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The impact of mineral nutrients in food crops on global human health

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Abstract

Nutrient sufficiency is the basis of good health, productive lives and longevity for everyone. Nutrient availability to people is primarily determined by the output of foods produced from agricultural systems. If agricultural systems fail to provide enough food diversity and quantity to satisfy all the nutrients essential to human life, people will suffer, societies will deteriorate and national development efforts will stagnate. Importantly, plant foods provide most of the nutrients that feed the developing world. Unfortunately, as a result of population pressures, many global food systems are not currently providing enough micronutrients to assure adequate micronutrient intakes for all people. This has resulted in an increasing prevalence of micronutrient deficiencies (e.g., iron deficiency, vitamin A deficiency, and iodine deficiency disorders) that now afflicts over three billion people globally mostly among resource-poor women, infants and children in developing countries. The consequences of micronutrient malnutrition are profound and alarming for human existence. Agricultural approaches to finding sustainable solutions to this problem are urgently needed. This review presents some ways in which plant nutritionists can contribute to preventing micronutrient malnutrition in sustainable ways.

Introduction

Humans are dependent on consuming enough diverse foods to provide all the required nutrients to sustain life. If food systems do not provide sufficient quantities and enough diversity of foods to meet these needs continuously, malnutrition will ensue among certain population groups, especially the poor, and their health and welfare will deteriorate (Welch et al., 1997). Starvation and regional famines are the commonly recognized results of severe calorie/protein malnutrition, and preventing these outcomes was the paramount goal driving the agricultural ‘green revolution’ during the latter half of the 20th century. However, other more subtle consequences of malnutrition include: impaired immune function, increased mortality and morbidity rates, lower worker productivity, diminished intellectual performance, less educational attainment, a lower livelihood, higher birth rates and a lower standard of living for all those affected (Welch and Graham, 1999).

Some consequences of micronutrient deficiences

- *Vitamin A* deficiency can lead to poor night vision, eye lesions and, in severe cases, permanent blindness; increased illness and death from infections.
- *Iodine* deficiency can cause goiter, mental retardation, brain damage and reproductive failure.
- *Iron* deficiency can cause nutritional anemia, problem pregnancies, stunted growth, lower resistance to infections, long-term impairment in mental function, decreased productivity and food-energy conversion and impaired neural motor development.
- *Zinc* deficiency can cause growth retardation, delayed skeletal and sexual maturity, dermatitis, diarrhoea, alopecia and defects in immune function with resulting increase in susceptibility to infection.

Because agriculture is the primary source of all nutrients required for human life, those national agricultural systems that do not provide sufficient nutrient output to meet these nutritional needs will ultimately fail, as well the food systems dependent on them. Pos-

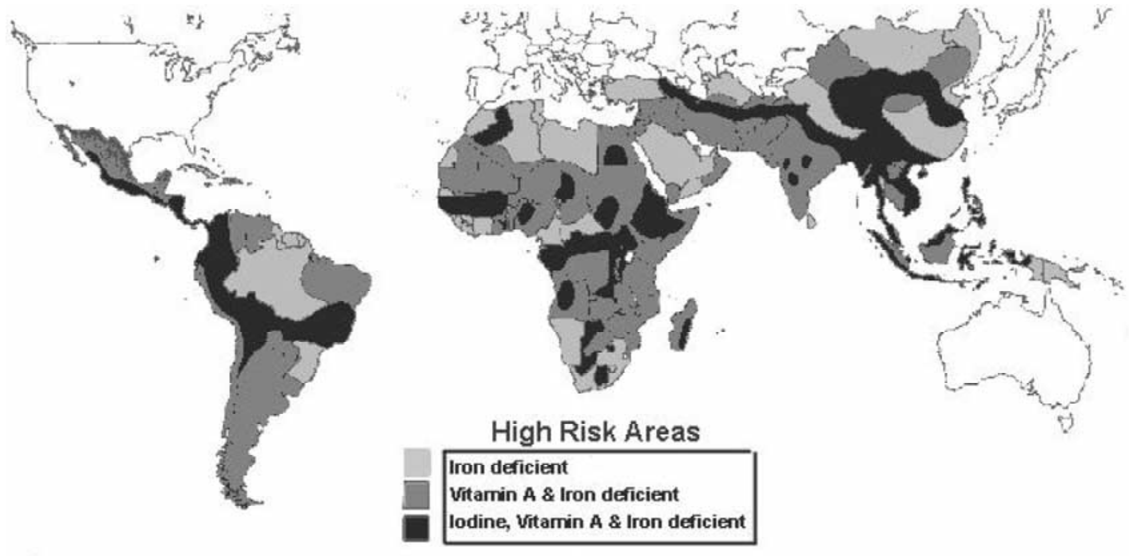

Figure 1. Global distribution of Fe, vitamin A and I deficiencies (map modified from Sanghvi, 1996).

sibly, changes in cropping systems over the past 60 years that resulted during the 'green revolution' are contributing to the dysfunction of food systems that can not meet all the nutritional needs of billions of people in various developing world regions (Graham and Welch, 2000; Graham et al., 2001).

In retrospect, the 'green revolution' resulted in many positive outcomes related to human nutrition. For example, between 1960 and 1990 globally:

- rice production more than doubled
- per capita food availability increased by 37%
- per capita calories available per day increased by 35%
- real food prices declined by 50%

However, there were some unforseen consequences of this agricultural revolution that have had profound affects on human health, felicity and world development.

Today, there are over 3.7 billion iron-deficient individuals and about 1 billion people that are or are at risk of developing iodine deficiency disorders (see Figure 1 for the global extent of problem). Additionally, there are over 200 million people that are vitamin A deficient (World Health Organization, 1999). Other micronutrient deficiencies (e.g., Zn, Se, vitamin C, vitamin D, and folic acid deficiencies) may be as wide spread as iron, iodine and vitamin A deficiencies, but there are no reliable data to confirm this although circumstantial evidence suggests that this may be so (Combs et al., 1996; World Health Organization, 1999).

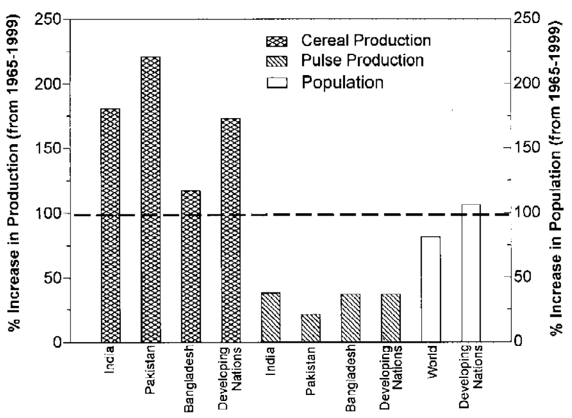

Figure 2. Trends in cereal and pulse production in some developing countries and in populations between 1965 to 1999 (data from FAOSTAT 1999).

What changes in agricultural systems might be contributing to the rise in micronutrient malnutrition globally? Figure 2 shows the trends in cereal and pulse production and in human populations for certain developing regions and nations from 1965 to 1999. Clearly, cereal production has exceeded population growth in these countries and regions. However, pulse production has not kept pace with population growth during this period. These crop production trends show that while the agricultural systems in these countries and regions were able to produce adequate quantities of cereal grains to supply enough energy and protein to prevent widespread famines, they have not been able to sustain the production of pulses. This

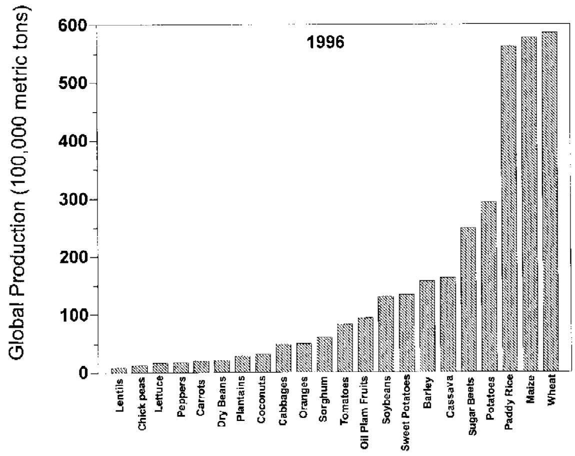

Figure 3. Global production of food crops in 1996 (data from Mann, 1997).

Table 1. Concentrations of Fe and Zn in whole cereal grains and pulse seeds

Plant food	Fe	Zn
	(μg g^{-1}, dry weight)	
Brown rice[1]	4	15
Whole maize[1]	21	22
Whole wheat[2]	37	31
Mung bean[3]	87	41
Black gram[3]	139	36
Cowpea[3]	67	45
Soybean[4]	97	43
Phaseolus bean[5]	65	37

[1]Data from Wolnik et al., 1985.
[2]Data from Wolnik et al., 1983.
[3]Unpublished data provided by R. M. Welch.
[4]Data from Holland et al., 1991.
[5]Data from Peck et al., 1980.

has affected the supply of available micronutrients produced in these nations because pulses are much richer sources of micronutrients (Table 1) compared to cereals which are usually milled and processed before consumption, further reducing their micronutrient content (Table 2) (Salunkhe and Deshpande, 1991). Furthermore, micronutrient-rich fruit and vegetable production has not kept pace with population growth in many nations (Welch and Graham, 1999). Finally, the decrease in food crop diversity brought about during the 'green revolution's' drive to improve cereal production and expand cereal crop acreage most likely is also a contributing factor (see Figure 3) (Graham et al., 2001).

Table 2. Effect of milling and polishing on micronutrient concentrations in rice grain (data from Salunkhe and Deshpande, 1991)

Micronutrient[1]	Whole brown rice	Polished rice	% Reduction
Iron (mg/kg)	30	10	67
Copper (mg/kg)	3.3	2.9	12
Manganese (mg/kg)	17.6	10.9	62
Zinc (mg/kg)	18	13	30
Thiamin (mg/kg)	3.4	0.7	80
Riboflavin (mg/kg)	0.5	0.3	40
Niacin (mg/kg)	47	16	66
Vitamin B_6 (mg/kg)	6.2	0.4	94
Folic Acid (μg/kg)	200	160	20
Pantothenic Acid (mg/kg)	20	10	50
Biotin (μg/kg)	120	50	58
Vitamin E (IU/kg)	20	10	50

[1]Dry weight basis.

Many food systems which sustain life in a number of countries today cannot produce enough of all the nutrients needed to satisfy human requirements. For example, Figure 4 shows the nutrient output of two food systems (a banana-based and a grain-based system) in Uganda that feed numerous individuals in that country (McIntyre et al., 2001). Figure 4 clearly show that the banana-based system does not provide enough vitamin A, Zn and Ca, and the grain-based system does not provide enough Zn and Ca to meet the Recommended Dietary Allowances (RDAs) for these nutrients established by the National Research Council, NAS, USA. If one uses the Recommended Nutrient Intake (RNI) value of 59 mg day^{-1} for Fe (i.e., for adult females between the ages of 19 and 50 preliminarily recommended by the joint FAO/WHO Expert Consultation (FAO/WHO, 2000)) instead of the USA's RDA for Fe of 15 mg day^{-1} then neither food system could supply enough Fe to meet the needs of people dependent on these systems for nourishment. These types of studies clearly indicate that many food systems are failing to provide enough nutrients to sustain healthy, active and productive lives for all citizens in many developing nations (Welch et al., 1997).

Improving plants as sources of micronutrients

What can plant nutritionists do to enhance the nutritional quality of plant foods? Cultural practices

Table 3. Effects of increasing Zn and Se supplies to wheat plants grown in nutrient solutions on the concentration of Zn and Se in mature wheat grain and bioavailable amounts of Zn and Se in the grain when fed to Zn-depleted rats in a single meal (data from House and Welch, 1989)

Zn supplied (μM)	Se supplied (μM)	Zn in grain (μg g^{-1}, dry wt.)	Se in grain (μg g^{-1}, dry wt.)	Bioavailable Zn (μg absorbed from meal)	Bioavailable Se (μg absorbed from meal)
1.0	0.3	8.8	0.6	5.9	0.41
1.0	1.5	9.3	3.8	5.5	2.03
5.0	0.3	33.0	0.6	18.7	0.42
5.0	1.5	36.1	4.3	15.4	1.91

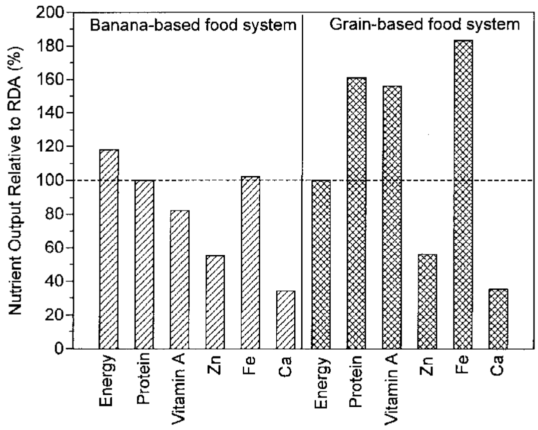

Figure 4. Output of nutrients (i.e., energy, protein, vitamin A, Zn, Fe and Ca) for two Ugandan food systems (banana-based and grain-based) relative to the recommended daily allowance (RDA) expressed as a percent of required nutrient intake (i.e., percent of RDA). Values were calculated on a consumption unit basis (data from McIntyre et al., 2001).

used by agriculturalists can affect the output of available nutrients from agricultural systems (Salunkhe and Deshpande, 1991; Welch, 1995). However, current agricultural practices are almost always directed at maximizing production while minimizing costs. Recently, in some nations, preserving the environment is becoming a more important objective of agriculture (i.e., 'sustainable' agricultural goals). Maximizing nutrient output of farming systems has never been a purport of either agriculture or of public policy. Yet, scientific knowledge is available that could greatly improve the micronutrients output of farming systems, and the available micronutrient content of the food crops produced. The debilitating effects of micronutrient malnutrition on people and societies and its current magnitude in developing nations certainly testifies to the need to consider doing so now. The following discussion briefly presents some examples of how some cultural and agronomic practices could be used to enhance the micronutrient output garnered from farming systems.

Cultural practices

Both macronutrient fertilizers containing N, P, K, and S, and certain micronutrient fertilizers containing, for example Zn, Ni, and Se, can have significant effects on the accumulation of micronutrients in edible plant products (Allaway, 1986; Grunes and Allaway, 1985). Other micronutrient fertilizers have very little if any effect on the amount of the micronutrient accumulated in edible seeds and grains when they are applied to soils or when used as foliar sprays (Welch, 1986). This is especially true for those micronutrient elements with limited phloem sap mobility such as Fe, B, V and Cr. Some examples of the effects of fertilizer practices on the micronutrient concentrations in edible plant parts are given below. For more detailed information concerning the effects of fertilization practices on micronutrient accumulation in plant foods refer to Allaway (1975), Grunes and Allaway (1985), Karmas and Harris (1988), Nagy and Wardowski (1988), Salunkhe and Desai (1988) and Welch (1997).

Excessive N fertilizers can adversely affect the accumulation of vitamin C in various vegetable crops such as lettuce (*Lactuca sativa* L.), beets (*Beta vulgaris* cicla L.), kale (*Brassica oleracea acephala* DC.), endive (*Cychorium endivia* L.), and brussels-sprouts (*Brassica oleracea gemmifera* DC.) by as much as 26% (cited in Salunkhe and Desai, 1988). However, increasing the amount of K fertilizer supplied to these crops significantly increased their vitamin C content by about 8–20% depending on the species. The concentration of β-carotene in carrot (*Ducus carota* subsp. *carota sativus* (Hoffm.) Arcang.) roots increased at first harvest in response to increases in the N supplied. β-carotene increased from 113 mg 100 g^{-1} root in those plants supplied 0.3 g N per pot to 126 mg 100 g^{-1} root dry weight (about 12% increase) for plants treated with 2.4 g N per pot (Habben, 1972 cited in Salunkhe and Desai, 1988). By the third harvest the increase in β-carotene level resulting from increasing N supply was only about 7%, but the late harvest resulted in an increase in the level of β-carotene even in the lowest N treatment from 113 to 136 mg 100 g^{-1} demonstrating a large effect of harvest date on β-carotene content of carrot.

Macronutrient treatments can influence the concentration of β-carotene and other micronutrients in carrots (Welch, 1997). Vereecke, in 1979 (cited in Salunkhe and Desai, 1988) reported results of studies concerning the effects of combined N, P, K and Mg fertilizers on β-carotene, Fe, Mn, Zn and Cu in carrot root. Treatments containing N, P and Mg increased the accumulation of β-carotene in carrot roots by 42% compared to roots from unfertilized control plants. Adding K to the combined N and P fertilizer treatments increased the β-carotene by 27% over-fertilized plants not receiving K. Removal of Mg from the fertilizer mix lowered the increase in β-carotene from 42 to 30%. Apparently, Mg was required for maximum β-carotene production in carrot roots furnished adequate N, P, and K. Vereecke also reported the effects of these treatments on Fe, Mn, Zn and Cu in carrot leaves at two harvest dates. Large effects were found on the Mn and Fe content of the leaves, but the other micronutrients determined were not greatly effected by fertilizer treatments. Combined treatments with N, P, K and Mg increased leaf Fe and Mn concentrations at a late harvest by 20% (from 194 to 234 μg Fe g^{-1} dry wt.) and 43% (56 to 136 μg Mn g^{-1} dry wt.), respectively.

The vitamin C concentration in fruits is also affected by macronutrient fertilizers. As with vegetable crops, excessive N fertilization has been reported to reduce vitamin C concentration in the fruits of several species including oranges, lemons, mandarins, cantaloupe, and apple. Also, higher rates of K fertilization are associated with greater concentration of vitamin C in fruits (Nagy and Wardowski, 1988). Apparently, the effects of Zn, Mg, Mn, and Cu fertilization on increasing vitamin C concentration in citrus fruits is limited to soils that are deficient in these elements. Supplying more of these elements than is required for optimum yield does not increase further vitamin C level in the fruit.

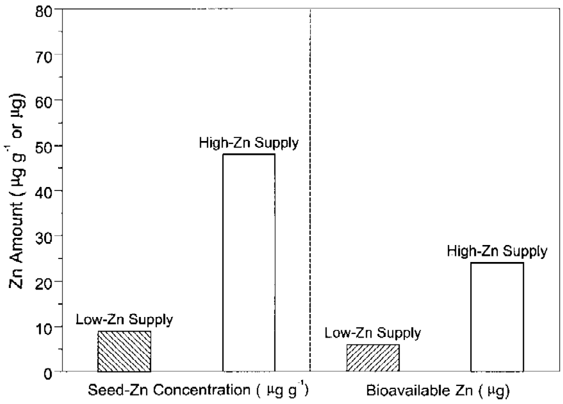

Figure 5. Effects of increasing Zn supply to pea (*Pisum sativum* L.) plants, grown in ^{65}Zn radiolabeled nutrient solutions, on Zn concentration (μg g^{-1}) and bioavailable Zn (μg Zn g-diet^{-1}) in mature pea seeds fed in single meals to Zn-depleted rats (data from Welch et al., 1974).

For certain essential micronutrient elements (e.g., Zn, Ni, and Se), increasing their supply to food crops can result in significant increases in their concentrations in edible plant products. For example, increasing the supply of Zn to pea plants (*Pisum sativum* L.) at levels in excess of that required for maximum yield has been shown to increase the concentration of bioavailable Zn in pea seeds (Peck et al., 1980; Welch et al., 1974). Furthermore, increasing the supply of Zn and Se to wheat, *Triticum aestivum* L. (see Figure 5) (House and Welch, 1989) is also effective. This has also been shown for navy beans (*Phaseolus vulgaris* L.) as well as other crops (Moraghan, 1994; Peck et al., 1980).

For iron, providing more to plants than required to sustain growth does little to further increase the Fe in edible seeds and grains (for example see Welch and Van Campen, 1975). The accumulation of micronutrient elements in seeds and grains is controlled by a number of processes including root-cell uptake, root-shoot transfer, and the ability of leaf tissues to load these nutrients into the vascular phloem elements which are ultimately responsible for delivering these nutrients to developing seeds and grains via the phloem sap (Welch, 1986). Phloem loading and unloading of these nutrients is tightly controlled by poorly understood hemostatic mechanisms in the plant and further research should be carried out to understand these processes if we are to significantly increase certain micronutrient elements, such as Fe, in staple seeds and grains (Welch, 1995).

Soil amendments are frequently used by farmers to adjust soil pH and to enhance plant growth properties of soils. Using lime ($CaCO_3$) raises soil pH, permitting acid-intolerant legume species to grow in soils that would otherwise be to acidic for their growth. It is also used to supply Ca to plants. However, adding lime may depress the uptake of Zn, Cu, Fe, and Co, and increase the uptake of Se and Mo by plants. A high soil-pH favors the oxidation of reduced forms of Se such as Se^{-2} and $SeO_3{}^{-2}$ to the more soluble and plant-available $SeO_4{}^{-2}$ anion. Gypsum ($CaSO_4$) and elemental S are used to decrease the pH of alkaline soils as well as to provide S for plant uptake and to ameliorate high-Na alkali soils. Using gypsum on alkaline soils could increase plant-available Fe, Mn, Zn, Cu, and Co by decreasing alkaline soil pH.

The use of farm-yard manures and other forms of organic matter can also change plant-available micronutrients by changing both the physical and biological characteristics of the soil. In many circumstances these changes improve soil physical structure and water holding capacity, resulting in more extensive root development and enhanced soil microflora and fauna activity, all of which can affect available micronutrient levels in soil to plants (Stevenson, 1991, 1994). However, very few controlled experiments have been done to determine which types of organic matter practices significantly enhance or depress the levels of micronutrients in edible portions of major food crops. More research should be carried out to understand the impact of various types of organic matter on crop nutritional quality.

Genetic manipulation

Breeding for micronutrient-dense varieties of staple foods is also a powerful tool to use in the fight against micronutrient malnutrition. Recent findings from an international project among several Consultative Group on International Agricultural Research (CGIAR) centers (including the International Food Policy Research Institute (IFPRI), the International Rice Research Institute (IRRI), the *Centro Internacional de Agricultura Tropical* (CIAT) and the *Centro International de Mejoramiento de Maiz y Trigo* (CIMMYT)), the University of Adelaide, Waite Campus, and the USDA, ARS U.S. Plant, Soil and Nutrition Laboratory show that it is possible to breed for enhanced levels of iron, zinc and provitamin A carotenoids in edible portions of rice, wheat, maize, beans and cassava (see Graham et al., 2001, for an extensive review of these findings). The findings show:

- there is enough genetic variation in concentrations of these micronutrients among lines in the major germplasm banks to justify selection
- micronutrient-density traits are stable across environments
- it is possible to combine micronutrient-rich traits with high yield
- genetic control is fairly simple making breeding for the traits economical
- several limiting micronutrients can be improved simultaneously
- both seedling vigor and nutritional quality are improved through genetically modifying seeds with micronutrient enrichment traits

Combining both human nutrition with improved agricultural productivity from such breeding efforts results in extremely high cost/benefit ratios for investing in this type of micronutrient intervention (i.e., better than 1:50). Furthermore, the adoption and spread of micronutrient-enriched seeds by farmers can be driven by profit incentives because micronutrient enriched seeds increase crop productivity when planted to micronutrient-poor soils (Graham et al., 2001). The benefits can be disseminated widely and they are sustainable once developed unlike current micronutrient interventions that rely on supplements or food fortificants (Graham et al., 2001; Graham and Welch, 2000; Welch et al., 1997).

Importantly, not only will it be necessary to increase the content of micronutrients in plant foods, but also the absorption and utilization (i.e., bioavailability) of micronutrients in meals containing plant foods must be improved (Graham and Welch, 1996). Plant foods can contain various substances, both antinutrient and promoter substances, that interact with micronutrients to either lower or enhance, respectively, their bioavailability to humans (Graham et al., 2001). These substances can also be manipulated by agricultural practices (Graham et al., 2001) and by genetic manipulation (Lucca et al., 2001; Watson, 1995).

Modern recombinant DNA technology can be used to enhance the nutritional quality of food crops such as increasing the amount and bioavailability of micronutrients in plants (DellaPenna, 2001; Forssard et al., 2000; Goto et al., 1999, 2000; Kishore and Shewmaker, 1999; Lucca et al., 2000, 2001). 'Golden rice' is such an example where recombinant DNA technology was used to improve the provitamin A content of rice-grain endosperm (Ye et al., 2000). Another example was reported by Goto et al. (1999). They enriched rice-grain endosperm Fe by transforming rice plants using a phytoferritin (a major protein storage form of Fe in plants) gene from soybean and a rice endosperm promoter gene. They were able to more then double the rice-grain concentration of Fe (i.e., from about 14 μg Fe g^{-1} in the non-transformed rice to about 37 μg Fe g^{-1} in the transformed rice) using this procedure. Lucca et al. (2001) also reported enriching the Fe concentration in rice-grain endosperm using the phytoferritin gene from pea plants.

A recent human study supports the contention that the Fe in soybean-phytoferritin is highly bioavailable to humans. The bioavailable Fe in intrinsically radiolabeled soybeans was determined in Fe-depleted women. The absorption of the labeled Fe averaged 27% of the dose when the soybeans were fed either as a soybean soup or as a soybean muffin in single meals (personal communication from Elizabeth C. Theil, Children's Hospital Oakland Research Institute, Oakland, CA). This finding suggests that, possibly, other staple food crops should be genetically modified to accumulate more phytoferritin in their edible portions. Doing so would give another powerful tool to nutritionists to use in addressing iron deficiency in the developing world.

Synergies exist between various micronutrients and their bioavailability to humans from plant food sources. For example, the bioavailability of Fe from cereal grains to humans is enhanced by β-carotene (Graham et al., 2001). Apparently, this interaction between Fe and β-carotene alleviates the negative effects of the antinutrient, phytate, on reducing Fe absorption from the human gut. Because cereal grains contain substantial amounts of phytate, modifying cereal grains to contain greater levels of both Fe and β-carotene would result in greatly improved nutritional value of cereal grains for humans. Modern transgenic technologies provide new tools to do such transformations. However, ingesting β-carotene-rich plant foods (such as carrots and sweet potatoes) with meals containing cereal grains could produce similar synergies and making more of these foods available in food systems is also an important tool to use in reducing micronutrient malnutrition.

Conclusions

Agriculture must change in ways that will closely link food production to human health and nutritional requirements. Holistic food system models hold promise in providing sustainable interventions to these complex nutrition and health problems (Combs et al., 1996). Plant nutritionists can and should play an important role in such efforts in the future. Sustainable solutions to micronutrient malnutrition can only be found in forming a nexus between agricultural production and human health. Because the magnitude of the problem is so great we must use every tool at our disposal to eliminate this scourge from the world.

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