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Food system strategies for preventing micronutrient malnutrition

Dennis D. Miller[a] and Ross M. Welch[a]

Abstract

Micronutrients are defined as substances in foods that are essential for human health and are required in small amounts. They include all of the known vitamins and essential trace minerals. Micronutrient malnutrition affects a third to a half of the global population. It causes untold human suffering and levies huge costs on society in terms of unrealized human potential and lost economic productivity. The goal of this paper is to identify deficiencies in the food system that lead to micronutrient malnutrition and explore and evaluate strategies for its prevention. We examine the impact of agricultural practices on micronutrients in the food supply, including cropping systems, soil fertility and animal agriculture. We then discuss the potential of biofortification –i.e. increasing the concentration of micronutrients in staple food crops through conventional plant breeding or genetic engineering– as a means to reduce micronutrient deficiency. In addition, we discuss the impact of food losses and food waste on micronutrients in the food supply, and we explore successful strategies to preserve micronutrients from farm to plate, including food fortification. Our review of the literature sheds light on the advantages and limitations of alternative interventions to reduce micronutrient deficiencies along the supply chain. We end with recommendations for actions that will reduce the prevalence of micronutrient malnutrition.

Key words: Micronutrient malnutrition, dietary diversity, food processing, food waste, fortification, food systems, soil fertility, fertilization, animal agriculture, biofortification, nutrition education.

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1. Introduction

Micronutrients are substances in foods that are essential for human health and are required in small amounts. They include all of the known vitamins and essential trace minerals. Micronutrient malnutrition develops when intakes of bioavailable micronutrients are too low to meet requirements. It affects ⅓ to ½ of the world population. The 3 most prevalent forms of micronutrient malnutrition are iron, iodine, and vitamin A deficiencies (Allen et al., 2006). Zinc and vitamin B-12 deficiencies are also widespread. Consequences of micronutrient malnutrition include increased mortality rates, especially in women and children; poor pregnancy outcomes; increased morbidity; impaired mental and physical development in children; and reduced work productivity in adults (Black et al., 2008).

Both the density and bioavailability of micronutrients in the diet are important for achieving optimal micronutrient status. Nutrient density is the amount of a nutrient in a food per calorie or unit weight. Bioavailability is the proportion of an ingested nutrient that is absorbed and utilized for some essential metabolic function.

Food systems are linked to the nutritional wellbeing and heath of individuals and populations through the nutrients and other bioactive components contained in the foods they supply. Agriculture is the foundation of all food systems in that agricultural products are the primary source of most nutrients. If agriculture cannot supply all the essential nutrients in amounts required for good health and productive lives, malnutrition develops. To date, the primary focus of agricultural research, policy, and practice has been on increasing yields with little attention paid to improving the nutrient output of farming systems. Increasing yields is important but the nutritional quality of crops produced must also be a priority if sustainable progress toward reducing the prevalence of malnutrition is to be realized.

A basic tenet of a nutritionally adequate diet is the principle that it must contain a variety of foods from several different food groups. Therefore, strategies for improving the nutritional status of populations should include efforts to increase dietary diversity. However, while agricultural production is a necessary component of an adequate food supply, it is not sufficient. A well-functioning food value chain is also necessary to deliver food to the consumer. The food processing sector is an important component of the food value chain. Food processing can reduce food waste, prevent nutrient losses, increase nutrient content through fortification, enhance the acceptability of foods to consumers, reduce risk of foodborne illness, provide jobs and economic development, and reduce the time and energy required for home food preparation. Conversely, food processing can be detrimental to nutritional quality when it manufactures foods that are high in added sugar, fat, and sodium or when it removes nutrient dense fractions from whole foods as is often the case in cereal milling operations.

A major cause of micronutrient malnutrition in low income populations is lack of access to a variety of foods. When incomes are low, people rely on inexpensive sources of calories, such as cereals and tubers, to meet energy needs (Bouis et al., 2011a). These foods tend to be poor sources of many micronutrients. More nutrient dense foods such as fruits, vegetables, and animal products are more expensive and, as a result, are often beyond the reach of the poor (Bouis et al., 2011a).

Aim of this review

The aim of this review is to identify deficiencies in the food system that lead to micronutrient malnutrition and explore and evaluate strategies for its prevention. We examine the impact of agricultural and food processing practices on micronutrients in the food supply. We then discuss the potential of fertilization, plant breeding, food processing, and food fortification for enhancing the availability of micronutrients to consumers in both developing and developed countries. We conclude with key lessons to guide intervention policies.

2. Strategies for Preventing Micronutrient Malnutrition

Numerous factors throughout the food system impact the concentrations and bioavailabilities of micronutrients in food supplies and in the diets of individuals and families. Figure 1 provides an overview of the factors that influence the nutritional quality of diets that are ultimately consumed by people. Clearly, the task of designing interventions for preventing micronutrient malnutrition is complex given the multifactorial nature of the problem. We will organize our discussion of strategies into three categories: 1) Agricultural Production Strategies, 2) Food Processing Strategies, and 3) Economic and Consumer Education Strategies.

3. Agricultural Production Strategies

3.1 Background

There is growing support for the notion that agricultural interventions have an important role to play in efforts aimed at improving the nutritional status of populations (Welch, 2001; Masset et al., 2012). Since most human foods are products of agricultural enterprises, it should be obvious that agricultural policies designed to increase the production of a wide variety of nutrient-dense foods and make them available at affordable prices will increase intakes of deficient micronutrients and, ultimately, reduce prevalences of micronutrient malnutrition. Unfortunately there have been only a very limited number of studies designed to assess the effectiveness of agricultural interventions on nutritional status. Given that so many factors influence micronutrients in foods, a holistic food systems approach to combating micronutrient malnutrition is the only way to achieve sustainable solutions to micronutrient malnutrition (Graham et al., 2007; Combs, Jr. et al., 1996; Welch and Graham, 2005). Such an approach requires trans-disciplinary collaborations that include the agricultural sector. Various agricultural strategies including the use of fertilizers, improvements in cropping systems, and plant breeding for enhanced nutritional quality can be used to improve micronutrient output of farming systems.

The Green Revolution that began in the 1960’s was designed to meet the demand for food by a rapidly growing population. It focused on increasing agricultural production by promoting high-yielding cereal crops. It was very successful in helping countries like India become self-sufficient in calories and protein but an unintended consequence was that cereals displaced other more micronutrient dense crops such as legumes and vegetables. This led to an increase in the prevalence of micronutrient deficiency diseases (e.g. iron, zinc, and vitamin A deficiencies) (Welch and Graham, 2000; ACC/SCN, 1992).

Replacing fruit and vegetable crops with cereals lowers micronutrient output from agricultural systems because cereal crops, as normally consumed (milled/polished), have low micronutrient density compared to traditional crops from more diverse cropping systems. This is shown in tables 1 and 2 which compare the micronutrient composition of some cereal and legume crops and the effects of milling on iron and zinc levels in rice, maize, sorghum and wheat (Welch and Graham, 1999). Clearly, legume seeds are denser in micronutrients than cereals, especially when the cereal grains have been milled to remove the bran and germ layers.

3.2 Cropping Systems

Substantial evidence supports the notion that changes in cropping patterns to include more nutrient dense crops will increase the nutrient output of farming systems (McIntyre et al., 2001; Graham et al., 2007). McIntyre et al. (2001) evaluated two hypothetical Ugandan cropping systems for their potential to provide foods that would meet human requirements for energy, protein, vitamin A, calcium, iron, and zinc. They modeled cropping strategies capable of providing enough of these nutrients given the same resource base embedded in that cultural base. Their model showed that major changes in the allocation of land to crops would have to occur to meet their goals of providing enough of these nutrients. Graham et al. (2007) proposed cropping system improvements and alternative crop combinations as strategies for meeting nutritional goals while maintaining or improving agronomic and societal acceptability within the farming systems. Balancing crop nutrition through fertilization and other means, which normally increases crop productivity, would reduce the land area required to grow staple food crops that people depend on for meeting calorie needs. The land freed up could then be dedicated to more nutrient-dense food crops. The authors (Graham et al., 2007) presented case studies that illustrated these principles and strategies. They concluded that it is possible to design cropping systems to meet human needs within the constraints of local resources provided farmers have the knowledge and economic incentives to do so.

3.3 Soil fertility/Fertilization

In general, well-nourished crops grown on fertile soils have higher micronutrient density in edible portions than nutrient-stressed crops grown on infertile soils (Welch, 1998; Welch, 2001). For example, pea and wheat plants grown on zinc adequate media or high-selenium media when compared to those grown zinc-deficient or low-selenium media on contained about three fold more zinc (pea seeds) and fivefold more selenium (wheat grain) in their edible parts (Welch and Graham, 2002). Thus, soil micronutrient status and soil amendments are important factors that impact the micronutrient output of these systems. Some of these factors are discussed below.

Levels of available micronutrients in soils are an important factor in determining micronutrient content of crops (Allaway, 1986; Welch and Graham, 2005). When trace elements that are essential for plant growth, such as zinc, are deficient in the soil, informed farmers with sufficient resources will use micronutrient fertilizers to correct deficiencies of these nutrients in order to improve crop yields. However, farmers are unlikely to fertilize with trace elements such as selenium and iodine that are essential for humans but not for the crop without incentives or government regulations that would make doing so profitable or mandatory.

Associations between zinc-deficient soils and zinc deficiency in humans in developing countries in the Global South have been reported (Alloway, 2008; Graham et al., 2012; Welch, 2008). This suggests that zinc deficiency in humans in these countries may be linked to low available levels of zinc in soils which results in diminished levels of zinc in the staple food crops harvested and, therefore, is responsible for low levels of zinc entering the food systems in those regions. About 50% of all agricultural soils on earth have been reported to be too low in crop-available zinc for optimal crop yields (Sillanpaa, 1982; Sillanpaa, 1990). In more developed countries with more diverse food systems and the infrastructure to transport foods long distances from different regions and even from different countries, associations between soil zinc levels and human zinc deficiency are most likely weaker.

Associations between low soil concentrations and micronutrient deficiencies in humans have also been reported for iodine and selenium (Allaway, 1975). In the USA, iodine deficiency disorders in people and livestock were linked to low iodine levels in the water and soils on which food and forage crops were grown (i.e., the “Goiter Belt” region) before the widespread use of iodized salt began in the 1920’s. Low levels of soil iodine occur because iodine is easily leached from soils by rain or irrigation water. Natural replenishment of soil iodine is primarily via biogeochemical cycling of iodine from ocean spray inland. Thus in areas far from oceans, soils usually contain very low levels of iodine and produce crops containing inadequate levels of iodine to meet human needs (Johnson et al., 2003). Even today, iodine deficiency disorders are common in some areas, mostly in South Asia and Africa (Andersson et al., 2012).

The selenium content of food crops is also related to the available levels of selenium in the soils on which they are grown (Banuelos and Ajwa, 1999). An endemic selenium deficiency disease (Keshan disease) that can cause sudden death in humans has been reported in the Keshan region of China (Ge and Yang, 1993). In the USA, a selenium map of the 48 conterminous states was prepared and used by epidemiologists to show a negative association between selenium in forage crops (and by inference selenium in soils) and cancer risk in humans (Combs, 2005).

Clearly, available essential trace element levels in soils play an important role in supplying these nutrients to food systems and ultimately to meeting the nutritional requirements of people dependent on the crops grown in these soils. Detailed reviews of the effects of fertilization practices on micronutrient accumulation in plant foods have been published (Allaway, 1975; Karmas and Harris, 1988; Nagy and Wardowski, 1988; Salunkhe and Deshpande, 1991; Welch, 1997).

Other soil related factors may also influence the micronutrient output of farming systems. Macronutrient fertilizers (e.g., fertilizers that contain nitrogen, potassium, phosphorus, sulfur, calcium and/or magnesium), and soil amendments, such as lime, gypsum and organic matter, can affect the available forms of micronutrients in soils and the concentrations of micronutrients in crops grown on them (Allaway, 1986; Grunes and Allaway, 1985). For example, excessive nitrogen fertilization lowered vitamin C concentration in the fruits of several species including oranges, lemons, mandarins, cantaloupe, and apple (Nagy and Wardowski, 1988). Conversely, higher potassium fertilization rates were associated with greater concentrations of vitamin C in fruits (Nagy and Wardowski, 1988).

Farmers frequently apply soil amendments and organic matter to improve soil health and crop productivity. Liming soils with calcium carbonate reduces soil acidity, allowing acid-intolerant plant species to grow. Liming also increases the calcium available to plants. However, amending soils with lime may reduce the uptake of certain micronutrients including zinc, copper, iron, and cobalt, and increase the uptake of selenium and molybdenum. An alkaline soil pH favors the oxidation of reduced forms of selenium (Se^{2-} and SeO_3^{2-}) to the more soluble and plant-available SeO_4^{2-} anion. Gypsum ($CaSO_4$) and elemental sulfur additions are used to decrease the pH of alkaline soils as well as to provide sulfur for plants and to ameliorate alkali soils high in sodium. Using gypsum and elemental sulfur on alkaline soils can increase available iron, manganese, zinc, copper, and cobalt by reducing the soil pH thereby increasing the solubility of these elements in the soil solution.

Farm-yard manure and organic matter additions to soils can affect plant-available micronutrient elements by changing the chemical, physical and biological characteristics of the soil. Moreover, these changes can influence the vitamin and antioxidant content of food crops (Blair, 2012). These changes may also improve soil physical structure and water holding capacity, resulting in more extensive root development and enhanced soil microbiota and fauna activity, all of which improve micronutrient element levels available to plants (Stevenson, 1991; Stevenson, 1994). However, much more research is needed to understand all the implications that soil amendments and organic matter have on the nutritional quality of food crops (Magkos et al., 2003; Benbrook, 2009).

Selenium fertilization of crops in Finland produced a doubling of selenium levels in the blood of the people residing there (Combs, Jr., 2000; Mäkelä et al., 1993). The Finish government mandated that selenium fertilizers be used on cereal crops in Finland in the 1980's. In China in the 1980's selenium fertilizers were used to produce high selenium tea that was made into an elixir and used as a supplement to address selenium deficiency. Selenium deficiency in livestock has also been addressed by the use of selenium fertilizers which has the added benefit of increasing the levels of selenium in the meat and milk from animals eating the forage grown on the fertilized soils (Allaway, 1986). So while selenium fertilization benefits both animal and human health, it is important to use caution in applying selenium to soils because too much can result in environmental pollution of surrounding waters from runoff from the fertilized fields. Therefore, monitoring systems must be in place to determine if too much selenium is being applied via fertilizers to agricultural land.

Iodine (as potassium iodate) additions to irrigation water were used in some villages in irrigated regions of Northwestern China (Cao et al., 1994; Ren et al., 2008). One application to the farmers' fields via irrigation water corrected iodine deficiencies in the villagers consuming the crops grown on these fields for at least four years at a low cost (about $0.05 per person per year). More importantly, this strategy addressed the primary cause of iodine deficiency - not enough available iodine in the soil to meet human needs. Additionally, livestock productivity was also improved by about 30% because the livestock were also deficient in iodine. Increases in livestock productivity would translate into more disposable income for the farm families and more opportunity to diversify their diets. Just using iodized salt would not have had this food system-wide effect. Correcting the root cause of the iodine deficiency within the agricultural system benefited the entire system.

Soil application of zinc fertilizers can increase zinc levels in edible portions of food crops (Cakmak et al., 2010; Cakmak, 2008; Welch, 2001), however, foliar applications of zinc at reproductive stages of crop development are most effective at increasing the amount of zinc accumulated in the grain of staple cereal crops such as wheat. Using both soil-applied zinc fertilizers and foliar sprays results in the maximum accumulation of zinc in grains (Yang et al., 2011). Zinc plays important roles in both biotic and abiotic stress resistance in crops. Too little soil zinc results in lower crop yields not only because it is essential for the plant but also because it reduces the negative impacts of pathogens, drought conditions, salt stress, and acid soils on crop productivity (Welch, 1995). Using zinc fertilizers can be a "win-win" situation for the farmer and for people with low zinc intakes because not only are zinc intakes increased in consumers but also crop yields can be increased.

3.4 Animal agriculture

Livestock and fish production on farms can make important contributions to the nutritional health and economic wellbeing of low income families (Randolph et al., 2007). Animals are potentially a significant source of income through sales of animals, milk, and eggs. Larger animals may also provide traction for farm implements, thereby enhancing crop productivity. The added income from selling animals and animal products may help people improve the nutritional quality of their diets by allowing them to purchase more micronutrient dense foods. Animals also play important roles in soil fertility and soil health by providing manures for use on fields (Randolph et al., 2007).

Animal-source foods are good sources of the micronutrients that are often lacking in staple foods such as cereals and tubers. Meats are excellent sources of iron, zinc, and several B vitamins including vitamin B-12. Milk is rich in vitamin B-12, vitamin A, riboflavin, and folate but is very low in iron (Dror and Allen, 2011). Indeed, animal products are the only natural source of vitamin B-12. Low intakes of animal-source foods explain the high prevalence of vitamin B-12 deficiency in many developing countries (Stabler et al., 2004). Vegans will almost certainly develop B-12 deficiency unless they consume foods fortified with the vitamin or take a B-12 supplement. Although the number of high quality observational studies and randomized controlled intervention trials are limited, there is substantial agreement that consumption of animal-source foods by young children improves growth, cognitive performance, and motor function (Dror and Allen, 2011). For example, in a large cross sectional study in Guatemala, Democratic Republic of Congo, Zambia, and Pakistan, Krebs et al. (2011) showed that meat consumption by toddlers was associated with lower rates of stunting.

Animal-source foods may provide nutritional benefits beyond what would be expected from the quantities of micronutrients they provide. Animal meats and fish contain substances known as "meat factors" that promote the absorption of iron and zinc from other foods consumed in the same meal, especially when these contain high levels of antinutrients, such as phytic acid and polyphenols (Fairweather-Tait and Hurrell, 1996; Welch, 2001). Only small quantities of meat are required to enhance the bioavailability of these micronutrients in diets high in legume seeds and whole cereal grains that contain high concentrations of these antinutrients (Leroy and Frongillo, 2007). Therefore, providing some animal-source foods in the diets of the poor who are dependent on staple food crops is an important strategy for decreasing iron and zinc deficiencies in these populations.

It should be noted, however, that the role of animal keeping in reducing micronutrient malnutrition among the poor is complicated and controversial. For example, it has been argued that food production efficiency could be dramatically improved by reducing meat consumption and relying more on plant-source foods (Goodland, 1997). Presumably, this would translate into greater food availability for the poor. It is beyond the scope of this paper to address this controversy. Interested readers are referred to a thoughtful analysis of the issue by Randoloph et al (2007).

3.5 Biofortification

Biofortification is an innovative strategy for addressing micronutrient malnutrition in a sustainable way. It involves the use of plant breeding and agronomic approaches such as micronutrient fertilizer applications to increase concentrations of key nutrients in staple food crops (Bouis et al., 2011b). Biofortification is currently being developed and deployed in the Global South (White and Broadley, 2009; Tanumihardjo SA, 2008; Bouis and Welch, 2010). It targets resource-poor rural inhabitants in developing countries where commercial food fortification may not be practical or even possible due to a lack of centralized food processing plants. Biofortification programs are under active development in regions around the world: the HarvestPlus program (www.harvestplus.org), the Biofort Brazil program (biofort.ctaa.embrapa.br) and the HarvestPlus-China program (www.harvestplus-china.org)]. The programs involve collaborations with interdisciplinary global alliances of scientific institutions and implementing agencies in various regions around the world. Crops targeted for biofortification include rice, wheat, maize, beans, sweet potato, cassava and pearl millet. Foods from the biofortified crops are enhanced in pro- vitamin A, iron, and/or zinc. Seeds for these crops are being distributed to several regions in Africa, Brazil, China and South Asia. Success of these biofortification programs is dependent on three principles: 1) biofortified crops must be high yielding and profitable to farmers to assure their adoption, 2) eating the biofortified crops must measurably improve the nutritional health of people in target populations under controlled conditions (efficacy established), and 3) farmers must adopt the crops and most consumers in target populations must accept and consume the crops in quantities sufficient to improve their nutritional health. This strategy is rural-based and designed to reach people in remote regions who typically suffer from higher rates of micronutrient malnutrition. When production surpluses are achieved, urban populations would also benefit if these crop surpluses were marketed in cities (Bouis et al., 2011b).

Biofortification efforts are showing successes in improving the micronutrient status of the rural poor in several countries. Orange flesh sweet potato (OFSP) varieties biofortified with pro-vitamin A carotenoids are being released in some countries in Africa (Low et al., 2007). OFSP have been shown to be efficacious and effective at improving the vitamin A status of villagers where they have been released, propagated and consumed. Orange flesh sweet potatoes have already been released in Nigeria. A recent study showed that biofortifying sweet potatoes with higher β-carotene levels is an effective way to improve the vitamin A status of target populations in Uganda (Hotz et al., 2012). High-iron biofortified rice was shown to be efficacious in improving the iron status of women in the Philippines (Beard et al., 2007). The Brazilian biofortification program is also releasing a number of biofortified crops in that country and a school lunch program that promotes locally grown biofortified food crops in rural schools has been launched (biofort.ctaa.embrapa.br).

Table 3 lists the expected release years for various biofortified crops being developed by the HarvestPlus program. The HarvestPlus program predicts that it will take a decade before biofortified crops are widely adopted in the Global South. Not until this occurs and impacts on nutritional health are confirmed will biofortification become a widely recognized global strategy for reducing micronutrient malnutrition. However, the future looks very bright for this strategy because of early successes with OFSP in Mozambique and Uganda .

The concept of biofortification continues to receive wide-spread attention as a possible viable strategy for helping to reduce micronutrient malnutrition, especially in the rural areas of the developing world. For example, at its May 2012 summit at Camp David, Maryland, USA, G-8 and African leaders issued a commitment to achieve global food security. One of the elements of their commitment was to "Support the accelerated release, adoption and consumption of bio-fortified crop varieties, crop diversification, and related technologies to improve the nutritional quality of food in Africa" (G8, 2012).

Genetic engineering is also being used to develop food crops enriched in vitamins (e.g., vitamins E, A, riboflavin and folic acid) and iron and zinc (Waters and Sankaran, 2011; White and Broadley, 2009). The Bill and Malinda Gates Foundation (www.gatesfoundation.org) is funding research (Grand Challenge #9 Grant Program) to develop transgenic staple food crops with multiple nutritionally enhanced traits (e.g., improved protein quality, improved bioavailable levels of iron and zinc, improved vitamin A levels, etc.) to enhance the nutritional quality of these foods with an emphasis on multiple limiting nutrients in the diets of the poor in developing nations. Transgenic approaches are the only way to increase some vitamins and other nutrients in certain staple food crops that do not accumulate them in their edible portions. For example, the genome of the rice plant does not contain genes encoding for the production of pro-vitamin A carotenoids in its grain which makes it impossible to breed for this trait in rice using traditional breeding techniques. Thus, rice plants were transformed using transgenic approaches to accumulate β-carotene in their grain. The transformed rice was dubbed "Golden Rice" because of its yellow color. Golden Rice has been under development for over a decade and was expected to be released to some farmers in 2012 (Tang et al., 2009; Swapan et al., 2007).

Biofortification of rice grains with iron using conventional plant breeding technologies, while theoretically possible, has met with limited success due to the relatively small variability in the rice gene pool and the fact that most of the iron in the rice kernel is concentrated in the bran layers which are largely removed during milling. Therefore, genetic engineering approaches will likely be necessary to significantly enhance the concentration and bioavailability of iron in the rice endosperm (Sperotto et al., 2012)(Johnson et al., 2011).

However, many obstacles must be overcome before Golden Rice and other transgenic biofortified crops can be released for planting. Individual property rights, public and government acceptance and safety issues must be addressed. Because of these obstacles, transgenic approaches to biofortified crops are costly and take significant amounts of time before releases to farmers are possible in many countries.

4. Food Processing Strategies

4.1 Background

Food processing has enormous potential to both increase dietary diversity and enhance concentrations of micronutrients in commonly consumed foods.

Processing in one form or another has been applied to raw foods for milennia. Early food processing technologies included fermentation of grapes to make wine; fermentation of wheat flour dough to make leavened bread; treatment of milk with rennet (an enzyme found it the stomachs of young sheep, goats, and cattle) to make cheese; treatment of maize with lime to prepare masa for tortilla making; and freeze drying potatoes to make Chuñu, an ancient Inca technique. In the early 19th century, Nicolas Appert discovered that heating foods in glass bottles and then corking them could preserve the food for extended periods. This led to the development of canning as an effective means for preserving a wide variety of foods. Many other technologies followed including freezing, refrigeration, pasteurization, freeze drying, highly mechanized mills for refining grains, sophisticated food packaging materials, modified atmosphere storage of fruits, food additives, food fortification and many more. Today, food processing is used to preserve foods, enhance food safety, improve flavor, add convenience, enhance nutritional value, and conserve energy (Floros et al., 2010).

Processing of fresh fruits and vegetables not only preserves them from spoilage and kills pathogens; it may also help to retain micronutrients. For example, spinach stored fresh for 7 days at room temperature loses 100% of its vitamin C while spinach that is frozen promptly after harvest and stored at – 20 °C for 10 months loses only 30% (Rickman et al., 2007a). Canning, which involves heating products sealed in cans at 121 °C for up to 30 minutes, can cause significant degradation of heat sensitive vitamins such as ascorbic acid and thiamin. However, once the process is complete, the products are shelf stable at room temperature for considerable periods of time. Nutrient losses in canned fruits and vegetables during storage are much lower than for fresh and frozen (Rickman et al, 2007b). Processed fruits and vegetables contribute significantly to nutrient intakes. For example, in the U.S., these foods provide 35% of dietary fiber, 40% of folate, 47% of potassium, 25% of vitamin A, and 51% of vitamin C (Dwyer et al, 2012).

Food processing has transformed the way people in developed countries eat and live their lives. Commercial food processing has largely replaced home food preservation in households across the industrialized world. Processed foods, along with modern kitchen appliances, have dramatically reduced the time spent on home food preparation, allowing more time for other activities. Unfortunately, many processedfoods contain high amounts of added sugar, fat, and sodium and these foods are associated with obesity, hypertension, and other chronic diseases (U.S. Dept. of Agriculture, 2010).

4.2 Impact of Food Waste on Micronutrients in the Food Supply

Food losses or food waste have long been recognized as major contributors to hunger and malnutrition. In fact, one of the original mandates for the Food and Agriculture Organization (FAO) of the United Nations in 1945 was reduction of food losses (Parfitt et al. 2010).

The terms "food losses" and "food waste" have slightly different definitions in the literature although the two are often used interchangeably. Both terms describe the diversion of edible human food away from human consumption. "Food loss" is often defined as the loss of edible food during the production and processing stages of the food supply chain (Gustavsson et al., 2011). These losses occur during harvesting, on-farm storage, transport to market or food processing facilities, processing, warehousing, and transport from warehouses to retail outlets. Some authors consider diversion of edible food stuffs to animal feed or biofuels to constitute losses while others do not. "Food waste", on the other hand, is often defined as losses that occur at the retail and consumer levels of the food supply chain. These losses are primarily determined by behaviors of retailers and consumers, e.g. when edible food is discarded because of blemishes or because it is past the "best if used by" date stamped on the label. Food losses are caused and/or accelerated by a variety of factors including rodents, insects, microbial spoilage, high ambient temperatures, high humidity, enzymatic reactions in the food, etc. (Floros et al., 2010). Data on the extent of food waste are difficult to find, incomplete, and probably inaccurate. A recent FAO report estimates that roughly ⅓ of food produced globally for human consumption is lost or wasted (Gustavsson et al., 2011). Lundqvist et al (2008) suggest that as much as 50% of food is lost from "field to fork". Their higher estimate may be due in part to the inclusion of foods suitable for human consumption that are diverted to animal feed. This food is not a total loss because the animals may ultimately be converted to foods that are consumed by humans.

If we are indeed wasting 30 to 50% of potentially available food, then strategies for reducing food loss and waste have the potential for dramatically improving food supplies. Moreover, food loss and waste along the food supply chain feeds back to agricultural production, requiring more production to feed the same number of people. This wastes seeds, fertilizer, irrigation water, labor, fossil fuels, and other agricultural inputs and uses land that could otherwise be left in its natural state (Floros et al., 2010).

On a per capita basis, food losses and food waste are actually greater in developed countries than in developing countries. Gustavsson et al. (2011) estimate that losses plus waste in Europe and North America are between 280 and 300 kg/person/year compared with 160 kg/person/year in sub-Saharan Africa and 120 kg/person/year in South and Southeast Asia. Much of this difference is accounted for by substantially greater waste by consumers in developed countries compared to developing countries.

Presumably, consumers in wealthy countries waste food because it is abundant, relatively cheap, and people can afford to throw out perfectly edible food.

As people become wealthier, they tend to diversify their diets to include more fruits, vegetables, meat, fish, and dairy (Parfitt et al. 2010). These foods are likely to be more perishable than the staple food crops like cereals and legumes that they partially replace. For example, food losses for cereals (from production through distribution) in developing countries are less than 20% while losses of fruits and vegetables approach 50% (Gustavsson et al., 2011). In the U.S., meat, poultry, and fish account for 41% of the total value of food wasted at the retail and consumer levels while dairy products, vegetables, fruits, and grain products account for 14%, 17%, 9%, and 6% respectively (Buzby and Hyman, 2012).

There is a continuing trend toward urbanization in many countries around the world. It is estimated that currently 50% of the global population lives in cities and that this will grow to 70% by 2050 (Parfitt et al., 2010). This trend may also increase food losses due to losses during transport and retail operations.

Because losses of nutrient dense fruits and vegetables and animal products are greater than losses of the less micronutrient nutrient dense cereals, food losses and food waste disproportionately impact the micronutrient content of the food supply.

The production, harvesting, transport, processing, and storage of food that is ultimately lost or wasted consumes energy (fossil fuels), water, fertilizer, and other inputs. This contributes to higher fuel prices, depletion of water resources, and greater greenhouse gas emissions. Therefore, reducing food losses and waste will not only expand the quantity and quality of food available for consumption but will also reduce energy and water consumption that otherwise would be expended on increased food production to replace the lost food. Policies designed to reduce food waste and food losses are urgently needed in developed and developing countries alike.

4.3 Impact of Food Fortification on Micronutrients in the Food Supply

Food fortification is a subset of food processing. The *Codex Alimentarius (1991)* defines food fortification or enrichment as "**..**the addition of one or more essential nutrients to a food whether or not it is normally contained in the food for the purpose of preventing or correcting a demonstrated deficiency of one or more nutrients in the population or specific population groups."

Several types of commercial fortification programs are in place in countries around the world. They include mass fortification, targeted fortification, voluntary fortification, and mandatory fortification.

Mass fortification refers to the addition of nutrients to foods that are generally consumed by all segments of the population (Allen et al., 2006), for example wheat flour or rice. It is the preferred approach when a majority of the population is at risk for a particular nutrient deficiency.

Targeted fortification is when a particular group within a population, e.g. infants, has a unique risk for nutrient deficiency. An example of targeted fortification would be the addition of nutrients to infant formulas or infant cereals (Allen et al., 2006).

Voluntary fortification is where a food company voluntarily adds nutrients to a food that is not mandated by the government to be fortified (Allen et al., 2006). Governments may issue regulations that define the concentrations and types of nutrients that may be added and the foods that are approved for nutrient addition without mandating that the foods be fortified (Allen et al., 2006). There are many examples of voluntary fortification, for example in many countries processed breakfast cereals are voluntarily fortified.

Mandatory fortification is where governments issue laws or regulations that require the fortification of certain foods (Allen et al, 2006). This type of fortification is typically implemented in countries where there is documented evidence of widespread nutrient deficiency diseases or low intakes of a particular nutrient. Mandatory fortification is preferred when there is a clear public health need and where consumer knowledge about nutrition is limited (Allen et al., 2006).

While food fortification is technically quite simple for most foods, it does require specialized processing equipment and trained personnel. To be sustainable over the long term, there needs to be an effective program in place for monitoring compliance by the food processors. Also, since the cost for food fortification over the long term is ultimately borne by the consumer, educational programs that teach people the benefits of fortification must be in place. The success of fortification programs in developed countries has been possible because they have large, centralized food processing plants that have the equipment and technical expertise required to add nutrients to foods in a consistent, controlled, and cost effective manner. Moreover, most consumers in developed countries have the means to afford processed foods which may be more expensive than foods grown locally in small kitchen gardens or by small holder farmers. In developing countries, food fortification is much more difficult. In many areas, most foods are grown locally on small holder farms and processed in small farm-scale or village-scale processing operations. Capital costs for installing and maintaining equipment for adding nutrients may be prohibitive. A lack of trained personnel to operate the machinery is another constraint to successful fortification programs in developing countries. Also, governments in developing countries may not have the resources to effectively monitor compliance, especially when there are many small processing companies operating.

Food fortification has the potential to significantly benefit the nutritional wellbeing of large segments of populations. In a 1994 report, the World Bank stated the following about food fortification: "No other technology offers as large an opportunity to improve lives at such low cost and in such a short time." (World Bank, 1994). Today, there are hundreds of millions of people who could benefit from fortified foods but do not have access to them.

To put fortification in perspective, it is useful to briefly review the history of commercial fortification. Fortification of foods dates to the early 1920's when Switzerland and the United States began adding potassium iodide to salt as a means of preventing goiter (Backstrand, 2002). The first half of the 20th century was a time of major advances in nutritional sciences with the discovery of many essential vitamins and minerals and the development of the concept that several common diseases of the time (goiter, pellagra, and rickets) were caused by some missing dietary factor (Backstrand, 2002). The first U.S. Recommended Dietary Allowances for several vitamins and minerals were published in 1943 (National Research Council, 1943). Also during this time, many vitamins were isolated and their molecular structures determined. This made it possible to synthesize sufficient quantities of these vitamins for addition to foods on a large scale.

In the years following salt iodization, goiter and cretinism were virtually eliminated in countries with salt iodization programs. The dramatic success of salt iodization was likely a critical factor in generating support for other fortification initiatives in subsequent years.

Rickets in children was widespread in large cities in the U.S. and Europe in the 19th and early 20th centuries. It has been reported that 80-90% of children in Boston, USA and Leiden, the Netherlands suffered from rickets in the late 19th century (Holick, 2006). In the 1930's, the U.S. and several countries in Europe began fortifying milk with vitamin D. This practice along with educational campaigns encouraging sun exposure virtually eliminated rickets in the U.S. and Europe.

When synthetic B vitamins became available in the 1930's, nutritionists in the United Stated began a campaign to add selected B vitamins and iron to flour and other cereal products. Entrance into the 2nd World War provided added incentive for enriching flour and bread because it was thought that vitamin and mineral deficiencies affected the ability of young men to perform as soldiers. The U.S. Army made the decision in 1942 to purchase only enriched flour (Bishai and Nalubola, 2002). In 1943, when it became apparent that voluntary fortification was not achieving the desired effect, the War Foods

Administration in the United States issued War Food Order No. 1 which mandated that all white bread be enriched with iron, riboflavin, niacin, and thiamin (Backstrand, 2002). This mandate by the U.S. federal government that white flour and other cereal products be enriched has since been revoked but most refined flour and cereal products in the U.S. are fortified voluntarily by the food industry today (Bishai and Nalubola, 2002).

Enriching flour and cereal products with the "basic four" nutrients (iron, niacin, riboflavin, and thiamin) remained the standard for enrichment in the U.S. until 1996 when the FDA added folic acid to the standard of identity for breads, flours, corn meals, rice, and other refined grain products as a strategy to reduce the incidence of neural tube defects in newborns (Backstrand, 2002).

Widespread vitamin A deficiency in Central America was known to be a serious public health problem as early as the 1950's. Following a conference in 1970 sponsored by the Pan American Health Organization titled "Hypovitaminosis A in the Americas", the Institute of Nutrition of Central America and Panama (INCAP) made a recommendation to fortify sugar with Vitamin A. Sugar was chosen as the vehicle since it was the only food widely consumed by the target populations. A sugar fortification program was begun in Costa Rica and Guatemala in which the sugar industry cooperated with government agencies to implement the program (Arroyave and Mejía, 2010). Studies verified that the program was effective in improving vitamin A status in children and increasing vitamin A concentrations in breast milk (Allen et al., 2006).

Studies in the 1980's revealed that iodine deficiency was the leading cause of impaired mental development in children worldwide and that adverse effects were seen even when goiter and cretinism were not prevalent. This led to a recommendation in 1990 by 70 heads of state that a goal be set to eliminate iodine deficiency disorders by the year 2,000, prompting the launch of Universal Salt Iodization (USI) programs in many countries around the world (Horton et al., 2008).

In 2002 at a meeting in Mauritius, a forum hosted by the Micronutrient Initiative and the U.S. Centers for Disease Control and Prevention proposed a global Flour Fortification Initiative (FFI) to encourage flour fortification worldwide (Flour Fortification Initiative, 2012). Due, in part, to the efforts of the FFI, wheat flour in more than 75 countries was being fortified with iron, folic acid, and other micronutrients by 2008.

4.4 Commercial Food fortification

Commercial fortification is arguably one of the most successful and cost effective public health approaches for preventing micronutrient malnutrition (Bishai and Nalubola, 2002). Perhaps more than any other public health intervention, food fortification requires collaboration and cooperation between industry and government agencies. Historically, food manufacturing companies have been willing to work with public health officials and government agencies to develop guidelines and technologies for adding nutrients to foods and to absorb much of the cost of fortification.

To be successful, commercial fortification should meet several important criteria (Dary and Mora, 2002):

- The food vehicle selected for fortification should be widely consumed by the target population in significant and consistent quantities year around.
- The food vehicle should be processed centrally on a relatively large scale.
- The added nutrient should not cause changes in the taste or appearance of the food.
- The food vehicle should not interfere with the bioavailability of the added nutrient.
- The nutrient should be stable in the food matrix under normal storage, transportation, and home preparation conditions.

- The addition of nutrients to foods should be regulated by an appropriate government agency to ensure consistent levels of the nutrient in the food vehicle and to prevent excessive intakes due to over fortification of too many foods.
- A monitoring system should be in place to ensure compliance.

The selection of nutrients to add to foods is based on evidence of low intakes of the nutrient in a population and/or on evidence for widespread nutrient deficiencies. These conditions vary from country to country and population group to population group. Therefore, fortification programs should be carefully designed to meet the nutrient needs of a given population. The following nutrients are often added to foods: iodine, iron, vitamin A, vitamin D, niacin, riboflavin, thiamin, folic acid, zinc, vitamin B12, and ascorbic acid. A more complete description of the so-called big three, iodine, iron, and vitamin A is given below.

The technology for adding micronutrients to foods is relatively simple for granular or powdered foods such as salt and cereal flours and for liquid foods such as milk. In these foods, a vitamin and mineral premix is simply mixed with the food during processing. For example, with flour fortification a feeder device delivers a small stream of the premix onto the flour as it moves along a conveyer belt. It is more difficult for whole kernel foods like rice because the rice kernels are much larger than the particles in the nutrient premix. In current practice, rice kernels are fortified by spraying them with a suspension of the nutrients in water. This spray forms a coating on the surface of the rice kernels. A major drawback to this approach is that the nutrients are easily washed off if consumers wash the rice before cooking, as is common practice in many cultures. PATH has developed a technology for the manufacture of Ultra Rice® designed to overcome the problems associated with fortification by surface coating (PATH, 2012). To make Ultra Rice®, a vitamin-mineral premix is mixed with rice flour and the mixture is combined with water and extruded through a die in the shape of a rice kernel. The extruded kernels are nearly identical in size and appearance and the vitamins are distributed throughout the kernels, not just on the surface. The fortified kernels are then mixed with unfortified rice kernels at a mix ratio of 1:100 to provide the desired level of fortification.

4.4.1 Iodine Fortification

Iodine deficiency remains a serious public health problem in many countries around the world. By some estimates, 2 billion people have inadequate iodine intakes (Horton et al., 2008). Countries in South Asia and sub-Saharan Africa have the highest prevalences of low intakes but the problem also exists, albeit on a milder level, in more developed regions including Europe, the U.S., and Australia (Zimmermann, 2009). Consequences of iodine deficiency can be severe. They include cretinism, still birth, increased infant mortality, goiter, and impaired cognitive development (Zimmermann, 2009). Iodine deficiency is the largest factor contributing to impaired cognitive development worldwide (Zimmermann et al, 2008).

While the consequences of severe iodine deficiency, cretinism and goiter, have been known for decades, it was not until the 1980’s that it began to be recognized that milder, subclinical iodine deficiency can impair cognitive development in children (Horton et al., 2008). This understanding prompted world leaders at the World Summit for Children in 1990 (UNICEF, 1990) to proclaim as one of its goals the “virtual elimination of iodine deficiency disorders”.

It is widely accepted that the most effective strategy for reducing the prevalence of iodine deficiency is universal salt iodization (USI). USI is defined as the situation in a country where all salt for human and livestock consumption is fortified with iodine. Salt is an ideal vehicle for delivery of iodine to people for a number of reasons (Zimmerman et al., 2008):

- Addition of iodine to salt is technically simple (a suitable iodine compound such as potassium iodide or potassium iodate is mixed with the salt prior to packaging and distribution)

- Salt fortification is inexpensive, costing only $0.05 per person per year (Horton et al., 2008)
- Salt consumption is nearly universal in humans
- Salt intakes are fairly constant and self-limiting
- In many countries, processing of salt for human and livestock consumption is conducted by a relatively small number of manufacturing companies
- Iodine compounds have minimal impact on the sensory properties of the salt or the food to which the salt is added

There has been substantial progress in reducing the prevalence of iodine deficiency since 1990. De Benoist et al (2008) estimate, based on urinary iodine concentration data from 130 countries that the number of countries where iodine deficiency is a public health problem decreased from 110 in 1993 to 47 in 2007. This represents impressive progress, however, an estimated 31.5% of school age children still have inadequate iodine intakes (de Benoist et al., 2008). Andersson et al (2012) provide a more recent assessment of progress on reducing iodine deficiency using urinary iodide concentration (UIC) data from the WHO Vitamin and Mineral Nutrition Information System Micronutrients Database. They report that the number of countries where iodine deficiency is common decreased from 54 in 2003 to 32 in 2011. However, they emphasize that low iodine intakes are still a major problem in Southeast Asian and African regions and that progress in reducing the prevalence of iodine deficiency appears to be slowing.

4.4.2 Iron Fortification

The World Health Organization estimates the global prevalence of anemia to be 47.4% among pre-school children, 41.8% among pregnant women, and 30.2% among non-pregnant women (McLean, E., 2009). While many factors contribute to anemia including malaria, hemoglobinopathies, and parasitic infections, iron deficiency is its primary cause. Prevalences of iron deficiency and anemia vary widely across regions with rates being much higher in developing countries than in developed countries. This suggests that diets have a major impact on iron status and therefore improving diets can be an effective strategy for improving iron nutrition in populations.

Iron is arguably the most difficult micronutrient to add to foods. There are two main reasons for this. First, iron in iron salts and iron chelates has a tendency to alter sensory properties of foods in ways that make the food unappealing to the consumer. For example, iron can catalyze lipid oxidation in foods. Products of this oxidation include aldehydes and carboxylic acids that have rancid flavors and odors. Also, iron may bind to polyphenolic compounds in foods causing the development of dark colors. Second, the iron in many fortificants has low bioavailability and this may diminish or even completely negate the effectiveness of an iron fortification intervention. Furthermore, the iron fortificants that are the most bioavailable are also the most likely to cause sensory defects in foods. Thus the choice of an iron fortificant for a particular application requires an understanding of factors that influence both iron bioavailability and iron interactions with food components. In spite of these challenges, iron fortification of foods has been in place in many countries since the 1940's and its use is spreading to an increasing number of countries around the world. Ranum and Wesley (2008) recently estimated that 78 countries either have iron fortification programs in place or are planning to implement one.

Progress on improving iron status through iron fortification of foods has been slow in many countries. However, there are success stories to report. One example is iron fortification of maize and wheat flours in Venezuela. A mandatory program for fortification of maize flour with a mixture of ferrous fumarate and electrolytic iron, vitamin A, thiamin, niacin, and riboflavin was implemented in 1992 (Mannar and Boy, 2002). Two years later, the prevalence of anemia and iron deficiency in children declined from 19 to 9% and from 37 to 17%, respectively. Yip et al. (1987) monitored the prevalence of anemia in children aged 9 months to 6 years over a period ranging from 1969 to 1986. They reported that the age-adjusted prevalence of anemia in these children in a middle class suburb of Minneapolis, Minnesota, USA declined from 6.2% in 1969 to 2.7% in 1986. During this time period, fortified infant formula and infant cereals became widely available and these products were likely responsible for the decline. In an effectiveness trial in Chile, powdered milk was fortified with ferrous sulfate (an iron source), ascorbic acid, zinc, and copper (Kain and Uauy, 2001). Anemia rates in children under 18 months fell from 30% to 8% in one year. Gera et al (2012) recently published a carefully done systematic review of randomized controlled trials on the effects of iron fortification on hematologic indicators of iron status. They concluded that iron fortification improves hemoglobin and serum ferritin concentrations and reduces risks of anemia and iron deficiency.

4.4.3 Vitamin A Fortification

The World Health Organization estimates that 5.2 million preschool children show signs of night blindness as a result of vitamin A deficiency and 190 million have low serum retinol concentrations, which signify vitamin A deficiency (Sherwin et al., 2012). Xerophthalmia, a drying of the conjunctiva and cornea of the eye, is the most well-known consequence of vitamin A deficiency. It leads to night blindness, Bitot's spots, corneal ulceration, and ultimately blindness. Vitamin A deficiency has also been associated with increased morbidity and mortality from measles, diarrhea, and respiratory and other infections, presumably due to impaired immune response caused by the deficiency (Mayo-Wilson et al., 2011). Vitamin A deficiency is more prevalent in areas where poverty is widespread and where the availability of vitamin A containing foods is limited (Sherwin et al, 2012).

A variety of food vehicles are used for vitamin A fortification including vegetable oils, margarine, milk and other dairy products, cereal flours, sugar, infant formulas, and complementary foods for children. Given that vitamin A is a fat soluble vitamin, it is relatively easy to fortify high fat foods with vitamin A since it readily dissolves in these foods. Also, dissolution in fats and oils protects vitamin A from oxidation.

4.4.4 Impact of Food Fortification

As mentioned above, many studies have demonstrated the effectiveness of food fortification. Recently, Eichler et al. (2012) conducted a systematic review of the literature on the effect of feeding fortified compared to non-fortified milk and cereal to children aged 6 months to 5 years. They analyzed 18 trials with a combined population of more than 5,400 children. They reported that micronutrient fortified foods were effective in increasing hemoglobin and serum retinol concentrations but not serum zinc concentrations. The risk of anemia was 57% lower in the children receiving fortified foods compared to control children.

4.4.5 Benefit/Cost analyses of food fortification

Benefit/cost estimates are difficult to make with any degree of certainty given the many variables affecting both benefits and costs. Benefit calculations take into account the prevalence and degree of nutrient deficiency, costs of treating nutrient deficiency diseases, assumptions on the value of a human life saved, impact of nutrient deficiencies on worker productivity, and other factors. Costs are driven by the costs of fortificants, installation and maintenance of equipment for adding nutrients to foods, quality control expenses, training of food processing personnel on the procedures for adding nutrients, government regulatory actions, social marketing, etc. Horton (2006) analyzed the economics of commercial food fortification with iron, iodine, and vitamin A. She estimated that costs related to iodine deficiency prior to the implementation of the Universal Salt Iodization effort at $35.7 billion per year and costs per year for salt iodization at $0.5 billion yielding a benefit:cost ratio of 70:1. Horton and Ross (2003), in a detailed analysis of the situation with iron fortification, estimated a benefit:cost ratio of 6:1

for a worker productivity benefit and 36:1 for combined worker productivity and cognitive benefits (iron deficiency retards cognitive development in children).

While it is clear that benefit-cost ratios for food fortification are very favorable, it requires a centralized food processing infrastructure, technical expertise, and government oversight that is not available in many rural areas in developing countries. In these situations, biofortification of staple food crops offers great potential (table 4).

5. Economic and Consumer Education Strategies

Achieving the ultimate goal of preventing micronutrient malnutrition by ensuring that people consume a wide variety of nutrient dense foods requires that agricultural and food systems produce, preserve, and distribute these foods to retail outlets that are accessible to consumers. Furthermore, the foods must be acceptable and affordable to consumers and consumers must have the resources, knowledge, and motivation to purchase and consume the proper variety of foods.

5.1 Income and dietary quality

Bouis et al. (2011a) make the case that dietary quality is associated with income in developing countries. When people are very poor, they rely on dietary staples like cereals which tend to be poor sources of many vitamins and minerals. Using examples from Bangladesh, Kenya, and the Philippines they show that intakes of animal foods and non-staple plant foods are higher in higher income households than in low income households while intakes of staple foods are similar across income groups. Since animal foods and non-staple plant foods such as fruits, vegetables, and legume seeds tend to be higher in micronutrients than unfortified staple foods, it follows that rising incomes should improve dietary quality.

Food prices are also a factor affecting dietary quality in developing countries. When prices of staple foods rise, as was the case recently, people spend a greater share of their incomes on staple foods because staple foods are the least expensive option for meeting calorie needs. This leaves less money for the purchase of animal and non-staple plant foods so consumption of these nutrient rich foods declines (Bouis et al., 2011a).

5.2 Nutrition education of consumers

Over the past several decades, governments around the world have been issuing food-based dietary guidelines (FBDGs) to promote good nutrition in their populations. The FAO supports and encourages the development and sharing of these guidelines (FAO, 2002) and recently launched a website that summarizes them for countries globally (http://www.fao.org/ag/humannutrition/nutritioneducation/fbdg/en/, accessed 04/02/2013). While there are some differences in specifics, the guidelines from different countries are remarkably similar. Most of them include some version of the following recommendations:

- Consume a variety of foods
- Cereals or other starchy foods should form the basis for most meals. Choose whole grain cereal foods more often.
- Consume plenty of fruits and vegetables
- Consume foods that are good source of protein such as legumes, meats and dairy products
- Limit foods that are high in solid fats and added sugars
- Balance calorie intake with energy expenditure to maintain a healthy weight
- Store and cook foods properly to avoid food borne illnesses
- If you drink alcohol, do so in moderation

The primary purpose of dietary guidelines is to educate health professionals, farmers, other food system professionals, and consumers on what constitutes a healthy diet. The challenge is to get consumers to follow the guidelines, a goal that is not being met in large segments of the population in both developed and developing countries. Micronutrient malnutrition affects at least 2 billion people worldwide (Boy et al, 2009). Stunting and underweight affect up to 50% of children in many countries (Dewey and Begum, 2011). Obesity rates exceed 30% of adults in the United States and other developed countries and are growing rapidly in developing countries around the world (Popkin, 2007).

A varied and diverse diet is essential for good nutrition. Conversely, monotonous diets consisting of a limited number of staple foods often lead to deficiencies in one or more micronutrients. People at greatest risk for micronutrient deficiency diseases rely on either refined cereals (rice, wheat, or maize) or tubers (cassava, potato) for the bulk of their calories and protein (FAO, 2002). These foods have low micronutrient density and do not meet requirements for most micronutrients. Adding fruits, vegetables, meats, and dairy products can dramatically improve the nutrient density of these diets. Figure 2 illustrates how the addition of selected foods to a rice-based diet can achieve nutritional adequacy for those micronutrients that are most commonly deficient in populations around the world. The foods selected for the diets are representative of foods that are commonly included in South Indian rice-based meals (Thankachan et al., 2012). All diets in the figure meet the calorie needs of a physically active woman aged 19-30 (2350 kcal). The rice only diet contained 1810 g of cooked, unfortified polished medium grain rice. Foods were added to the rice-only diet at the expense of rice so that the total calorie values of all diets are held constant. The nutrient composition of the respective diets was calculated using a nutritional analysis software package which calculates nutrient composition using data from the USDA National Database for Standard Reference (Cengage Learning, 2011). The amounts of the foods added were chosen to be representative of amounts normally consumed in the course of one day. The approach used was similar to the one used by the FAO (2002). This exercise clearly shows that a carefully chosen varied diet can be nutritionally complete even without fortification.

One constraint preventing people from following dietary guidelines is lack of continuous access to a wide variety of foods. There are multiple reasons for this and the reasons vary depending on income, geographic location, access to land for growing food, soil fertility, agricultural practices, food storage and food processing infrastructure, food value chains, access to nutrition education, food advertising, and food prices to name a few. In many developing countries, the variety of foods available is often limited and low income people may not have the financial means to purchase a variety of foods even if they are available (Semba, 2012). But often it is not just lack of access. In the United States, for example, where an abundance of a wide variety of foods is available at affordable prices, intakes of foods from several food groups fall far short of goals recommended in the Dietary Guidelines for Americans (U.S. Dept. of Agriculture, 2010). Usual intakes by Americans of whole grains, vegetables, fruits, dairy, and seafood fall considerably below the goals. Conversely, intakes of solid fats, added sugars, refined grains, and sodium exceed recommended upper limits by large margins.

6. Conclusions

Micronutrient malnutrition affects one-third to one-half of the global population. The consequences of this preventable public health crisis are severe and far-reaching both in terms of human health and the health of economies in countries where malnutrition is prevalent. As the global population continues to expand toward a projected plateau of 9 billion people by 2050 and climate change, urban sprawl, and declining soil fertility impact agricultural productivity, the challenge of providing all people with nutritionally adequate diets will become ever more daunting.

The ideal solution to the problem of micronutrient malnutrition is a varied diet composed of appealing, safe, and nutrient dense foods from several food groups that is accessible and affordable to all people. Furthermore, people must have the knowledge and motivation to be able to make healthy food choices for themselves and their families. Unfortunately, we do not live in an ideal world and there are many obstacles that must be overcome if we are to meet this challenge. However, there are opportunities for investments that can significantly reduce the prevalence of micronutrient malnutrition. We make the following recommendations for action:

1. *Expand commercial food fortification programs*. Commercial fortification of foods should be expanded to reach a much larger proportion of the global population. It is a proven strategy for preventing micronutrient malnutrition and is very cost effective. There should be a renewed commitment by international organizations and national and local governments to expand programs such as Universal Salt Iodization and the Flour Fortification Initiative. More research and development on technologies for rice fortification is needed. Relatively small investments in commercial fortification can have rapid and large impacts.
2. *Develop and implement technologies to biofortify foods*[1]. Biofortification is a very promising strategy for increasing intakes of micronutrients, especially in rural populations in resource poor countries. Additional investments in both conventional plant breeding and genetic engineering are needed to accelerate already impressive progress in the effort to develop biofortified foods. It is critically important that governments expedite and streamline approval mechanisms for the safe release of genetically engineered crops such as golden rice.
3. *Reduce food losses and food waste.* Preventable food losses and food waste account for up to 50% of agricultural food production in many countries. Foods with the highest losses are often foods that are the most micronutrient dense such as fresh fruits and vegetables. Improvements in post-harvest handling of agricultural crops and meat, milk, and eggs have tremendous unrealized potential for preventing micronutrient malnutrition. Investing in research and development in the area of appropriate food processing and food storage technologies for developing countries is a cost effective strategy for preventing micronutrient malnutrition.
4. *Build human capacity in agriculture, food processing, and nutrition education.* The appropriate application of technology will be key to meeting the challenge of preventing micronutrient malnutrition. This will require a well-educated workforce that can identify, adapt, develop, and implement agricultural, food processing, and education technologies, especially in developing countries. Governments must provide the necessary funding to secondary schools, colleges, and universities to prepare people for careers in agriculture, food technology, and related fields.
5. *Adopt a holistic systems approach to the problem.* Many interacting factors affect the ultimate content of micronutrients in human diets (figure 1). Therefore, a holistic systems approach that encompasses the entire food system from farm to plate should form the conceptual framework for a comprehensive strategy to address the problem of micronutrient malnutrition. In the future, closer linkages must to be forged between the agricultural community, the nutrition and health communities, and government policy makers to assure that agricultural policies meet nutrition and health goals if we are to find sustainable solutions to malnutrition. If agricultural systems cannot meet the nutritional needs of consumers then food systems will always be dysfunctional since agriculture is the primary producer of nutrients.

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[1] Commercial fortification and biofortification are complimentary strategies and the use of one does not necessarily exclude the use of the other. Commercial fortification is more appropriate for urban populations where processed, packaged foods are available and widely consumed. Biofortification will be most beneficial in rural areas where people rely mostly on locally grown and minimally processed foods. Table 4 provides a comparison of the two forms of fortification.

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Table 1. Typical concentrations of selected nutrients in major staple foods*.

Crop	**Ca**	**Fe**	**Zn**	**Riboflavin**	**Total folate**
(dry weight)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(µg/kg)
Cereal Grains					
Polished Rice	123	8	12	0.61	78
Milled Wheat	170	13	8	0.45	295
Yellow Maize	78	30	25	2.24	212
Legume Seeds					
Kidney Bean	1620	93	32	2.48	4465
Great N. Bean	1960	61	26	2.65	5398
Bengal Gram	1187	71	39	2.40	6296
Mung Bean	1451	74	30	2.56	6872
Cowpea	858	101	62	1.52	4686
Green Pea	1183	70	59	6.24	3075

*Data from USDA Nutrient Composition Tables of Foods (http://ndb.nal.usda.gov/).

Table 2. Effects of milling on the iron and zinc concentrations (µg/g dry weight) in grains and flours of maize rice, sorghum, and wheat (Welch and Graham, 1999).

Crop	**Milling Fraction**	**Iron µg/g**	**Zinc** µg/g
Maize	Whole grain	23	21
	Degermed grain	11	4
Rice	Brown rice	16	28
	Polished rice (90% extraction)	5	17
Sorghum	Whole grain	179	54
	Refined flour (64% extraction)	36	10
Wheat	Whole wheat flour	36	26
	White flour (70% extraction)	12	7

Table 3. Actual or expected release years for various biofortified staple food crops by the HarvestPlus program [modified from (Bouis et al., 2011b)].

Crop	**Micronutrients**	**Nations of 1st release**	**Agronomic Traits**	**Year**
Sweet potato	Provitamin A	Uganda, Mozambique	Disease resistance, drought tolerance, acid soil tolerance	2007
Bean	Iron, zinc	Rwanda, Democratic Republic of. Congo	Virus resistance, heat and drought tolerance	2012
Pearl millet	Iron, zinc	India	Mildew resistance, drought tolerance, disease resistance	2012
Cassava	Provitamin A	Nigeria, Democratic Republic of. Congo	Disease resistance	2011
Maize	Provitamin A	Zambia	Disease resistance, drought tolerance	2012
Rice	Zinc, iron	Bangladesh, India	Disease & pest resistance, cold & submergence tolerance	2013
Wheat	Zinc, iron	India, Pakistan	Disease & lodging resistance	2013

Note: HarvestPlus also supports biofortification of the following crops: banana/plantain (vitamin A), lentil (iron, zinc). potato (iron, zinc) and sorghum (zinc, iron).

Table 4. A comparison of commercial fortification and biofortification as strategies for preventing micronutrient malnutrition in populations.

Commercial Fortification	**Biofortification**
Long history of successful use	New concept in early stages of development
Targeted to consumers who rely on processed, packaged foods, i.e. urban populations	Targeted to consumers who grow their own food, i.e. rural populations in poor countries
Nutrients are added to foods post-harvest	Plants are genetically modified to contain enhanced concentrations of micronutrients
Technology is well developed	Conventional plant breeding and genetic engineering technologies are available, development of biofortified crops in early stages
Proven effective for iodine, vitamin D, iron, folate, niacin, thiamin, vitamin A	Proven effective for vitamin A; efficacy trials for iron and zinc ongoing
May be applied to both plant and animal sourced foods (wheat and maize flour, rice, sugar, salt, margarine, milk, yogurt)	Primarily for plant sourced foods (wheat, maize, rice, beans, sweet potatoes, cassava); may be applied to animal sourced foods in future
Most successful in foods that are centrally processed, difficult to apply to foods that are grown for home use or direct marketed to consumers by farmers	Crops are nutritionally enhanced compared to conventional crops; no post-harvest addition of nutrients is required.
Nutrients must be added to every batch of the harvested food	Once seeds are developed and distributed, the biofortified trait will be carried forward year after year provided seeds from the previous year's harvest are planted
Requires specialized food processing equipment	Once seeds are developed and distributed, no specialized equipment is required
Training of plant workers is necessary to ensure consistent and accurate addition of nutrients	No specialized training of farmers or processors is required
Costs: Increased production costs to food processers (purchase and maintenance of specialized equipment, training of workers, purchase of micronutrient premixes, lab analyses to ensure compliance with government standards). Salaries for government inspectors charged with monitoring compliance.	Costs: Research and development costs for developing biofortified seeds; Production and dissemination of biofortified seeds; social marketing for ß-carotene enriched crops
Benefit:cost ratio: extremely favorable	Benefit:cost ratio: extremely favorable

Figure 1. Factors affecting concentrations and bioavailabilities of micronutrients in human diets.

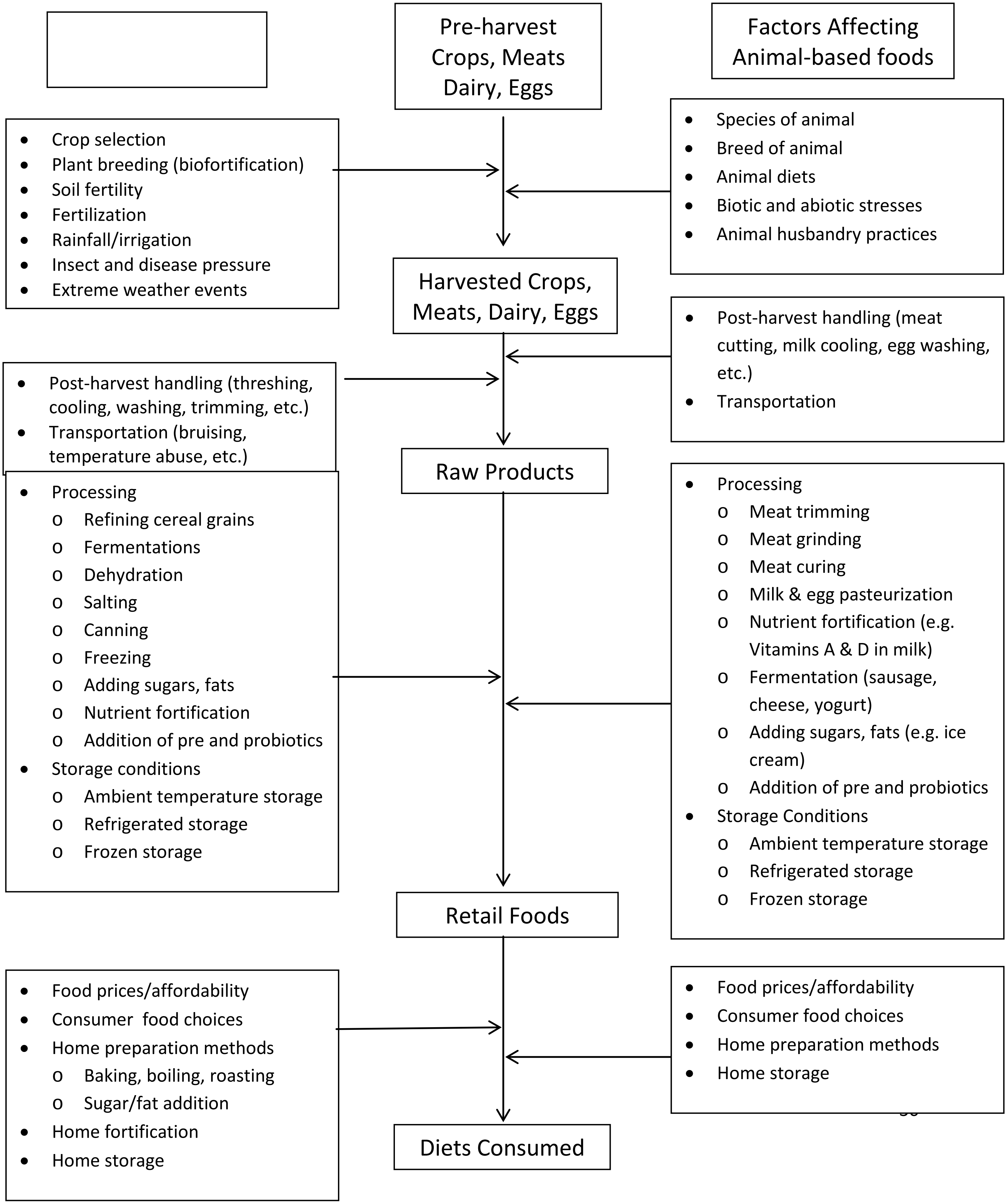
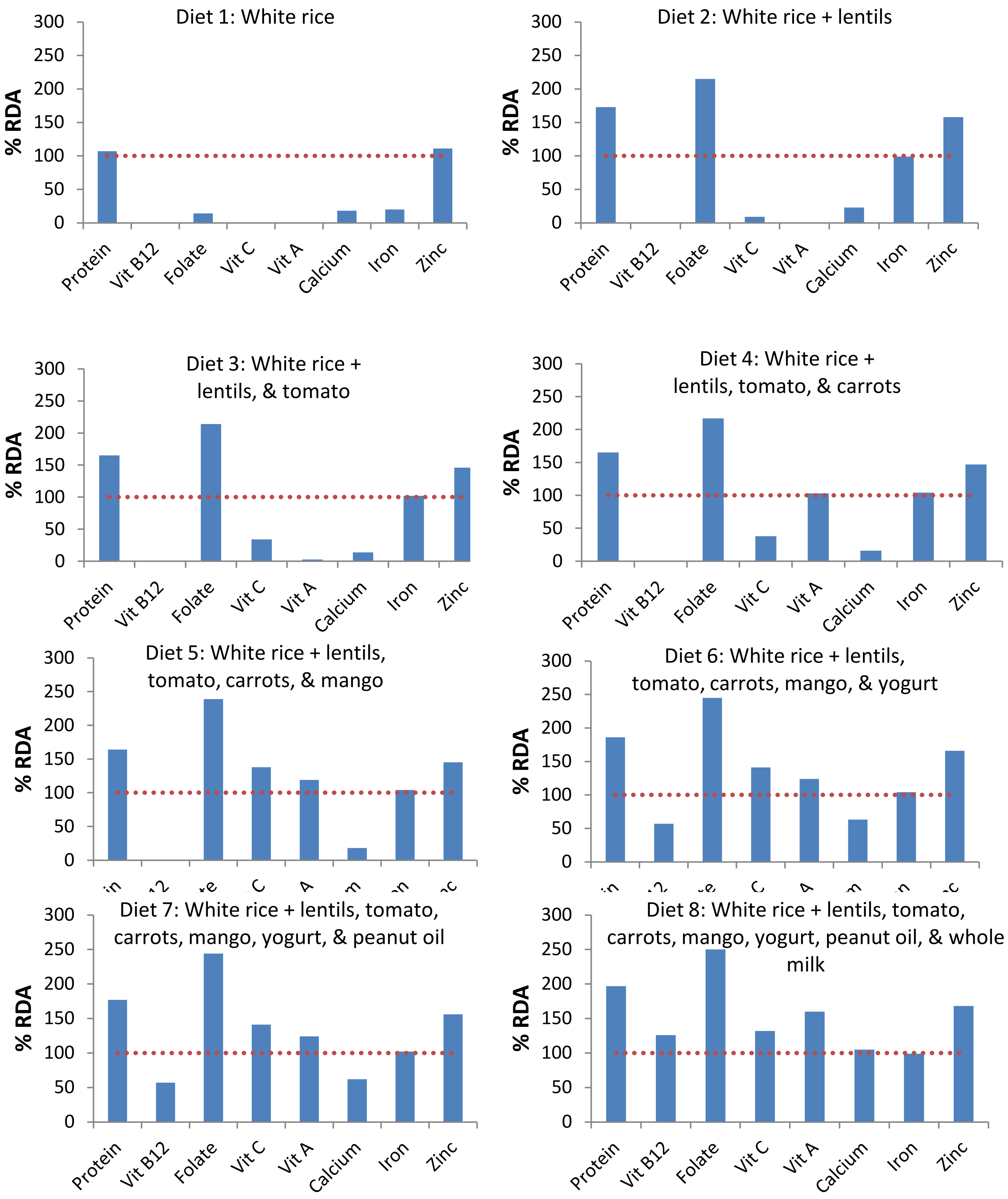


Figure 2. An illustration of the nutritional impact of adding variety to diets. Eight rice-based diets were formulated to provide 2,350 kcal/day. When foods were added, the quantity of rice was reduced by an amount required to keep the total calorie value constant. Foods were added in amounts equal to 1 typical serving, except for milk where 2 servings were added. The nutrient levels are expressed as a percentage of the Recommended Dietary Allowances for a physically active woman of childbearing age.



Diet 1: White rice

Diet 2: White rice + lentils

Diet 3: White rice + lentils, & tomato

Diet 4: White rice + lentils, tomato, & carrots

Diet 5: White rice + lentils, tomato, carrots, & mango

Diet 6: White rice + lentils, tomato, carrots, mango, & yogurt

Diet 7: White rice + lentils, tomato, carrots, mango, yogurt, & peanut oil

Diet 8: White rice + lentils, tomato, carrots, mango, yogurt, peanut oil, & whole milk

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