AGRICULTURAL AND MOLECULAR GENETIC APPROACHES TO IMPROVING NUTRITION AND PREVENTING MICRONUTRIENT MALNUTRITION GLOBALLY

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Contents

Summary

The world population is expanding very rapidly, and expected to grow from 6 billion in 2002 to around 8 billion in 2020, with very high numbers of undernourished people. About 50 percent of the world population suffers from micronutrient deficiencies (micronutrient malnutrition), particularly in the developing world. Micronutrient deficiencies, such as iron (Fe), zinc (Zn), and vitamin A deficiencies, are critical nutritional issues and result in severe impairments of human health and development, such as impaired physical growth, immune system function, mental and cognitive development, and increases in anemia, maternal mortality, and infections. A large number of the world's peoples rely on a few staple cereals (e.g. wheat, rice, and maize) as a major source of dietary energy and protein, which, as commonly eaten, are extremely poor in certain micronutrients such as Fe, Zn, and vitamin A. Currently, food systems cannot provide enough balanced micronutrients to meet the daily requirements and sustain the well-being of people in the developing world. Heavy and monotonous consumption of cereal-based foods with low concentrations and limited bioavailability of micronutrients has been considered a major reason for the high prevalence of micronutrient deficiencies in many developing countries. Traditional plant breeding approaches hold great promise and provides more cost-effective and sustainable solutions when compared to other approaches, such as supplementation and food fortification programs, in reducing the extent of micronutrient deficiencies globally. In recent years, international agricultural research institutes, especially the Consultative Group on International Agricultural Research (CGIAR) centers, have made impressive progress in screening and developing plant genotypes with enhanced amounts and utilization (biological availability) of micronutrients in edible parts of staple food crops, such as cereal grains. Substantial genetic variations have been found in different food crops for higher levels of Fe, Zn and vitamin A and also for lower levels of antinutrients (i.e. phytic acid and tannins). These variations are currently being exploited to increase levels of micronutrients and eliminate antinutritional substances by using traditional and marker-assisted breeding approaches as well as genetic engineering techniques. The efforts to manipulate the genes affecting nutritional quality traits of food crops have already yielded significant progress. Presently, several transgenic plants are available containing enhanced concentration of Fe, vitamin A, and S-containing amino acids and lower levels of antinutrients such as phytate. In the future, top priority should be given to development of plant genotypes with enhanced levels of more than one micronutrient. To speed progress and maximize international awareness, agriculture, health, and nutrition sectors, at both national and international level, should stress social, economic, and health consequences of micronutrient deficiencies, and provide significant funding opportunities for the development of sustainable, agriculture-based approaches to preventing micronutrient deficiencies.

1. Introduction

Micronutrients are the essential mineral elements and vitamins that are required by humans in tiny amounts. Their low, required intake not withstanding, they are absolutely essential for human life and just as important as all other nutrients (e.g. essential amino acids, fatty acids, and water) for good health and well-being. Remove any one of them from people's diets and those individuals will develop deficiency disorders that dramatically diminish health, vitality, cognitive abilities, work efficiency, longevity, and quality of life.

Disturbingly, deficiencies of micronutrients (i.e. micronutrient malnutrition or "hidden hunger") currently afflict more than 2 billion people or about half of the world's population. The consequences of micronutrient deficiencies to human health and well-being are insidious and devastating to those people and societies most affected. Micronutrient malnutrition mostly occurs in women, infants, and children of resource-poor families in the developing world. These deficiencies lead to increased national mortality and morbidity rates, substandard health, lost worker productivity (impairing social and national development efforts), impaired cognitive function, and reduced educational attainment, depressed family livelihoods, and a poor quality of life.

1.1. Agriculture, the Availability of Micronutrients, and Health

People's health depends on their consuming enough nutrients in proper proportions to meet their daily requirements. Importantly, nearly all the nutrients consumed by humans are derived either directly from agricultural products (i.e. food crops and animal products) or via processed foods prepared from such products. Therefore, the agricultural sector plays a paramount role in providing nutrients to satisfy human needs. If agricultural systems do not provide enough nutrients in proper balance to meet these needs then some people in certain sectors of society will develop nutrient deficiencies that adversely affect their lives and society suffers.

Unfortunately, providing adequate nutrient output to meet human needs has never been an accepted or explicit goal of agriculture. Generally, crop productivity and profit motives drive agricultural enterprises in free market economies. These driving forces behind agricultural production can result in over production of some nutrients while the needed levels of some nutrients are not met. This is especially true for the micronutrients. It is essential that governments support agricultural policies that will encourage adequate levels of all nutrients for their citizenry. If not, widespread nutritional diseases will develop, the underprivileged will suffer, economies will decline, national development may stagnate, society will regress, civil unrest may ensue, and political systems may falter. Examples of imbalances in nutrient output of agricultural systems and the effects on human health are discussed below as they pertain to certain global regions.

1.1.1. Micronutrient Requirements

The known micronutrients include fifteen trace elements and thirteen vitamins. Table 1 lists these nutrients, their required dietary levels for adult males and examples of food sources rich in these nutrients. Other micronutrients may be added to this list in the future. For example, cadmium (Cd), aluminum (Al), lithium (Li), and lead (Pb) have been considered for inclusion on the list of essential micronutrients, although available scientific evidence does not warrant their inclusion to date.

Micronutrient	RDA[a] (mg day^{-1})	Examples of foods that are rich sources
Elements		
Iron (Fe)	10	meats, poultry, fish, eggs, liver, peas, nuts, dried fruits
Iodine (I)	150	iodized salt, seafood, seaweed, dairy products
Zinc (Zn)	15	meat, poultry, fish, dairy products
Selenium (Se)	0.07	shellfish, kidney, liver, meats, poultry, garlic, Brazil nuts
Copper (Cu)	1.5–3.0[b]	liver, shellfish, nuts, seeds, whole grains, potatoes
Molybdenum (Mo)	0.075–0.25[b]	milk, beans, whole grains, leafy vegetables, liver
Chromium (Cr)	0.05–0.2[b]	meats, whole grains, broccoli, brewer’s yeast
Manganese (Mn)	2.0–5.0[b]	whole grains, nuts, vegetables, fruits, beans
Silicon (Si)	—[c]	whole grains, pectin from citrus fruits, high fiber vegetables
Nickel (Ni)	—[c]	buckwheat, rye, barley, peas, beans
Boron (B)	—[c]	fruits, leafy vegetables, nuts, legume seeds, wine, beer
Vanadium (V)	—[c]	whole grains, shellfish, spinach, parsley, mushrooms
Arsenic (As)	—[c]	seafood
Tin (Sn)	—[c]	canned foods, nuts
Fluoride (F)	1.5–4.0[b]	seafood with bones, tea
Vitamins		
Vitamin A	1.0	liver, eggs, cheese, butter, red peppers, carrots, pumpkin
Vitamin C	60	fruits, vegetables, organ meats
Vitamin D	0.005	fish liver oil, salmon, sardines, corn oil, poultry skin
Vitamin E	10	wheat germ, sunflower and safflower oils, whole grains
Vitamin K	0.08	green leafy vegetables
Thiamin	1.5	brewer’s and baker’s yeast, liver, cereal grains
Riboflavin	1.7	green leafy vegetables, meats, dairy products, broccoli

Niacin	19	beans, chicken, pork, buckwheat, whole grains, yeast, peas
Vitamin B_6	2.0	meats, whole grains, vegetables, nuts
Biotin	30–100[b]	royal jelly, brewer's yeast, milk, liver, egg yolk, vegetables
Pantothenic acid	4–7[b]	liver, heart, mushrooms, avocados, broccoli, whole grains
Folate	0.2	liver, mushrooms, green leafy vegetables, soybeans
Vitamin B_{12}	0.002	meat and bone meal, fish meal, whey, liver, oysters, eggs

Notes: [a] Recommended dietary allowance: values are for males 25–50 years of age; data from Recommended Dietary Allowances, National Research Council (NRC), National Academic Press, 1989.
[b] Estimated safe and adequate daily dietary intake; no recommended dietary allowance is reported.
[c] No intakes were recommended for these micronutrients by the NRC, NAS in 1989.

Table 1. Micronutrient requirements of adult men and examples of rich food sources

1.1.2. Changing Cropping Systems: Unforeseen Consequences of the "Green Revolution"

During the middle of the twentieth century the agricultural community was faced with an enormous challenge: how to provide enough food to feed a global population that would more than double during the subsequent fifty years. Not having done so would have resulted in widespread famines and extensive human misery in many developing countries. The success of this massive agricultural undertaking (now referred to as the "Green Revolution") is one of the most impressive accomplishments of the millennium. Its success was almost entirely the result of dramatic increases in the yields of the cereal crops—rice, wheat, and maize—in the developing world. Unfortunately, there were some unforeseen consequences of the cereal cropping systems used to create the "Green Revolution."

Providing enough "food" does not necessarily mean that the food produced will supply enough of all the nutrients needed to support good health. This appears to be the case for the agricultural systems fostered during the "Green Revolution." While whole cereal grains provide enough carbohydrates (calories) and protein to stave off famine, they do not provide enough of all the utilizable micronutrients needed to sustain life, being very low in bioavailable amounts of many micronutrients compared to other staple food crops, such as pulse seeds (see Table 2). For example, they fail to provide enough iron and zinc as well as several vitamins (e.g. vitamin A and vitamin C).

Plant food	Fe	Zn	Mn	Cu	Mo	Cr	Ni
	($\mu g\ g^{-1}$ dry weight)						
Brown rice[1]	22	14	11	2.4	0.78	0.088	–

Soft wheat[2]	–	22	35	4.5	–	0.370	0.31
Mung bean[3]	87	41	14	13.0	3.20	0.251	2.04
Black gram[3]	139	36	19	7.9	0.16	0.530	3.43
Cowpea[3]	67	45	16	6.3	1.47	0.272	3.44
Soybean[4]	97	43	26	15.5	–	–	–
Red kidney bean[5]	64	30	12	6.8	–	–	–

Notes: [1] Data from Doesthale et al. (1979).
[2] Data from Zook et al., (1970).
[3] Unpublished data provided by R. M. Welch.
[4] Data from Holland et al. (1991).
[5] Data from Holland et al. (1991).

Source: Welch (2001).

Table 2. Comparisons between the micronutrient element concentrations in whole cereal grains and pulse seeds

Additionally, modern refining operations further degrade the nutritional value of cereal grain (see Table 3) by removing the micronutrient-rich germ and aleurone layers of the grains. Thus, other foods besides cereals must be eaten with processed cereals to maintain the micronutrient balance needed for good health.

Micronutrient [a]	Brown rice	Polished rice	% removed
Iron (mg kg^{-1})	30	10	67
Copper (mg kg^{-1})	3.3	2.9	12
Manganese (mg kg^{-1})	17.6	10.9	62
Zinc (mg kg^{-1})	18	13	30
Biotin (µg kg^{-1})	120	50	58
Folic acid (µg kg^{-1})	200	160	20
Niacin (mg kg^{-1})	47	16	66
Pantothenic acid (mg kg^{-1})	20	10	50
Riboflavin (mg kg^{-1})	0.5	0.3	40
Thiamin (mg kg^{-1})	3.4	0.7	80
Vitamin B_6 (mg kg^{-1})	6.2	0.4	94
Vitamin E (IU kg^{-1})[b]	20	10	50

Notes: [a] Dry weight basis.

[b]IU = International Unit.

Source: Salunkhe and Deshpande (1991).

Table 3. Polishing and milling operations dramatically reduce many micronutrients in whole brown rice grain

Modern cereal cropping systems have resulted in dramatic reductions in food diversity for all nations. Today, twenty-two crop species (see Figure 1) account for most of the food crops produced on earth. Not only have the types of food crop species declined, but the genetic diversity in each food crop has also dramatically decreased since the turn of the century (see, for example, the data for the United States in Figure 2). Indeed, the spread of modern cereal cropping systems has been paralleled by a decline in production of many traditional staple foods that are much richer in micronutrients compared to processed cereal crops, as shown for pulses in Figure 3. Clearly, increases in cereal production more than kept pace with population growth during the twentieth century, but pulse production lagged far behind cereal production not even keeping up with population increases. This shrinking diversity in the world's food basket has lowered the availability of foods rich in many micronutrients. Obviously, those agricultural changes that occurred during this period have resulted in greatly increased cereal production, but at the expense of food crop diversity, resulting in lower balanced micronutrient output of these modern agricultural systems.

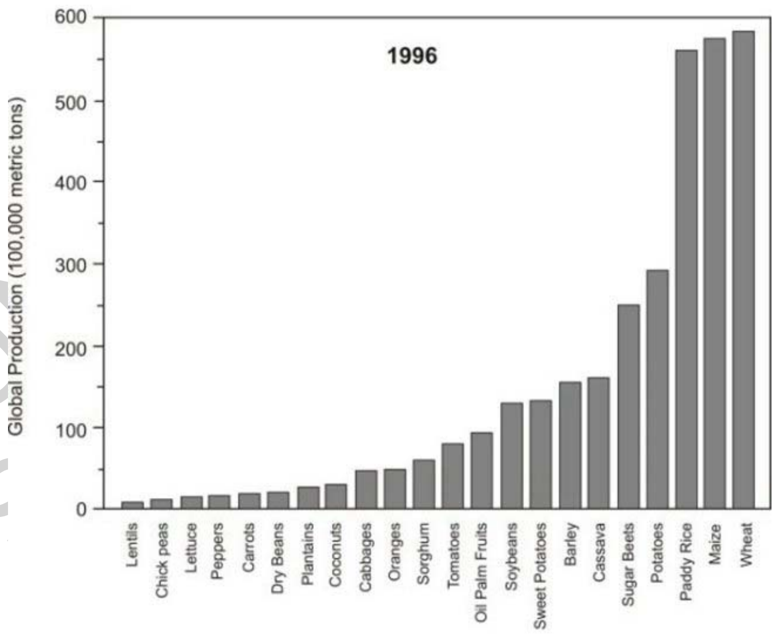

Figure 1. Globally, twenty-two major food crops dominated available food supplies in 1996
Source: Mann (1997).

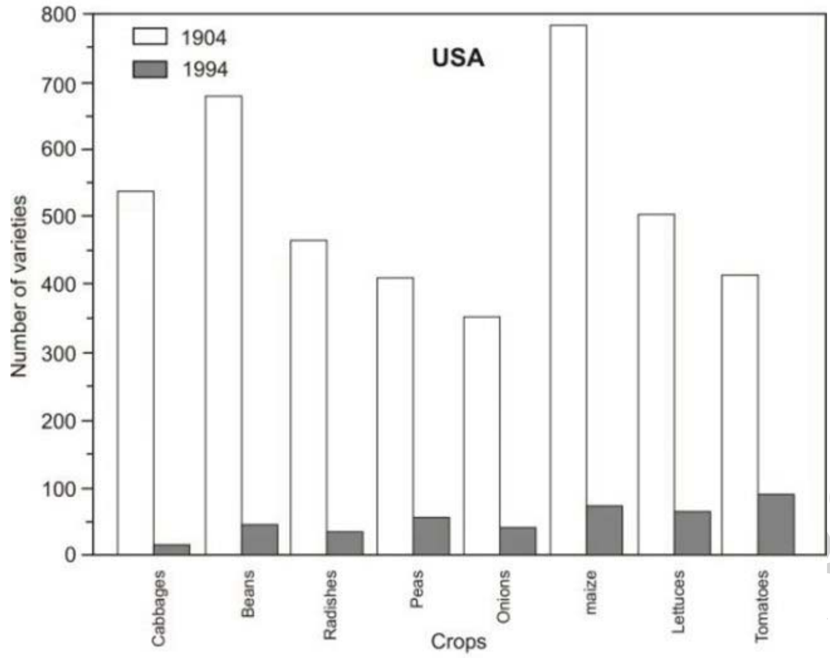

Figure 2. The number of varieties of certain crop species grown in 1904 as compared to the number of varieties of those same species grown in 1994 in the US
Source: Edwards (1996).

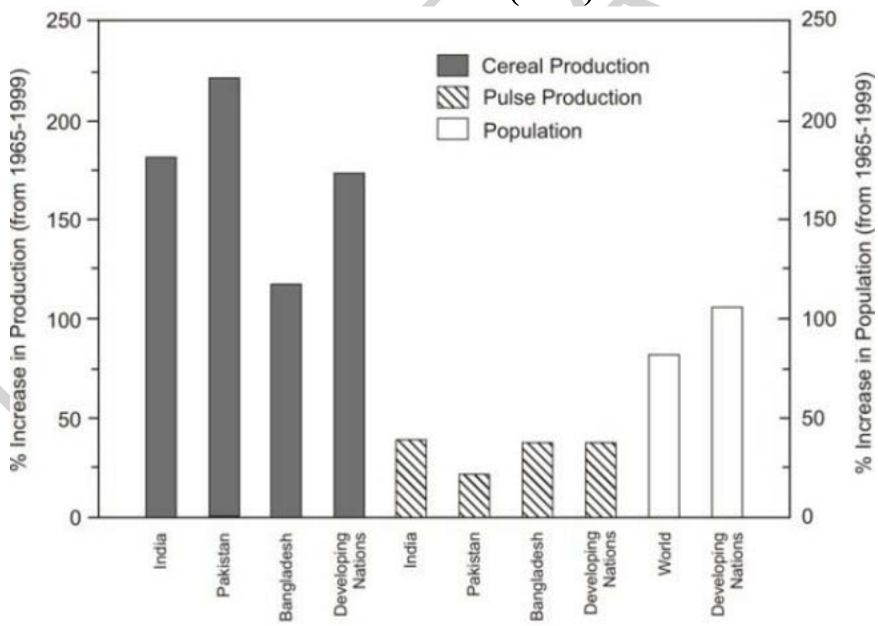

Figure 3. Percent increases in cereal and pulse production in developing nations and certain South Asian countries and associated population changes 1965–99
Source: FAOST database (1999) http://apps.fao.org.

What effects have modern cereal cropping systems had on the nutritional health of people in the developing world? As a result of reductions in food diversity resulting from the introduction of these systems, the availability of certain micronutrients has declined and micronutrient deficiencies have increased in certain population groups within developing countries.

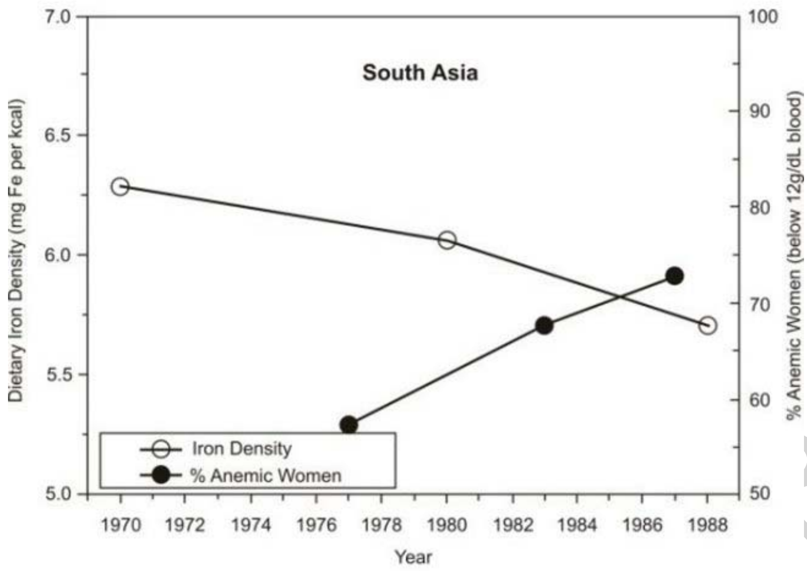

Figure 4. Trends in South Asian dietary Fe density and in Fe deficiency anemia in women 1970–88

Source: redrawn from Welch and Graham (1999).

This is especially true for iron deficiency anemia among women of childbearing age in South Asia (see Figure 4). Globally, iron deficiency has grown from about 30 percent in the 1960s to over 40 percent in the mid-1990s. These trends are expected to continue unless ways are found to increase the availability of iron and other micronutrients in food systems of developing nations.

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Bibliography

Bouis, H.; Graham, R. D.; Welch, R. M. 2000. The Consultative Group on International Agricultural Research (CGIAR) Micronutrients Project: Justification and Objectives. *Food Nutrition Bulletin*, No. 21, pp. 374–81. [This study reports on the CGIAR Micronutrient Project and its preliminary results.]

Cakmak, I.; Kalayci, M.; Ekiz, H.; Braun, H. J.; Kilinc, Y.; Yilmaz, A. 1999. Zinc Deficiency as a Practical Problem in Plant and Human Nutrition in Turkey: a NATO-Science for Stability Project. *Field Crops Research*, No. 60, pp. 175–88. [Comprehensive overview of results obtained from a long-term project dealing with Zn deficiency problem in Turkey.]

Cakmak, i.; Ozkan, H.; Braun, H. J.; Welch, R. M.; Romheld, V. 2000. Zinc and Iron Concentrations in Seeds of Wild, Primitive and Modern Wheats. *Food Nutrition Bulletin*, No. 21, pp. 401–03. [Research paper reporting on Zn and Fe concentrations in seeds of different wild, primitive and modern wheats.]

DellaPenna, D. 1999. Nutritional Genomics: Manipulating Plant Micronutrients to Improve Human Health. *Science*, No. 285, pp. 375–9. [This review covers roles of nutritional genomics in manipulating micronutrient concentration in plants.]

Edwards, R. 1996. Tomorrow’s Bitter Harvest. *New Scientist,* No. 151, pp. 14–15. [Commentary on the potential impact of the rapid loss of genetic diversity among crops on agricultural productivity.]

Frossard, E.; Bucher, M.; Machler, F.; Mozafar, A.; Hurrell, R. 2000. Potential For Increasing the Content and Bioavailability of Re, Zn And Ca in Plants for Human Nutrition. *Journal of Agricultural and Food Chemistry,* No. 80, pp. 861–79. [A review paper covering a wide range of aspects dealing with increasing concentration and bioavailability of micronutrients in food crops by plant breeding and genetic engineering.]

Goto, F.; Yoshihara, T.; Shigemoto, N.; Toki, S.; Takaiwa., F. 1999. Iron Fortification of Rice Seeds by the Soy Bean Ferritin Gene. *Nature Biotechnology,* No. 17, pp. 282–6. [This research paper describes increases in Fe concentration in transgenic rice by overexpression of a soy bean ferritin gene.]

Graham, R. D.; Senadhira, D.; Beebe, S. E.; Iglesias, C.; Ortiz-Monasterio, I. 1999. Breeding for Micronutrients Density in Edible Portions of Staple Food Crops: Conventional Approaches. *Field Crop Research,* No. 60, pp. 57–80. [Comprehensive review on progress obtained in a long-term research project dealing with improvement of nutritional quality of staple food crops.]

Graham, R. D.; Welch, R. M.; Bouis, H. E. 2001. Addressing Micronutrient Malnutrition Through Enhancing the Nutritional Quality of Staple Foods: Principles, Perspectives and Knowledge Gaps. *Advances in Agronomy,* No. 70, pp. 77–142. [A comprehensive review on the role of agricultural approaches to provide adequate and balanced nutrients to the world population.]

Huang, C.; Graham, R. D. 2001. Improving Nutritional Quality and Agronomic Characteristics of Crop Plants Through Plant Breeding. In: *Perspectives on the Micronutrient Nutrition of Crops.*K. Singh, s. Mori, R. W. Welch (eds.) Scientific Publisher, Jodhpur, India. pp. 225–46 [This review paper provides comprehensive overview on improvement of food crops with high nutritional quality through plant breeding.]

Lucca, P.; Hurrell, R.; Potrykus, I. 2001. Genetic Engineering Approaches to Improve The Bioavailability and the Level of Iron in Rice Grains. *Theoretical and Applied Genetics*, No. 102, pp. 392–7. [Research paper reporting engineering of the genes involved in iron bioavailability in rice seeds.]

Mann, C. 1997. Reseeding the Green Revolution. *Science*, No. 277, pp. 1038–43. [Commentary on the need for a new “Green Revolution” and greater investment in agricultural research.]

Marschner, H. 1995. *Mineral Nutrition of Higher Plants*. London, Academic Press. 889 pp. [This book covers a wide range of aspects on the mineral nutrition of higher plants.]

National Research Council 1989. *Recommended Dietary Allowances*. Washington, D. C., National Academy Press. 284 pp. [A comprehensive document about the recommended dietary allowances of essential nutrients.]

Pinstrup-Andersen, P.; Pandya-Lorch, R.; Rosegrant, M. W. 1999. *World Food Prospects: Critical Issues for the Early Twenty-first Century. 2020 Vision Food Policy Report*. Washington, D. C., International Food Policy Research Institute. 32 pp. [Comprehensive overview on the state of food insecurity and the role of agricultural approaches to meet global demand for food production.]

Raboy, V. 2000. Low-phytic-acid Gains. *Food Nutrition Bulletin*, No. 24, pp. 423–7. [This review paper provides an overview on genetics and breeding of cereal genotypes with low-phytic acid content in seeds.]

Rengel, Z.; Batten, G. D.; Crowley, D. E. 1999. Agronomic Approaches for Improving the Micronutrient Density in Edible Portions of Field Crops. *Field Crops Research*, No. 60, pp. 27–40. [Comprehensive overview of the effects of fertilizers, soil amendments, and cropping systems on micronutrient density in edible parts of field crops.]

Rosegrant, M. W.; Leach, N.; Gerpacio, R. V. 1999. Alternative Future for World Cereal and Meat Consumption. *Proceedings of the Nutrition Society*, No. 58, pp. 219–34. [This paper reviews long-term prospects for cereal and meat supply and demand resulting from changes in global income and population growth.]

Salunkhe, D. K.; Deshpande, S. S. 1991. *Foods of Plant Origin: Production, Technology, and Human Nutrition.* AVI Book. New York, Van Nostran Reinhold. 501 pp. [Book covering various aspects of food production and nutritional quality of major food crops, including cereals and legume seeds.]

Van den Berg, H.; Faulks, R.; Granado, H. F.; Hirschberg, J.; Olmedilla, B.; Sandmann, G.; Southon, S.; Stahl, W. 2000. The Potential for the Improvement of Carotenoid Levels in Foods and the Likely Systemic Effects. *Journal of Agricultural and Food Chemistry*, No. 80, pp. 880–912. [Comprehensive review on functions, synthesis, and genetic manipulation of carotenoids.]

Vansuyt, G.; Mench, M.; Briat, J. F. 2000. Soil-Dependent Variability of Leaf Iron Accumulation in Transgenic Tobacco Overexpressing Ferritin. *Plant Physiology and Biochemistry*, No. 6, pp. 499–506. [Research paper reporting the effects of soil factors on leaf concentration of Fe in transgenic rice plants].

Welch, R. M. 2001. Micronutrients, Agriculture and Nutrition: Linkages for Improved Health and Well Being. In: *Perspectives on the Micronutrient Nutrition of Crops.* Eds.: K. Singh, S. Mori, R. W. Welch. Scientific Publisher, Jodhpur, India. pp. 247–89 [This review describes importance of micronutrients for plant and human nutrition, and emphasizes importance of plant breeding approaches to minimize the extent of micronutrient deficiencies in humans globally.]

Welch, R. M.; Graham, R. D. 1999. A New Paradigm for World Agriculture: Meeting Human Needs. Productive, Sustainable, Nutritious. *Field Crops Research*, No. 60, pp. 1–10. [This paper describes a new paradigm for agricultural and nutritional communities to provide adequate and balanced nutrition to human populations.]

Welch, R. M.; House, W. A.; Beebe, S.; Cheng, Z. 2000. Genetic Selection For Enhanced Bioavailable Levels of Iron in Bean *(Phaseolus vulgaris* L.) seeds. *Journal of Agricultural and Food Chemistry,* No. 48, pp. 3576–80 [Research paper reporting bioavailability of Fe from different bean genotypes by using feeding experiments with rats.]

WHO. 2000. Malnutrition Worldwide. http://www.who.int/ nut/malnutrition/worldwide.htm [This website provides the updated information on the global prevalence of micronutrient deficiencies in humans.]

Yang, X.; Ye, Z. Q.; Shi, C. H.; Zhu, M. L.; Graham, R. D. 1998. Genotypic Differences in Concentrations of Iron, Manganese, Copper, and Zinc in Polished Rice Grains. *Journal of Plant Nutrition*, No. 21, pp.1453–62. [Research paper dealing with genotypic variation in micronutrient concentrations of polished rice seeds.]

Ye, X.; Al-Babili, S.; Kloti, A.; Zhang, J.; Lucca, P.; Beyer, P.; Potrykus. I. 2000. Engineering the Pro-Vitamin A (B-Carotene) Biosynthetic Pathway into (Carotenoid-Free) Rice Endosperm. *Science*, No. 287, pp. 303–5. [Research paper describing a recombinant DNA technology to improve provitamin A concentration in rice endosperm.]

Yilmaz, A.; Ekiz, H.; Torun, B.; Gültekin, I.; Karanlik, S.; Bagci, S. A.; Cakmak, I. 1997. Effect of Different Zinc Application Methods on Grain Yield and Zinc Concentration in Wheat Grown on Zinc-deficient Calcareous Soils in Central Anatolia. *Journal of Plant Nutrition*, No. 20, pp. 461–71. [Research paper describing effects of different Zn application methods on leaf and seed concentration of Zn in wheat plants grown in Zn deficient soils.]

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