice grain zinc concentration and zinc bioavailability (216, 218–223). On the other hand, application of zinc to soil as fertilizer in addition to a foliar spray proves to be an important strategy to increase the grain zinc content of rice grown in soils with low background levels of zinc (224). Selenium, which is an essential trace element for human health and proved to be a potent antioxidant, has been also increased by the application of selenate as a foliar spray or as fertilizer in rice (216, 225–230).

Wheat Agronomic Biofortification

Agronomic biofortification has been very efficiently utilized in wheat grain quality improvement. Inclusion of iron in foliar urea fertilizers has been positively correlated with high iron accumulation (231). Application of foliar zinc has reduced human zinc deficiency in regions with potentially zinc-deficient soil and also improved its bioavailability by reducing antinutrient factors like phytic acid (233). Due to significant effects of zinc fertilizers on grain yield, the total amount of zinc-containing NPK fertilizers increased from 0 in 1994 to a record level of 400,000 t per annum in 10–15 years in Turkey. Use of zinc-containing fertilizers increased zinc concentration in grain, and obviously contributed to human nutrition and health in Turkey, especially in rural areas, where wheat provided more than 50% of the daily calorie intake (206). Agronomic biofortification of Se in wheat has been adopted with success in Finland (207). Compound fertilizers supplemented

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