Symposium on "Food Technology for Better Nutrition"

COMPREHENSIVE
REVIEWS
IN FOOD SCIENCE AND FOOD SAFETY

Table of Contents

COMPREHENSIVE
REVIEWS
IN FOOD SCIENCE AND FOOD SAFETY

Introduction to Symposium on "Food Technology for Better Nutrition" New Delhi, November 30 to December 1, 2007

Food being an essential requirement for survival, mankind has been engaged in the quest for food ever since the dawn of creation and has used technology within means for securing edible food. Food technology, therefore, is as ancient as mankind. With advances in science and technology and with changing needs induced by development, the scope for food technology has vastly increased. Advances in science have also opened up new possibilities with biofortification and genetic engineering, which could result in enhancing the nutritive value of foods.

The "Green Revolution" in India has contributed to significant augmentation of the production of wheat and rice. Millets, pulses, and legumes, however, did not receive adequate attention. As a result, consumption of millets has decreased and intake of pulses, which is a major source of protein and micronutrients in Indian vegetarian diets, has also diminished.

Changes in lifestyles, occupational pattern, and urbanization have also contributed to changes in culinary practices and dietary habits, and have increased the need for safe "convenience foods." India is the largest producer of milk and the 2nd largest producer of vegetables and fruits. Even so, intake of milk is marginal and intake of vegetables and fruits, which are a major source of micronutrients, continues to be inadequate. Nearly a third of fruits and vegetables produced in the country is now being lost due to lack of proper storage and infrastructural facilities for processing and preserving. Current advances in food technology, if wisely implemented, could contribute to overcome these deficiencies.

Apart from sophisticated food technology procedures such as biofortification and genetic engineering, which can make valuable contributions, there is also a need to promote village-based and cottage-based food technology to prevent ongoing wastage of foods and to better harness food resources. Such village-based technology can also contribute to income generation and poverty reduction.

The Nutrition Foundation of India, an independent nongovernmental scientific organization devoted to the promotion of health and nutritional well-being of people had organized a Symposium on "Food Technology for Better Nutrition." The foundation is grateful for the support extended by International Agencies—The Food Policy Research Inst., World Food Program, and the Food and Agriculture Organization. The participants included not only Indian scientists but also outstanding experts from the United States, Thailand, and from international agencies.

The symposium had 3 major themes:

1. Technology for improving the nutrient content of crops through biofortification
2. Technology for reducing wastage of vegetables and fruits and processing of millets, oils, and vegetables
3. Food fortification to combat micronutrient deficiencies

In earlier years, millets were part of Indian diets but, as was pointed out earlier, millet intake has now diminished considerably. Technologies for improved production of millets and technologies such as blanching, acid treatment, malting, fermenting, and dry heating and popping for processing of millets to reduce antinutritional factors and increase the digestibility and shelf life were discussed at the symposium.

The potential beneficial effects of efforts of the Malaysian Palm Oil Board in developing and patenting technologies for processing palm oil, which preserves phytonutrients in palm oil, were presented at the symposium. Apart from ß-carotene, it is a rich source of tocopherols and tocotrienols, which are powerful antioxidants and metabolic regulators.

Combating goiter and iodine deficiency disease through iodization of common salt has been India's success story. At the symposium, it was pointed out that this technology has to be vigorously pursued since goiter has not yet been totally eliminated.

In recent years, efforts to combat widespread micronutrient malnutrition have attracted considerable attention of nutrition scientists. The relative merits of fortification, use of sprinkles that provide a mixture of micronutrients, and a food-based approach have been under discussion.

The outstanding presentation by Dr. Sherry A. Tanumihardjo addressed this important question. This presentation showed that, contrary to some earlier claims, vegetables containing provitamin A carotenoids were successful not only in ensuring vitamin

A nutrition but also were shown to be safer than fortification procedures. Because of bio-regulation at levels of absorption and conversion, vitamin A toxicity is not reached with food-based approach. These findings must not only help in deciding appropriate strategy for combating vitamin A deficiency but also provide a powerful argument for augmentation of production and consumption of vegetables and fruits for ensuring improved nutritional status.

The NFI is grateful to the editor Dr. Manfred Kroger of *Comprehensive Reviews in Food Science and Food Safety* for the generous offer to publish the proceedings of this important symposium and the efficient and capable help with editing the participants' contributions.

C. Gopalan President
Nutrition Foundation of India
(E-mail: nutritionfoundationofindia@gmail.com)

COMPREHENSIVE
REVIEWS
IN FOOD SCIENCE AND FOOD SAFETY

Horticulture and Nutritional Security Strategies for Sustained Development of Horticulture in India

G.L. Kaul

ABSTRACT: Horticultural crops are well known for their nutritional values for human health and, therefore, constitute a cheap and effective source of nutritional security for the masses. Their specific role in improving vitality and resistance against human diseases/disorders, in particular the degenerative diseases due to high antioxidant activities has received considerable attention from the experts and is highlighted in this study. Fortunately, Indian planners have promoted growth of these crops and related entrepreneurship in the country since the 8th Plan period. The study analyzes major challenges facing Indian horticulture in general and fruits and vegetables, the 2 major sources of nutrition, in particular. Problems of low productivity, postharvest losses, inferior quality of the products, and environmental hazards pose a serious threat as a potential source of nutritional security for the masses. Major advances are highlighted in bringing about perceptible changes through R&D initiatives for improving productivity and enhancing nutritional quality of the produce through improved varieties and hybrids, molecular marker-aided breeding and developing transgenic plants with resistance against biotic and abiotic stresses, and higher nutritional and other economic traits, including longer shelf life. Strategies are proposed for ensuring sustained development, laying emphasis on biotechnology, improved and environmentally safe production and postharvest systems, organic farming, use of electronics, and so on.

Introduction

Horticulture crops, particularly fruits and vegetables (F&V), are known worldwide as the cheapest and sustainable sources of vitamins (C, A, B_6, thiamin, niacin, E), minerals, and dietary fiber. Their contribution as a group is estimated at 91% of vitamin C, 48% of vitamin A, 27% of vitamin B_6, 17% of thiamin, and 15% of niacin, 16% of magnesium, 19% of iron, and 9% of calories, while potato, legume vegetables, and tree nuts (almond, filbert, pecan, pistachio, and walnut) contribute 5% of protein in the U.S. diet (Kader 2001). F&Vs are more productive per unit area than cereals and pulses, and thus require much less area (banana 0.03 ha or mango 0.16 ha) to obtain the caloric requirement per adult per year (1100000 kcal) as compared to 0.44 ha for growing wheat (IIHR 2004). Fruits are also a rich source of organic acids such as citric in citrus fruits and tartaric in grapes, besides providing dietary fiber essential for intestinal activity (IIHR 2004). The USDA 2000 Dietary Guidelines encourage consumers to have at least 2 servings of fruits and 3 servings of vegetables each day. In some countries, consumers are encouraged to eat up to 10 servings of F&Vs (Kader 2001). Accordingly, the Recommended Dietary Allowances (RDA) of the Indian Council of Medical Research (ICMR) provides for daily consumption of 120 g of fruits and 280 g of vegetables per person for an average Indian for a balanced diet.

Several F&Vs contain significant levels of phytochemicals supplying antioxidants, called dietary antioxidants, such as beta-carotene, vitamin C, lycopene, vitamin E, lipoic acid, flavonoids, and polyphenols (Table 1). The levels of the antioxidants also vary among different crops (Table 2). These act as scavengers of free radicals and reactive oxygen species, produced in the body by

MS 20070908 Submitted 12/7/2007, Accepted 3/18/2008. Author last worked in Assam Agricultural Univ., Jorhat, Assam, India. Direct inquiries to author Kaul (E-mail: glkaul@hotmail.com).

normal metabolic processes and also generated from external toxins such as pollutants, cigarette smoke, and ozone. These antioxidants prevent the free radicals from disrupting chemical stability of living cells, and in the process, protect individuals from chronic diseases such as cancer, stroke, and cardiovascular and many other degenerative diseases (Singh and others 2005). A chemical (resveratrol) found in the skin of red grapes and in red wine is reported to help fight type 2 diabetes (Sun and others 2007). Scientists from the Univ. of Leicester, U.K., are reported to work on pills made from isolated chemical compounds such as resveratrol from red wine, curcumin from turmeric, and anthocyanins from bilberries that stop the cells becoming malignant, a technique called chemoprevention (Times 2007a). Further, tangerine peel, which contains the compound Salvestrol Q40, has been reported having ability of destroying the enzyme P450CYP1B1 found in human cancer cells (Times 2007b), and may thus provide a treatment for breast, lung, and ovarian cancers. Scientists of UCLA have isolated for the first time the active ingredient of curcuminoids (bisdemethoxycurcumin), a natural substance found in turmeric root that stimulates the immune system to destroy brain-clogging proteins that cause Alzheimer's disease (Fiala and others 2007). Regular intake of foods rich in vitamin C is reported to help prevent ageing of skin, linking the role of vitamin C in the synthesis of collagen-a protein that helps keep skin elastic, gives structure to bones, cartilage, muscle, and blood vessels (Sinha 2007). All these reports establish the importance of regular intake of F&Vs for better health for humans.

Table 1 — Major antioxidants supplying fruits and vegetables.

Sample	Antioxidants	Fruits and vegetables
1	Beta-carotene	Mango, papaya, carrot, fennel, kale, pumpkin, red pepper, lettuce, spinach, sweet potato
2	Vitamin C	Orange, lime, aonla, guava, broccoli, Brussel's sprout, celery, leek, green onion, summer squash
3	Lycopene	Tomato, watermelon
4	Vitamin E	Green leafy vegetables, sweet potato, mango, papaya, guava
5	Lipoic acid	Spinach, beet, broccoli
6	Flavonoids	Onions, soybeans, pineapple, pomegranate
7	Polyphenols	Grape, nuts, orange, strawberry

Table 2 — Antioxidant levels in fruits and vegetables–ORAC units per 100 samples.

Crop	ORAC units	Crop	ORAC units
Prunes	5570	Kale	11770
Raisins	2830	Spinach	11260
Blueberries	2036	Brussels sprout	1980
Strawberries	1540	Alfalfa sprouts	1930
Plums	949	Broccoli	1890
Oranges	750	Beets	1840
Red grapes	739	Red bell pepper	1710
Cherries	670	Onion	1450
Kiwi fruit	602	Corn	1400
Grapefruit (pink)	483	Eggplant	1390

ORAC = Oxygen Radical Absorbance Capacity.
Source: Dan Roberts: Tufts Univ., Boston, Mass., U.S.A. (www.mdsupport.org/library/antiox.html).

Horticulture in India

India is endowed with a unique agro-climatic diversity conducive for growing a variety of horticulture crops, which covered a total area of 20.20 million hectares (MHA) in 2004–2005 with an annual production of 169.80 million metric tons (MT) (Table 3). India presently accounts for nearly 10% of world fruit production, 11.6% of vegetable production, and continues to be the 2nd largest producer of F&Vs after China. Among fruits, India ranks 1st in mango, banana, sapota, and acid lime. In vegetables, India is 1st in okra and 2nd in peas, cauliflower, onion, cabbage, brinjal, and tomato (NHB 2005).

Major efforts for the development of horticulture in the country started since the VIII Five-Year Plan (1993–1998) only when horticulture was acknowledged as a sustainable means for diversification of Indian agriculture for improving land productivity, generating employment, enhancing potential for agro-based industry and exports, and, above all, provide much-needed nutritional security to the masses. Consequently, the Central Plan outlay for this sector (excluding outlay for R&D) saw a phenomenal rise from Rs. 27 crores (USD 6.75 million) in the VII Five-Year Plan (1988–1993) to Rs. 1000 crores (USD 250 million) in the VIII Five-Year Plan. The thrust for the sector continued in subsequent Plans. Presently, a Natl. Horticulture Mission has been launched covering all the states with a proposed outlay of Rs.15000 crores (USD 3.75 billion) for 2 plan periods to double the annual production to 300 million MT. Investments by the Government of India (GOI) for research in horticulture started only in the IV Five-Year Plan with allocations of Rs. 3.48 crores (USD 0.87 million), which subsequently rose to Rs. 213 crores (USD 53.25 million) in the IX Five-Year Plan.

Research achievements made so far include among others about 500 improved varieties and F-1 hybrids of different F&V crops released so far. These include 50 in fruits, 216 in vegetables, 34 in potatoes, and 24 in other tuber crops. Notable among these are new varieties with high nutrient contents, such

Table 3 — Increase in area, production, and productivity of horticulture crops during 1991–1992 to 2004–2005.

	Area (MHA); production (MMT); yield (T/HA)		
Commodity	**1991–1992**	**2004–2005**	**% increase**
A. Total horticulture			
Area	12.8	20.2	57.8
Production	96.6	169.8	75.8
Yield	7.5	8.4	12.0
B. Fruits			
Area	2.87	4.96	72.8
Production	28.6	49.3	72.4
Yield	10.0	10.7	7.0
C. Vegetables			
Area	5.6	6.75	20.5
Production	58.5	101.4	73.3
Yield	10.5	15.0	42.8
D. Plantation crops			
Area	2.3	3.1	34.8
Production	7.5	13.2	76.0
Yield	3.3	4.2	27.3
E. Spices			
Area	2.0	5.2	160.0
Production	1.9	5.1	168.4
Yield	0.9	1.0	11.1

Source: Indian Horticulture Database NHB (2005).
MHA = million hectares; MMT = million metric tons; THA = metric tons/hectare.

as carotene in Amrapali mango (16830 μg/100 g pulp), Surya papaya (4309 μg), and Arka Chandan pumpkin (3331 μg), vitamin C in Arka Jeet musk melon (41.6 mg) and Arka Ahuti tomato (26.95 mg), and oleoresin in Paprika (5.77%). Similarly, new regular bearing varieties, free from spongy tissue and high-yielding mango hybrids, soft seeded guava and pomegranate, drought tolerant/resistant selections in pomegranate, ber, aonla, and custard apple, and so on among fruits, and disease resistant hybrids in potato, brinjal, tomato, okra, French bean, water melon, and pea, apart from excellent table varieties/hybrid goods for processing, long distance transport, are other notable innovations (Kaul 2005). Improved management and plant protection technologies have contributed to higher productivity and quality in different crops.

Challenges Facing Indian Horticulture

Indian horticulture faces serious challenges to achieve twin objectives of becoming globally competitive, and provide nutritional security to its masses on a sustainable basis. These are analyzed hereunder with respect to F&Vs mainly.

Demand and supply

The total production of F&V in India in 2004–2005 was 49.3 and 101.4 million MT, respectively (Table 3). The demand of the 2 groups of commodities, using the RDA norms of ICMR, is likely to rise to 64.4 and 150.2 million MT respectively (including demand for exports), and for the projected population of around 1.4 billion by 2026. Filling this huge gap is going to be quite daunting, considering the limitations in horizontal expansion due to shrinking land resources, thus leaving improving productivity per unit area (vertical expansion) the major avenue available for reaching the production goals.

Low productivity

The overall production of horticultural crops improved by over 75% and the area expanded by over 57% during the period from 1991–1992 to 2004–2005 (Table 3), while the overall productivity showed only 12% increase, despite huge investments made in the recent past. F&Vs registered increases of only 7% and 42% in their productivity during this period, with current average productivity only 10 and 15 MT/ha, respectively, much below world average. This is mainly due to senile and unproductive old plantations, slow spread of high-yielding varieties/hybrids of vegetables, severe biotic and abiotic stresses, environmental degradation, postharvest losses, unorganized marketing, and so on. Unless the indigenous production increases and marketing are organized, the retail prices will continue to remain unaffordable for the public, thus restricting consumption to only a small percentage of India's population.

Postharvest losses

The total loss at wholesale and retail levels put together, as assessed by the Indian Council of Agricultural Research (ICAR) in mid-1990s, was 26.10% in tomato followed by onion (18.16%), citrus (17.10%), banana and mango (over 16% each), and potato (7.96%) (Kaul 2005). These losses directly affect their availability and quality. All investments and efforts made for improving postharvest management (PHM) have ended so far at the storage level of bulk quantities of a few commodities, with no care taken at the retail level. Consequently, the fresh produce continues to be sold in open stalls, road side kiosks, carts, footpaths, and so on, exposed directly to weather elements, thus causing serious loss in quality of the produce adding to the other losses. Mango fruits sold in push carts in Bangalore were found to have lowest firmness (1.71 to 2.96 kg) and TSS (16.33° Brix) as compared to firmness of 4.25 to 5.55 kg and TSS of 25.20° Brix for those sold in environmentally controlled units in the same city (Table 4). Similar results were found with tomato fruits. The negative effect of such practices on the antioxidant and other nutritional levels of the fresh produce can be easily presumed. It is this very stuff the consumers purchase at a fairly high price and get poor quality in return, depriving them of nutritients, and also contributing to low average consumption of F & V by the people, thus leading to problems of malnutrition.

Threats to quality

Quality of the produce also suffers due to several factors, primary ones being chemical/pesticide residues, high levels of toxic leachates in groundwater, environmental pollution, and so on. The problem of high pesticide residues following indiscriminate use of harmful pesticides/chemicals is assuming serious proportions, thus making consumers vulnerable to health disorders. Use of copper sulfate in okra to enhance its green color, carbofuron in brinjals for better sheen, phosphomidone and methyl parathion for imparting white color to cauliflower curds, are a few of the well known instances of malpractices adopted by the unscrupulous producers/traders for quick gains, having direct impact on human health. About 20% of the total samples checked by the Centre for Science and Environment, Delhi, failed the maximum residue limits (MRL) set under the PFA Act, despite the fact that MRLs set in the country are far lower than those set by international bodies (Ghosh 2007). Use of sewage water carrying appreciable loads of heavy metals such as lead, chromium, nickel, and copper for irrigating vegetables render these unfit for human and animal consumption (Joshi and Luthra 2000).

Research Strategies

Research strategies specific to meeting the above challenges are summarized as follows:

Conserving plant genetic resources

India is endowed with a rich wealth of genetic resources of horticultural crops comprising 66 genera and 899 species, of which 190 (109 species in fruits, 54 in vegetables, and 27 in spices and condiments) are of economic importance (Ghosh 2007). This diversity is a national asset, which includes land races, primitive strains, obsolete cultivars, and indigenously developed and exotic improved lines/cultivars. These have to be collected, conserved, and catalogued to prevent gene erosion due to depletion of forest area and clandestine transfer to other countries. The IPR and Plant Breeders' Rights issues have induced urgency to protect India's genetic resources and utilize these for gene isolation and crop improvement.

Table 4 — Quality parameters of mango samples collected from different retail markets of Bangalore (2005–2006).

Sample	Retail outlet	Texture (kg)	Acidity (%)	TSS (° Brix)
1	HOPCOMS	4.25	0.55	25.20
2	Byataranapura	2.96	0.47	24.80
3	Tindlu	2.00	0.28	16.33
4	Highway	2.03	0.79	20.23
5	Food World	5.44	0.62	20.10
6	City Market	2.27	0.45	20.98
7	Push cart	1.71	0.47	18.40
8	CD at 1%	1.76	0.15	2.91

Source: Indian Inst. of Hort. Research, Bangalore, India.

Improving productivity

Increasing per unit area yield of fruits in particular will call for increasing plant population per unit area through adoption of high-density planting using dwarf genotypes including transgenics, canopy management, and so on. Inducing dwarfing either through use of genetically dwarfed rootstocks such as nucellar seedlings in mango, aneuploids in guava, *Z. rotundifolia* in ber, or breeding of scion cultivars for dwarf stature would be the other options available. The major candidates for this would be mango, guava, litchi, sapota, apple, walnut, sweet orange, and mandarins. Breeding in vegetables would have to be highly goal-specific, such as resistance against biotic stresses due to viral (Tospo, TLCV in tomato, YVM in okra, CVMV of capsicum and chillies), bacterial (wilt in tomato), and fungal (powdery mildew in capsicum and chillies) diseases. Chronic problems such as mango malformation, alternate bearing, guava wilt, spongy tissue, citrus decline, and bunchy top virus of banana need to be resolved through a long-term multidisciplinary approach. At the same time, complete packages of practices appropriate for different agro-climatic regions are required for rejuvenating old and unproductive fruit plantations, which presently occupy prime lands throughout the country.

Developing transgenics

Transgenic walnut resistant to codling moth produced using Bt gene was the first of its kind in tree fruits, followed by transgenic apple resistant to codling moth, transgenic squash, melons, and papaya resistant to virus (Dandekar and others 2002). In India, 16 transgenics have been evolved so far in select vegetables and fruits with resistance against insects and diseases. Transgenics in papaya and banana with improved shelf life are other significant additions (Kaul 2005). Recent advances made in our understanding of plant-pathogen interactions have led to the discovery of several resistance genes (R) from plants. Genes can be mined from microbial sources, from organisms that are effective biocontrol agents for fungal and insect resistance. For abiotic stresses a variety of genes that are expressed by plants in response to abiotic stresses like drought, salinity, and cold have been described (Shinozaki and Yamagauchi-Shinozaki 1997).

Developing transgenics with dwarfing gene is another strategic option available. The best candidate genes at present are the *rol* genes A, B, C, and D from *Agrobacterium rhizogenes*, which have been shown to influence internodal distance, adventitious rooting, apical dominance, and seed set (Costantino and others 1994). More dwarf genes can be identified and isolated from available genotypes in fruit crops such as dwarf Malling and MM series apple rootstocks, aneuoploids of guava, and Vellaikolumban in mango for which complete genome analysis would be required to locate the specific genes.

In vegetables, low-cost molecular techniques already developed and in use need to be deployed for increasing the efficiency of classical breeding programs. Novel strategies are required for exploiting male sterility for hybrid seed production through biological manipulations using molecular biology tools. Manipulation of plant systems such as suppression of pollen formation by changing the temperature or day length for a longer period is 1 of the options. Similarly, delayed senescence or "stay-green" traits enable plants to continue producing food for a longer period resulting in higher yields (Kush 2002).

Reducing postharvest losses

Loss assessment has to be made on a country-wide basis through scientific surveys, as was done earlier, to identify the change in loss, if any, due to investments made and technologies adopted so far. Developing cost-effective on-farm PHM systems for fresh produce would continue to be research priority to help small farmers to reduce losses and earn better returns. Hence, concepts such as zero- or low-energy storage system, use of locally available packing material, preharvest management, efficient and small mechanical devices, besides standardization of CA and MA storage techniques, would continue to be priority areas. On the biotechnological front, several genes have already been isolated for manipulation of ripening and shelf life. These include genes for enzymes involved in ethylene biosynthesis and cell wall hydrolysis. Success has been achieved in modifying fruit ripening in tomato to provide a longer shelf life. This holds promise for crops like mango, banana, papaya, and other climacteric fruits and vegetables (Kush 2002).

Irradiation of fresh produce with very low doses of gamma radiation have been successfully demonstrated in mango, potato, onion, black pepper, chillies, ginger, garlic, raisins, meat products, among others, and endorsed by the Ministry of Health, GOI, for commercial application. The Bhaba Atomic Research Centre (BARC) has set up the commercial food irradiation facility "Poton" at Nasik in Maharashtra for irradiating onions and potato, reducing the losses by 20% in these commodities (Kaul 2005). However, its application has to be standardized for all other major F&Vs, and the constraints in its widespread use have to be properly analyzed.

Developing nondestructive methods for sorting F&Vs for internal disorders such as infestation of borers, fruit fly, stone weevil, or spongy tissue, granulation, or even bruised, immature, or cracked fruits before packing assumes priority. Techniques such as acoustic response, ultrasonics, and photometry are now commonly being used in the developed countries, which need to be tested in India as well. More recent innovation is the machine vision, also referred to as computer vision grading of fruits to replace human visual inspection. This involves image generation, image processing, image interpretation, and actuation of a separation mechanism; it shows either external or internal features of certain quality characters such as color, size, shape, injury, and defects (Kachru and Kotwaliwale 2002).

Enhancing nutritional qualities

High carotenoid content in Amrapalli mango, Surya papaya, and Arka Chandan pumpkin, and vitamin C–rich Arka Jeet muskmelon are a few Indian successes of enhancing nutrient levels in F&Vs through breeding. Levels of nutrients like tocopherols have been altered through manipulation of gamma-tocopherol methyl transferase activity. Iron content can also be manipulated through overexpression. Carotenoid content can be improved in fruit crops like banana as in the case of golden rice. However, a holistic understanding of relevant transport and partitioning mechanisms is required before attempting genetic manipulation for increasing nutritive quality (Grusak and Della Penna 1999).

Identifying varieties high in antioxidant capacity should become 1 of the major targets of germplasm evaluation and crop improvement programs. Transgenic plants with increased contents of flavonoids, carotenoids, and ascorbic acid by overexpression of genes have been created in some F&Vs. A high-flavonoid tomato has been developed through traditional breeding methods using a wild tomato species, *Lycopersicon pennellii* v. puberulum (Willitis and others 2005). Transgenic tomato plants with fruits containing high beta-carotene have been produced as a result of the almost complete cyclization of lycopene (Ambrosio and others 2004). Suppression of an endogenous photomorphogenesis regulatory gene (DETI) enhances both carotenoid and flavonoid contents in tomato without changing the other quality parameters (Davuluri and others 2005). Instances of transgenic lettuce cultivars with high levels of resveratrol developed using *Agrobacterium tumefaciens*-mediated transfer of stilbene synthase gene (Vst 1) from grapes have been reported (Chai and Ng 2003). In grapes, resveratrol was increased 3-fold using the resveratrol synthase gene (Lee and Payee 2004). Similarly, results have shown that basal levels of ascorbic acid in transgenic lettuce and strawberries can be increased several-folds by expressing a single gene from the animal ascorbic acid biosynthesis pathway (Kim and others 2004).

Protecting nutritional qualities

Several research leads are available on bioremediation of metal contaminants in soil for revalidation, which will be of great significance for the peri-urban cultivation of F&V in India. The Horticulture and Food Research Inst. of New Zealand has developed a phyto-remediation technique based on the capabilities of trees, grasses, and aquatic plants for removing, destroying, or segregating hazardous substances like Cu and Cd, thus preventing these pollutants from leaching into ground water (Kaul 2005). *Brassica juncea* (cv. Vardan) is reported to have a high potential for removing Cd from contaminated soil. Similarly, lime, farmyard manure, tree leaves, zeolites, superphosphate and fly ash have been effective in reducing Cu, Ni, Cd, Zn, and Pb in growing media, while sawdust and coir pith could effectively be utilized for the removal of Cr from tannery effluents (Joshi and Luthra 2000).

Evolving biocontrol measures, including use of biopesticides, and integrated pest management (IPM) for crop production systems assumes high priority for tackling the problem of pesticide residues. Some progress has already been made in this direction. IPM strategies have been successfully evolved for cabbage, tomato, and potato against specific pests, apart from biological control of mealy bugs in grape, scale insect in citrus, weevil in sweet potato. However, much more needs to be done to develop fool-proof packages for specific pests and diseases in different crops. On the legal front, stringent implementation of the provisions of PFA Act and monitoring of pesticide residue levels in F&Vs at the farm gate, as well as at the wholesale market yard levels, becomes an urgent requirement.

The concept of organic farming is catching on fast in India to improve quality of farm produce, combat harmful effects of excessive fertilization and pesticide use on soil microflora, soil fertility, and quality, and, above all on human health. The international demand for organically grown food products is reported to have increased from 23 billion US$ in 2002 to 40 billion in 2006, of which India's share was hardly Rs. 50 crores (USD 12 million). Worldwide, about 31 MHA are reported to be managed organically, with India recording about 0.42 MHA (Vandana 2007). Research studies have shown appreciable gains not only in productivity of the crop, but also on higher levels of Ca, Fe, Mg, Mo, P, K, and Zn, besides protecting soil health. According to British scientists, organic fruits and vegetables were found to contain 40% more antioxidants besides high levels of Fe and Zn minerals, while organic tomatoes were found to have double the level of flavonoids in a 10-y study of the Univ. of California (Ungoed-Thomas 2007). For widespread adoption of this farming system, location-specific research is required to identify optimum mix of different components and practices useful for individual crops growing in different agro-climatic situations along with cost-benefit analysis for making the concept economically viable for small and marginal farmers.

In conclusion, consumption of fruits and vegetables in adequate quantities is the most sustainable and economically viable avenue available for promoting nutritional security to the Indian masses. Hence, major thrust will be needed for enhancing production and quality of F&V to meet the demand through developing high-yielding varieties/hybrids with higher nutrient contents, and to develop package of practices for improving productivity on a sustainable basis and for large-scale adoption of organic farming and drastically reducing postharvest losses.

References

Ambrosio DC, Giorio G, Marino I, Merendino. 2004. Virtually complete conversion of lycopene into beta-carotene in fruits of tomato plants transformed with the tomato lycopene beta-cyclase (tlcy-b) cDNA. Plant Sci 166(1):207–14.

Chai T, Ng I. 2003. Production of resveratrol in transgenic red lettuce for chemoprevention of cancer and cardiovascular diseases. In: Bhojwani SS, Soh WY, editors. Proceedings Asia Pacific Conference on Plant Tissue Culture and Agrobiotechnology, Singapore. p 133–45.

Costantino P, Capone I, Cardarelli M, De Paolis A, Mauro ML, Trovato M. 1994. Bacterial plant oncogenes: the *rol* genes' saga. Genetica 94:203–11.

Dandekar AM, Fisk HJ, McGranahan GH, Urastsu SL. 2002. Different genes for different folks in tree crops: what works and what does not. Hortscience 37(2):281–6.

Davuluri GR, Tuinen AV, Fraser PD, Manfredonia A. 2005. Fruit-specific RNAi-mediated suppression of DETI enhances carotenoid and flavonoid content in tomatoes. Nature Biotechnol 23(7):890–5.

Fiala M, Liu PT, Espinosa-Jeffrey A, Rosenthal MJ. 2007. Innate immunity and transcription of MGAT-III and Toll-like receptors in Alzheimer's disease patients are improved by bisdemethoxycurcumin. PNAS 104:12849–54.

Ghosh A. 2007. Adulterators cook up a health hazard. New Delhi, India: The Times of India, Oct. 15.

Grusak MA, Della Penna D. 1999. Improving the nutrient composition of plants to enhance human nutrition and health. Ann Rev Plant Physiol Plant Mol Biol 50:133–61.

IIHR. 2004. Fruits in nutritional security. Technical Bulletin 18. Bangalore, India: Indian Institute of Horticultural Research. p 1–3.

Joshi UN, Luthra YP. 2000. An overview of heavy metals: impact and remediation. Curr Sci 78(7):2–4.

Kachru RP, Kotwaliwale N. 2002. Advances in separation techniques for fruits and vegetables. In: Chadha KL, Choudhary ML, Prasad KV, editors. High-tech horticulture. New Delhi, India: Horticultural Society of India.

Kader A. 2001. Importance of fruits, nuts, and vegetables in human nutrition and health. Perishables Handling Quarterlys (106):4–6.

Kaul GL. 2005. Challenges and research priorities for sustained development of horticulture in India: role of IARI. Paper presented in the Scientific Convention of the Centenary Year of IARI, Feb 15–18. New Delhi, India. New Delhi, India: Indian Agricultural Research Institute.

Kim B, Park SY, Jeon BY, Hwang DY, Min BW. 2004. Metabolic engineering increased vitamin C levels in lettuce by overexpression of L-gulono-gamma-lactone oxidase. J Korean Soc Hortic Sci 45(1):16–20

Kush A. 2002. New biology for developing improved cultivars of horticulture crops. In: Chadha KL, Choudhary ML, Prasad KV, editors. High-tech Horticulture. New Delhi, India: Horticultural Society of India.

Lee M, Payee JA. 2004. Molecular switch for the induction of resveratrol biosynthesis in grapes. Nat Prod Sci 10(5):248–51.

NHB 2005. Indian horticulture database. Gurgaon, India: National Horticulture Board, Govt. of India.

Shinozaki K, Yamaguchi-Shinozaki K. 1997. Gene expression and signal transduction in water response. Plant Physiol 115:327–34.

Singh J, Kalloo G, Singh KP. 2005. Eating a plateful of vegetables keeps cancer away. Ind Hort 549(4):4–9.

Sinha K. 2007. Orange a day keeps wrinkles away. New Delhi, India: The Times of India, Oct. 11.

Sun C, Zhang F, Ge X, Yan T, Chen X, Shi X, Zhai Q. 2007. SIRT1 improves insulin sensitivity under insulin-resistant conditions by repressing PTP1B. Cell Metab 6:307–19.

Times. 2007a. Pills made from rice, berries to fight cancer. New Delhi, India: The Times of India, Oct. 04.

Times. 2007b. Tangerine peel could fight cancer. New Delhi, India: The Times of India, Sep. 13.

Ungoed-Thomas J. 2007. Organic food may help lengthen lives. New Delhi, India: The Times of India, Oct. 29.

Vandana S. 2007. Organic farming: the real green revolution for protecting the earth, farmers, livelihoods and public health. In: Souvenir, national seminar on organic agriculture: hope of posterity. Ghaziabad, India: National Centre of Organic Farming. p 11–23.

Willitis MG, Kramer CM, Prata RTN, de Luca V. 2005. Utilisation of the genetic resources of wild species to create a nontransgenic high flavonoid tomato. J Agri Food Chem 53(4):1231–6.

COMPREHENSIVE
REVIEWS
IN FOOD SCIENCE AND FOOD SAFETY

Biofortification of Staple Crops: An Emerging Strategy to Combat Hidden Hunger

Sherry A. Tanumihardjo, Howarth Bouis, Christine Hotz, J.V. Meenakshi, and Bonnie McClafferty

ABSTRACT: Diverse diets rich in micronutrients offer the ultimate sustainable solution to undernutrition. Unfortunately, poverty drives food consumption habits. For the poor, a simple meal consisting mostly of staple foods make up the daily diet. A diet based predominantly on staple food lacks adequate essential nutrients and thus can lead to hidden hunger. The biofortification strategy targets the poor by naturally adding nutrients to these staple foods through plant breeding. Biofortified crops offer a rural-based intervention that, by design, initially reach these more remote populations, which comprise a majority of the undernourished in many countries, and then extend to urban populations as production surpluses are marketed. In this way, biofortification complements fortification and supplementation programs, which currently work best in centralized urban and peri-urban areas and then reach into rural areas only with good infrastructure. Initial investments in agricultural research at a central location can generate high recurrent benefits at low cost as adapted biofortified varieties become available in country after country across time at low recurrent costs. HarvestPlus is working to develop and distribute varieties of food staples that are high in iron, zinc, and provitamin A through an interdisciplinary, global alliance of scientific institutions and implementing agencies in developing and developed countries. HarvestPlus, comanaged by the International Center for Tropical Agriculture and the International Food Policy Research Institute, collaborates with the India Biofortification Project to develop biofortified varieties of rice, wheat, and maize for India.

Introduction

The word "biofortification" is derived from the Greek word "bios" which means "life" and the Latin word "fortificare" which means "make strong." Although the concept is new to the international community in relationship to staple crops, biofortification of plants has occurred for centuries. In fact, carrots were not always orange as commonly used in Europe and the United States and red as used in India. Carrot domestication occurred about 1000 years ago in Central Asia, and carrots then were either yellow or purple (Simon and others 2008). These colors became known across the Middle East and North Africa and in both Europe and China by the 15th century. Orange carrots were 1st reported in Europe in the 16th century and eventually in Asia and are therefore considered a relatively recent development. Red carrots with both lycopene and β-carotene (Mills and others 2007) became popular in Asia after the domestication of the orange carrot. Thus, this broad array of carrot color was known 400 years ago, but orange came to be the preferred color in most of the world soon after their 1st appearance (Simon and others 2008). Through traditional plant breeding, these carrots were optimized for their orange color and organoleptic qualities (Surles and others 2004). Because orange color of carrots equates to vitamin A value, carrots could be considered biofortified (Porter Dosti and others 2006). Carrots continue to be biofortified as purple–red–orange carrots have now been developed to contain anthocyanins, lycopene, and β-carotene (Mills and others 2008).

Unfortunately, the inclusion of vegetables such as carrots and green leaves into the diet of the poor is difficult for a variety of reasons (Tanumihardjo and others 2007). When cost constraints exist in a household, the situation usually results in a diet that favors foods high in fat and carbohydrate and not fruit and vegetables (Darmon and others 2002; Drewnowski and Specter 2004). Therefore, less emphasis has been placed on diet diversification than supplementation and fortification. While biofortification of staple crops could be considered a form of dietary diversification, it differs in that it nutritionally improves the main energy sources of the diet without depending on the addition of

---

MS 20070907 Submitted 12/6/2007, Accepted 2/27/2008. Author Tanumihardjo is with Dept. Nutritional Sciences, Univ. of Wisconsin-Madison, Madison, WI, U.S.A. Authors Bouis, Hotz, Meenakshi, and McClafferty are with HarvestPlus, Intl. Food Policy Research Inst., Washington, D.C., U.S.A. Direct inquiries to author Tanumihardjo (E-mail: sherry@nutrisci.wisc.edu).

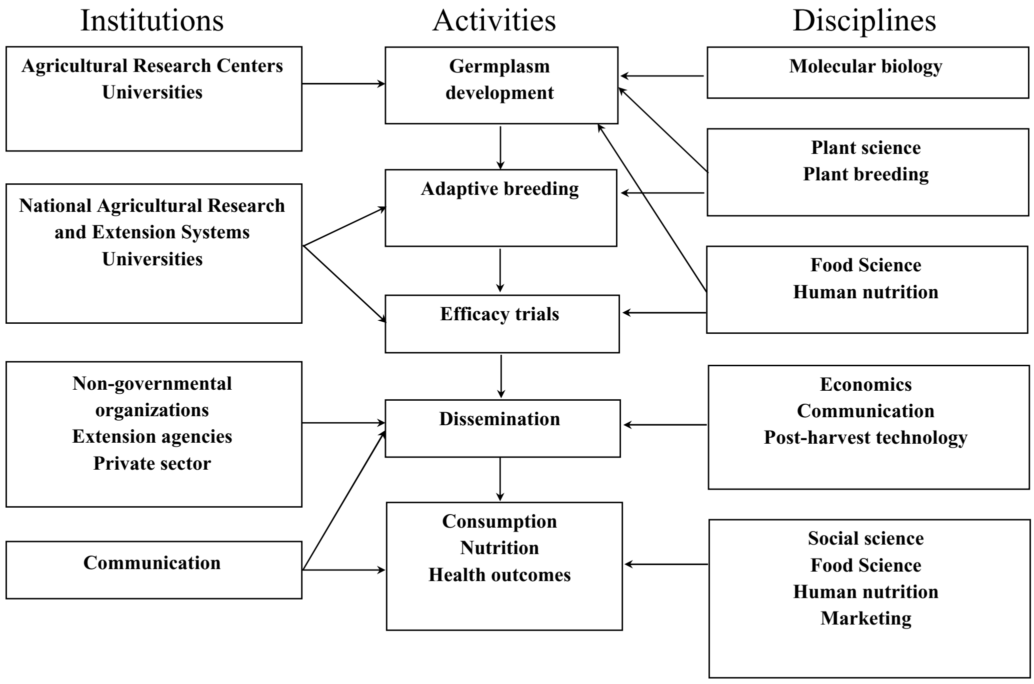

Figure 1 — Successful biofortification of staple crops with targeted nutrients requires a concerted effort from a variety of disciplines orchestrating essential activities at multiple institutions.

complementary foods. Nutritionists do not dispute the benefits of a diversified diet, but it is often difficult to achieve this idealized diet in resource-poor areas of the world (Tanumihardjo and others 2007).

Between 1965 and 1999, dramatic changes have occurred in worldwide crop production. In the developing world, a 175% increase in cereal crops but only a 35% increase in pulses, has occurred to supply food to the more than 100% increase in population. Forecasts for 2007 include a 4% increase in worldwide cereal crop production over 2006 (FAO 2007). Along with these changes, prices for staple foods have decreased while prices of other plant and animal foods have increased. Therefore, poor populations necessarily choose staple foods to meet their energy needs (Tanumihardjo and others 2007). Because most staple foods are not nutrient-dense, micronutrient deficiencies are common in poor populations. In some instances, overt signs of deficiency are not evident, which leads to a condition called hidden hunger (Dalmiya and Schultink 2003).

Biofortification of staple crops with micronutrients has emerged rather recently (Nestel and others 2006) as a means to combat hidden hunger. A key advantage of biofortification is that it targets the poor who eat high levels of noncommercially processed and often nonmarketed staple foods. Biofortification can be considered rural-based and complements fortification and supplementation efforts, which sometimes cannot reach rural communities. Although the initial investments can be high, it is cost-effective because research can be propagated to other countries saving time and resources. Biofortification requires a concerted, multidisciplinary approach to accomplish its activities through multiple institutions (Figure 1).

Table 1 — Crops currently undergoing biofortification and their primary and secondary targeted nutrients.

Crop	Targeted nutrients
Rice	Zinc and iron
Wheat	Zinc and iron
Maize	β-Carotene and zinc
Cassava	β-Carotene
Beans	Iron
Sweet potato	β-Carotene
Pearl millet	Iron and zinc
Banana and plantain	β-Carotene
Lentil	Iron
Potato	Iron
Sorghum	Iron

Nutrients Targeted by Biofortification

Micronutrients that have been targeted for biofortification into a variety of staple crops are vitamin A, iron, and zinc (Table 1). Justification for these nutrients is based on population needs, and the crops selected for biofortification of particular nutrients is based on their consumption by vulnerable populations, and the potential to achieve increased levels of those micronutrients through conventional breeding. Each of these nutrients will be reviewed separately.

Vitamin A

Globally, over 250 million children under the age of 5 y have vitamin A deficiency (WHO 2003) and supplementation programs are a common and effective approach to address this issue (Sommer and Davidson 2002; Ross 2002). In fact, a meta-analysis of 8 studies showed an overall reduction of 23% in childhood mortality (Beaton and others 1993). However, supplementation programs require recurrent costs each year and include not only the vitamin A supplements, but also human resources for distribution and monitoring of the programs.

Crops that have been targeted for biofortification with provitamin A carotenoids include sweet potato (van Jaarsveld and others

2005, 2006; Low and others 2007), maize (Howe and Tanumihardjo 2006a, 2006b), cassava (Thakkar and others 2007), and rice (Paine and others 2005; Datta and others 2007; Tang and others 2007). Traditional breeding methods have been used for sweet potato, maize, and cassava; and because provitamin A does not exist naturally in rice grain, efforts have focused on genetic engineering (Yonekura-Sakakibara and Saito 2006). Though vitamin A as the preform must be carefully administered to minimize hypervitaminosis A, when biofortifying crops with provitamin A carotenoids, issues of quality control and safety are not necessary or relevant. Conversion to vitamin A is more controlled and the risks of hypervitaminosis A from provitamin A-containing foods are almost nonexistent. While β-carotene supplementation may increase the risk of cancer in smokers (The Alpha-Tocopherol Beta Carotene Cancer Prevention Study Group 1994; Liu and others 2000), high intakes of provitamin A from food may result in hypercarotenemia, but reports of toxic side effects are few (Bendich and Langseth 1989). In fact, diets high in vegetables and fruits can reduce the risk for cancer (World Cancer Research Fund 1997) and cardiovascular disease (Bazzano and others 2002), improve bone health (Tucker and others 1999; Prynne and others 2006), and reduce age-related cognitive decline (Morris and others 2006).

Substantial levels of β-carotene are present in many varieties of sweet potato and regular consumption does improve vitamin A status (Haskell and others 2004; van Jaarsveld and others 2005; Low and others 2007). The bioconversion factor for sweet potato was 13.4 μg β-carotene to 1 μg retinol when 80 g sweet potato was fed as a snack daily to men (Haskell and others 2004). In a highly controlled, school-based study that fed 125 g per school day to children for 5 mo, a significant improvement was measured in liver reserves of vitamin A (van Jaarsveld and others 2005). A small amount of fat was added to the sweet potato to aid absorption because it was fed as a snack (Haskell and others 2004; van Jaarsveld and others 2005). Although a small amount of fat is needed, it does not seem to be a limiting factor for general meal composition (Ribaya-Mercado and others 2007). Current efforts include developing sweet potato varieties that are well accepted by target groups and educating individuals to purchase and consume orange varieties. The effectiveness of introducing orange-fleshed sweet potato into Mozambique (Low and others 2007) showed dietary intake of vitamin A increased from sweet potato and serum retinol concentrations improved in the children from intervention households. Sweet potato in Africa could be considered a success story (Table 2).

Maize has been targeted for biofortification for decades as scientists try to improve the protein quality (FAO 1992). Complementing maize with beans and vegetables is certainly desirable, but does not always occur in poorer regions of the world (Hotz and Gibson 2001). Current efforts to biofortify maize with provitamin A carotenoids have been successful. Provitamin A levels in maize have reached 15 μg β-carotene equivalents (βCE) per gram dry weight and varieties are being tropicalized that have 10 μg/g dry weight. Animal studies show that maize is efficacious in maintaining vitamin A status (Howe and Tanumihardjo 2006a). Human studies are currently planned in a developing country setting to determine efficacy of a locally produced variety.

Table 2—A success story for sweet potato: key elements that occurred for a successful population-wide intervention to introduce orange-fleshed sweet potato in Africa.[a]

Goal achieved
1. Active behavior change to include orange varieties
2. Agronomic "equality" crucial for successful adoption
3. Assistance to understanding and overcoming constraints to adoption was crucial
4. Farmers actively participated in breeding and varietal selection
5. Seeds systems are in development
6. Product and markets are in development

[a] Two studies in South Africa (van Jaarsveld and others 2005) and Mozambique (Low and others 2007) evaluated the efficacy and effectiveness, respectively, of orange-fleshed sweet potato.

Iron

Iron deficiency continues to be the most prevalent deficiency in both the developed and developing world. Estimates are staggering with reports of 2×10^9 (Allen and others 2006) to 3.5×10^9 people (United Nations 2000) who have iron deficiency. Sufficient iron is needed for many biochemical processes, including electron transfer reactions, gene regulation, transport of oxygen, and cell growth and differentiation (Beard 2001). Among crops that have been targeted for increased iron content are rice, wheat, pearl millet, beans, lentil, sorghum, and potato.

Rice is consumed as a staple food by 3×10^9 people and many of them are among the poorest in the world (Cantrell and Reeves 2002). Rice biofortified with iron was used in a 9-mo feeding trial in the Philippines (Haas and others 2005). The trial enrolled religious sisters in convents which allowed a high level of intervention control. The investigators chose to focus their study on nonanemic subjects because not all anemia is caused by iron deficiency. The intervention included a high-iron rice group and a low-iron rice control group. By using under-milled biofortified rice, the intervention group added 1.5 mg iron to their diets from a base intake of 8.5 mg iron per day. The intervention resulted in a significant increase in serum ferritin concentration ($P \leq 0.01$) among the nonanemic women, indicating an increase in body iron stores. Further, the increase in total body iron was found to be greater in those subjects who had lower body iron stores to begin with.

Zinc

Zinc is an important trace element for health and development. Humans rely on zinc to heal wounds, grow, repair tissues, and assist in blood clotting. Zinc also serves as a catalytic or structural cofactor in many proteins (Coleman 1992). Although options for indicators of zinc status are more limited than those available for assessing iron and vitamin A status, estimates of the amount of zinc in the food supply suggest that the risk of inadequate dietary zinc may be widespread, affecting 2×10^9 individuals. Maternal zinc deficiency has been associated with both adverse maternal and fetal outcomes (IZiNCG Steering Committee 2004). A meta-analysis in prepubertal children showed that supplemental zinc caused a large increase in children's serum zinc concentrations and positive responses in height and weight (Brown and others 2002). Many other studies have also indicated that supplemental zinc substantially reduces the risk of common childhood infections, such as diarrhea and pneumonia, and among particularly vulnerable groups of children reduces mortality rates (Black 2003).

Crops that have been targeted for zinc enhancement include rice, wheat, maize, and pearl millet (Table 1). When the iron content of plants is increased, often zinc is improved because it is also a divalent ion (Sautter and others 2006). To date, a bioefficacy study in humans of a zinc-biofortified crop has not been conducted (Hotz and McClafferty 2007).

Target Levels of Nutrients in Biofortified Crops

One question that is important to plant breeders is, "What are the target levels for provitamin A carotenoids, iron, or zinc?" In general, to compute breeding target levels, it is necessary to know: (1) per capita consumption levels of the food staple; (2) retention of nutrients in storage, processing, and cooking; (3) bioavailability of the nutrient; and (4) nutrient intake from other foods (Table 3). It is also important to consider the level of other nutrients in the diet that may act as enhancers, such as fat for provitamin A carotenoids and vitamin C for iron. Often precise data on these points are unavailable and must be estimated.

In addition, nutrient requirements vary by gender and age. For example, an infant aged 12 mo is assigned an "adequate intake" of 500 μg vitamin A, yet the "estimated average requirement" of a 1-y-old child is 210 μg. This can lead to confusion when trying to set target levels for nutrients in crops. Furthermore, "recommended dietary allowances of nutrients" are meant to cover 97% to 98% of the populations' nutrient requirements. Biofortification is considered a population-based intervention and as such a biofortified crop needs to be targeted to the average consumer in the population. Should a biofortified crop cover 100% of the estimated average requirement? Certainly most populations will be eating other foods. Perhaps the additional micronutrient added through biofortification should cover 25% to 50% of the estimated average requirement (Hotz and McClafferty 2007). Another issue that arises is, "how much of the staple food is consumed by the population targeted?" Surprisingly, very little quantitative data are available on staple food intakes in developing countries for particular age, gender, and income groups (Hotz and McClafferty 2007).

Minimum target levels have been estimated for several crops using data available (Hotz and McClafferty 2007). Assumptions included age, physiological state, staple food intake, baseline micronutrient content of the crop, micronutrient retention after preparation, and bioavailability (minerals) or retinol equivalency (provitamin A) (Table 3). For example, after taking these assumptions into account, 14.5 μg iron and 24 μg zinc would be needed in polished rice to provide an additional 30% to 50% and 40% to 50% of the iron and zinc requirements, respectively, for women and children in populations where rice intakes are high.

"Intermediate" target levels may be important for some crops. These are target levels that are approachable with current available methodologies and will allow a crop to be evaluated in a population of interest at a stage of development that might not yet be ideal. For example, maize provitamin A target levels were initially set at 15 μg βCE/g on the plate. On the plate means that the percent retention of the provitamin A carotenoids (Li and others 2007) was accounted for. This target level was based on a bioconversion factor of 12 μg βCE to 1 μg of retinol (12:1). However, we now know that bioconversion of provitamin A carotenoids in maize may be much better than 12:1 when the population is vitamin A-depleted (Howe and Tanumihardjo 2006a). Therefore, a maize bioefficacy trial in humans would not have to wait until the maize had a provitamin A concentration of 15 μg/g on the plate but could proceed with a level of perhaps 10 μg/g dry weight with locally produced maize. This would depend on the sensitivity of the assay used to measure changes in vitamin A status (Vitamin A Tracer Task Force 2004) and the level of maize the population group consumed on a daily basis.

Table 3—Factors to consider when evaluating target levels of nutrients in staple crops.

Crop specific factors
- Per capita consumption levels of the food staple
- Baseline micronutrient content of the crop
- Retention of nutrients in storage, processing, and cooking

Target group specific factors
- Age of target group
- Physiological state, such as growing child, pregnancy, or lactation
- Bioavailability of iron or zinc or projected retinol equivalency (provitamin A)
- Nutrient intake from other foods

Costs Associated with Interventions

All interventions to improve nutrition "cost" something. Even social marketing involves the production and dissemination of flyers and brochures and education efforts. A recent evaluation of the costs associated with the distribution of 500 million vitamin A capsules each year was undertaken (Neidecker-Gonzales and others 2007). After including labor, total costs were estimated at US$0.5 in Africa, US$1 in Asian developing countries, and US$1.5 in Latin America. The range was US$0.51 in Ghana to US$2.27 in South Africa for evaluations that occurred from 1991 to 2004 (Neidecker-Gonzales and others 2007).

Iron fortification appears to be more cost-effective than supplementation (Baltussen and others 2004). However, iron supplementation has a larger impact on population health. Average annual costs for iron fortification varied between US$0.06 and US$0.015 per beneficiary in an analysis published in 2004 (Baltussen and others 2004). In the same analysis, iron supplementation targeted to pregnant women was estimated to cost between US$10.42 in South East Asia to US$50.16 in Europe for each pregnant women (Baltussen and others 2004). Recently, the iron fortification of rice in the Philippines was estimated to cost US$0.02 per kilogram. With an average per capita rice consumption of 300 g/d, the cost to fortify rice with iron can be estimated at US$2 per person per year. If trying to cover a population of 500 million people (half the population of India), that is a cost of US$1 $\times 10^9$ per year.

The record of zinc addition to foods in the United States by food manufacturers dates back to 1970 (Rosado 2003). Zinc fortification has been proposed in staple foods such as rice, wheat, and maize or condiments such as salt (IZiNCG Steering Committee 2004). Recommendations for fortificants have been made (Rosado 2003) and technical considerations discussed (IZiNCG Steering Committee 2004). Addition of zinc to foods would probably occur alongside other micronutrient addition. A cost evaluation estimated that the total annual costs associated with the addition of zinc to wheat flour would be about double that of iron, that is, total annual costs of US$1.94 for wheat flour fortification with iron (US$0.84) and zinc (US$1.10) per metric ton (IZiNCG Steering Committee 2004).

A useful metric for quantifying the potential benefits of any public health intervention, including biofortification, is the consequent reduction in the number of disability-adjusted life years (DALYs) that are lost annually due to micronutrient malnutrition. Put simply, DALYs are a measure of the total number of days that are spent in ill-health each year, accounting for both the severity of the condition and its duration. Recent estimates indicate that the annual burden of iron and zinc deficiencies in India is high, amounting to 4 million and 2.8 million DALYs lost, respectively, each year (Meenakshi and others 2007). Even with a pessimistic assumption of no more than 30% coverage, rice biofortification could result in a 5% decrease in the burden of iron deficiency and up to a 20% reduction in the burden of zinc deficiency. Similarly, the biofortification of wheat with iron and zinc could contribute a further 6% and 9% reduction in the DALY burden of iron and zinc deficiencies, respectively. These benefits in DALYs saved each year could be achieved at a cost that is lower than that of fortification and supplementation. Also, they are likely to be seen more in rural areas, where the coverage of alternative interventions such as fortified staple foods is likely to be lower;

in this sense, biofortification has a rural niche.

Annual costs for biofortification efforts are currently US$25 to 30 million per year. This number is meager considering the sustainability of the approach, DALYs saved, and population coverage that would be expected with the successful implementation of the approach.

Biofortification Through Genetic Modification

A crop targeted for biofortification through genetic modification is *Golden Rice*. The highest carotenoid concentration recorded to date is 37 μg/g dry weight (Paine and others 2005), and rice with values of 5 and 20 μg/g have been fed to humans (Tang and others 2007). The β-carotene from *Golden Rice* has a similar conversion rate to vitamin A (Tang and others 2007) as maize (Howe and Tanumihardjo 2006a); therefore, a significant impact on vitamin A status could be achieved if it was adopted by the groups that need it. Currently, high β-carotene rice varieties adapted to the United States' growing environment are being back-crossed into popular high-yielding varieties that grow well in Asia. This backcrossing is nearly completed and varieties will be field-tested soon at the Intl. Rice Research Inst. in the Philippines. Because there are general concerns (precautionary principal) of safety for genetically modified crops (Séralini and others 2007), prolonged animal studies may be warranted using transgenic rice before wide-spread introduction into various rice-consuming countries. Such animal studies are common in the regulatory process that genetically modified crops must pass before being approved for release.

Strategies and Barriers to Acceptance

Two general strategies for dissemination of biofortified staple foods are being employed: (1) where nutrients are invisible to the consumer (iron and zinc), nutrient density bred into the highest-yielding, highest-profit lines being released by agricultural researchers; adoption is driven through farmers' demand for agronomically superior seeds, which account for a high proportion of total supply of that food staple in a country, and (2) where nutrients are visible (provitamin A carotenoids), adoption is driven through demand creation and marketing, that is, delivering nutrition messages that explain how consumption of orange-colored varieties that would replace white varieties can improve family nutrition.

In the latter case, consumers need to be convinced through nutrition education that the change in the color of the food consumed may result in improved nutrition and health. Focusing on children may be an important strategy because many nutrition education efforts are geared toward expectant and new mothers by promoting maternal health and "improved" weaning foods. Social marketing to pregnant and lactating mothers to change the "color" of their staple foods during late stage pregnancy and early lactation may, in fact, have a favorable outcome on intake of that food by the infant at weaning (Mennella and others 2001). Another application of biofortified staple foods could be in the development of nutrient-dense ready-to-use foods that are used for supplementary or emergency feeding to moderately undernourished children (Maleta and others 2004). Supplementary foods that do not require the addition of extra vitamins and minerals, may be easier to adapt to a variety of health care situations. Acceptance of colored staples may take several generations to be adopted. Convincing local farmers to grow biofortified crops is also necessary to ensure a constant supply in the marketplace. With the adoption of good seed and extension systems, viable markets, and strong demand (Nestel and others 2006), biofortification efforts will be successful.

In summary, based on data in animal models and humans, biofortification of staple crops with provitamin A carotenoids and iron can make a difference in populations that adopt these varieties. Zinc efficacy studies with a biofortified food have yet to be performed (Hotz and McClafferty 2007) but they are on the horizon. More sensitive methods to assess zinc status than serum concentrations may be needed to better assess impact. In some instances, biofortified crops that have invisible traits will be more easily adopted than those with visible changes. For example, as long as high-zinc wheat has similar agronomic traits as locally grown varieties, they may be quickly adopted because there is no behavior change expected on the side of the consumer. On the other hand, it will take more nutrition education for a mother who has eaten white maize her entire life to adopt an orange variety. Perhaps efforts could begin by promoting the improved varieties as more nutritious for her children.

Conclusions

The initial costs of biofortification may seem high in some sense, but are less than the cost of 1 y of expenditures on supplements and commercial fortification. Moreover, after widespread acceptance, biofortification as a strategy to overcome micronutrient malnutrition is sustainable. If one keeps in mind that it took 600 y for the orange carrot to appear, after the initial domestication of the yellow and purple carrot, biofortification of staple crops to improve nutrition is in its infancy.

Acknowledgments

Work by the Tanumihardjo lab in this review was sponsored by HarvestPlus contract numbers 2005 × 217.UWM, 8029, and 8037; the Natl. Research Initiative of the USDA Cooperative State Research, Education, and Extension Service, grant nr 2003–35200-05377; and Hatch Wisconsin Agricultural Experiment Station WIS04975.

References

Allen L, de Benoist B, Dary O, Hurrell R. 2006. Guidelines on food fortification with micronutrients. World Health Organization, Geneva, Switzerland, and Food and Agricultural Organization of the United Nations, Rome, Italy.

Baltussen R, Knai C, Sharan M. 2004. Iron fortification and iron supplementation are cost-effective interventions to reduce iron deficiency in four subregions in the world. J Nutr 134:2678–84.

Bazzano LA, He J, Ogden LG, Loria CM, Vupputuri S, Myers L, Whelton PK. 2002. Fruit and vegetable intake and risk of cardiovascular disease in US adults: the first National Health and Nutrition Examination Survey epidemiologic follow-up study. Am J Clin Nutr 76:93–9.

Beard J. 2001. Iron biology in immune function, muscle metabolism and neuronal functioning. J Nutr 131:568S–80S.

Beaton GH, Martorell R, L'Abbé KA. 1993. Effectiveness of vitamin A supplementation in the control of young child morbidity and mortality in developing countries: summary report. Univ. of Toronto, Toronto, Canada.

Bendich A, Langseth L. 1989. Safety of vitamin A. Am J Clin Nutr 49:358–71.

Black RE. 2003. Zinc deficiency, infectious disease and mortality in the developing world. J Nutr 133:1485S–9S.

Brown KH, Peerson JM, Rivera J, Allen LH. 2002. Effect of supplemental zinc on the growth and serum zinc concentrations of prepubertal children: a meta-analysis of randomized controlled trials. Am J Clin Nutr 75:1062–71.

Cantrell RP, Reeves TG. 2002. The cereal of the world's poor takes center stage. Science 296:53 p.

Coleman JE. 1992. Zinc proteins: enzymes, storage proteins, transcription factors, and replication proteins. Ann Rev Biochem 61:897–946.

Dalmiya N, Schultink W. 2003. Combating hidden hunger: the role of international agencies. Food Nutr Bull 24:S69–S77.

Darmon N, Ferguson EL, Briend A. 2002. A cost constraint alone has adverse effects on food selection and nutrient density: an analysis of human diets by linear programming. J Nutr 132:3764–71.

Datta SK, Datta K, Parkhi V, Rai M, Baisakh N, Sahoo G, Rehana S, Bandyopadhyay A, Alamgir M, Ali MS, Abrigo E, Oliva N, Torrizo. 2007. Golden rice: introgression, breeding, and field evaluation. Euphytica 154:271–8.

Drewnowski A, Specter SE. 2004. Poverty and obesity: the role of energy density and energy costs. Am J Clin Nutr 79:6–16.

[FAO] FAO Corporate Document Repository. 1992. Improvement of maize diets. Chapter 8. In: Maize in human nutrition. Rome, Italy. http://www.fao.org/docrep/t0395e/t0395e0c.htm. Accessed Nov 13, 2007.

[FAO] FAO Corporate Document Repository. 2007. Crop prospects and food situation. http://www.fao.org/docrep/009/j9630e/j9630e00.htm. Accessed Nov 13, 2007.

Haas JD, Beard JL, Murray-Kolb LE, del Mundo AM, Felix A, Gregorio GB. 2005. Iron-biofortified rice improves the iron stores of nonanemic Filipino women. J Nutr 135:2823–30.

Haskell MJ, Jamil KM, Hassan F, Peerson JM, Hossain MI, Fuchs GJ, Brown KH. 2004. Daily consumption of Indian spinach (*Basella alba*) or sweet potatoes has a positive effect on total-body vitamin A stores in Bangladeshi men. Am J Clin Nutr 80:705–14.

Hotz C, Gibson RS. 2001. Complementary feeding practices and dietary intakes from complementary foods amongst weanlings in rural Malawi. Eur J Clin Nutr 55:841–9.

Hotz C, McClafferty B. 2007. From harvest to health: challenges for developing biofortified staple foods and determine their impact on micronutrient status. Food Nutr Bull 28:S271–S9.

Howe JA, Tanumihardjo SA. 2006a. Carotenoid-biofortified maize maintains adequate vitamin A status in Mongolian gerbils. J Nutr 136:2562–7.

Howe JA, Tanumihardjo SA. 2006b. Evaluation of analytical methods for carotenoid extraction from biofortified maize (Zea mays sp.). J Agric Food Chem 54:7992–7.

IZiNCG Steering Committee (Hotz C, Brown KH, editors). 2004. Assessment of the risk of zinc deficiency in populations and options for its control. Food Nutr Bull 25(Suppl 2):S94–S203.

Li S, Tayie FAK, Young MF, Rocheford T, White WS. 2007. Retention of provitamin A carotenoids in high β-carotene maize (*Zea mays*) during traditional African household processing. J Agric Food Chem 55:10744–50.

Liu C, Wang XD, Bronson RT, Smith DE, Krinsky NI, Russell RM. 2000. Effects of physiological versus pharmacological beta-carotene supplementation on cell proliferation and histopathological changes in the lungs of cigarette smoke-exposed ferrets. Carcinogenesis 21:2245–53.

Low JW, Arimond M, Osman N, Cunguara, B, Zano F, Tschirley D. 2007. A food-based approach introducing orange-fleshed sweet potatoes increased vitamin A intake and serum retinol concentrations in young children in rural Mozambique. J Nutr 137:1320–7.

Maleta K, Kuittinen J, Duggan MB, Briend A, Manary M, Wales J, Kulmala T, Ashorn P. 2004. Supplementary feeding of underweight, stunted Malawian children with a ready-to-use food. J Pediatr Gastroenterol Nutr 38:152–8.

Meenakshi JV, Johnson N, Manyong VM, deGroote H, Javelosa J, Yanggen D, Naher F, Gonzalez C, Garcia J, Meng E. 2007. How cost-effective is biofortification in combating micronutrient malnutrition? An *ex ante* assessment. HarvestPlus Working Paper 2, Washington, D.C.

Mennella JA, Jagnow CP, Beauchamp GK. 2001. Prenatal and postnatal flavor learning by human infants. Pediatrics 107:88e–93e.

Mills JP, Simon PW, Tanumihardjo SA. 2007. β-Carotene from red carrot maintains vitamin A status but lycopene bioavailability is lower relative to tomato paste in Mongolian gerbils. J Nutr 137:1395–400.

Mills JP, Simon PW, Tanumihardjo SA. 2008. Biofortified carrot intake enhances liver antioxidant capacity and vitamin A status in Mongolian gerbils. J Nutr 138. Forthcoming.

Morris MC, Evans DA, Tangney CC, Bienias JL, Wilson RS. 2006. Associations of vegetable and fruit consumption with age-related cognitive change. Neurology 67:1370–6.

Nestel P, Bouis H, Meenakshi JV, Pfeiffer W. 2006. Biofortification of staple food crops. J Nutr 136:1064–7.

Neidecker-Gonzales O, Nestel P, Bouis H. 2007. Estimating the global costs of vitamin A capsule supplementation: a review of the literature. Food Nutr Bull 28:307–16.

Paine JA, Shipton CA, Chaggar S, Howells RM, Kennedy MJ, Vernon G, Wright SY, Hinchliffe E, Adams JL, Silverstone AL, Drake R. 2005. Improving the nutritional value of Golden Rice through increased pro-vitamin A content. Nat Biotechnol 23:482–7.

Porter Dosti M, Mills JP, Simon PW, Tanumihardjo SA. 2006. Bioavailability of β-carotene (βC) from purple carrots is the same as typical orange carrots while high-βC carrots increase βC stores in Mongolian gerbils (*Meriones unguiculatus*). Br J Nutr 96:258–67.

Prynne CJ, Mishra GD, O'Connell MA, Muniz G, Laskey MA, Yan L, Prentice A, Ginty F. 2006. Fruit and vegetable intakes and bone mineral status: a cross-sectional study in 5 age and sex cohorts. Am J Clin Nutr 83:1420–8.

Ribaya-Mercado JD, Maramag CC, Tengco LW, Dolnikowski GG, Blumberg JB, Solon FS. 2007. Carotene-rich plant foods ingested with minimal dietary fat enhance the total-body vitamin A pool size in Filipino schoolchildren as assessed by stable-isotope-dilution methodology. Am J Clin Nutr 85:1041–9.

Rosado JL. 2003. Zinc and copper: proposed fortification levels and recommended zinc compounds. J Nutr 133:2985S–9S.

Ross DA. 2002. Recommendations for vitamin A supplementation. J Nutr 131:2902S–6S.

Sautter C, Poletti S, Zhang P, Gruissem W. 2006. Biofortification of essential nutritional compounds and trace elements in rice and cassava. Pro Nutr Soc 65:153–9.

Séralini G-E, Cellier D, Spiroux de Vendomois J. 2007. New analysis of a rat feeding study with a genetically modified maize reveals signs of hepatorenal toxicity. Arch Environ Contam Toxicol 52:596–602.

Simon PW, Tanumihardjo SA, Clevidence BA, Novotny JA. 2008. Role of color and pigments in breeding, genetics, and nutritional improvement of carrots. In: Culver CA, Worlstad RE, editors. Color quality of fresh and processed foods. ACS Symposium Series 983. Washington, D.C.: ACS Books.

Sommer A, Davidson FR. 2002. Assessment and control of vitamin A deficiency: the Annecy Accords. J Nutr 132:2845S–50S.

Surles RL, Weng N, Simon PW, Tanumihardjo SA. 2004. Carotenoid profiles and consumer sensory evaluation of specialty carrots (*Daucus carota, L.*) of various colors. J Agric Food Chem 52:3417–21.

Tang G, Qin J, Grusak M, Russell RM. 2007. Quantitative determinations of vitamin A value of Golden Rice given as single or multiple meals. In: Consequences and control of micronutrient deficiencies: science, policy, and programs—defining the issues. Istanbul, Turkey: Micronutrient Forum; 105 p. (Abstract W29).

Tanumihardjo SA, Anderson C, Kaufer-Horwitz M, Bode L, Emenaker NJ, Haqq AM, Satia JA, Silver HJ, Stadler DD. 2007. Poverty, obesity and malnutrition: an international perspective recognizing the paradox. J Am Diet Assn 107:1966–72.

Thakkar SK, Maziya-Dixon B, Dixon AG, Failla ML. 2007. β-Carotene micellarization during *in vitro* digestion and uptake by Caco-2 cells is directly proportional to β-carotene content in different genotypes of cassava. J Nutr 137:2229–33.

The Alpha-Tocopherol Beta Carotene Cancer Prevention Study Group. 1994. The effect of vitamin E and beta carotene on the incidence of lung cancer and other cancers in male smokers. N Engl J Med 330:1029–35.

Tucker KL, Hannan MT, Chen H, Cupples LA, Wilson PWF, Kiel DP. 1999. Potassium, magnesium, and fruit and vegetable intakes are associated with greater bone mineral density in elderly men and women. Am J Clin Nutr 69:727–36.

United Nations Standing Committee on Nutrition, Geneva (Switzerland) in collaboration with the International Food Policy Research Institute. 2000. Fourth report on the world nutrition situation. Washington, D.C.: Intl. Food Policy Research Inst.

van Jaarsveld PJ, Faber M, Tanumihardjo SA, Nestel P, Lombard CJ, Benade AJ. 2005. β-Carotene-rich orange-fleshed sweet potato improves the vitamin A status of primary school children assessed with the modified-relative-dose-response test. Am J Clin Nutr 81:1080–7.

van Jaarsveld PJ, Marais DW, Harmse E, Nestel P, Rodriguez-Amaya DB. 2006. Retention of β-carotene in boiled, mashed orange-fleshed sweet potato. J Food Comp Anal 19:321–9.

Vitamin A Tracer Task Force. 2004. Appropriate uses of vitamin A tracer (stable isotope) methodology. Washington, D.C.: ILSI Human Nutrition Inst.

World Cancer Research Fund. 1997. Food, nutrition, and the prevention of cancer: a global perspective. Washington, D.C.: American Inst. for Cancer Research.

[WHO] World Health Organization. 2003. Immunizations, vaccines, and biologicals. Vitamin A supplementation. Available from: http://www.who.int/vaccines/en/vitamina.shtml. Accessed Nov 4, 2007.

Yonekura-Sakakibara K, Saito K. 2006. Review: genetically modified plants for the promotion of human health. Biotechnol Lett 28:1983–91.

COMPREHENSIVE
REVIEWS
IN FOOD SCIENCE AND FOOD SAFETY

Nutritional Attributes of Processed Tomatoes

Sudhir Singh, Jagdish Singh, and Mathura Rai

ABSTRACT: Tomatoes are a rich source of the natural pigment lycopene, an antioxidant with immunostimulatory properties. The fruit is also rich in ascorbic acid, β-carotene, and phenolics. A true assessment of the nutritional quality and health benefits of processed tomato-based foods depends not only on the total lycopene content, but also on the distribution of lycopene isomers. Controlling lycopene isomerization behavior during production and storage of tomato products can improve the product quality. The discoloration in tomato-processed products depends on the cis and trans behavior of the lycopene pigment. Commercial tomato processing revealed that the total cis-lycopene varied from 2.5% to 10%. Tomato soup and sauce processed from paste at 104 °C for 50 min was not significantly altered in the isomer content. Conventional air-drying decreases lycopene retention in tomato samples due to the influence of heat and oxygen. Dehydration methods significantly affected the formation of cis-isomers and decrease in trans-isomers. Osmotically dried tomato contained less cis-isomers when compared with those directly air-dried and vacuum-dried. The health attributes of lycopene can be further explored in the development of functional foods.

Introduction

Agriculture continues to be the main stay of life for a majority of the Indian population. Significant progress has been made in agricultural production since independence in 1947. There has been a 4-fold increase in the agricultural production of food grains since independence. However, an estimated number of about 800 million living in South Asia and sub-Saharan Africa are considered to be suffering from *hidden hunger* iodine deficiency disorders, vitamin A deficiency, and iron deficiency disorder (Singh and others 2006).

The Government has identified horticultural crops as a means of diversification for making agriculture more profitable through efficient land use, optimum utilization of resources, and creating employment of rural masses. Recent efforts of breeders towards evolution of high-yielding, disease-resistant varieties have been more rewarding in terms of increased production, productivity, and availability of a much larger volume of horticultural crops. Economic reforms during the last decade improved the generation of employment, lowered inflammation rate, and increased export and foreign exchange reserves, and so on.

The major contribution of vegetables to human health has always been thought to be the large amounts of vitamin A, the folic acid vitamin, and the vitamin C, as well as a good amount of some minerals. Epidemiological data support the association between high intake of vegetables and fruits and low risk of certain chronic diseases. Vegetables are rich sources of a variety of nutrients, including vitamins, trace minerals, dietary fiber, and many other classes of biologically active chemicals. These phytochemicals can have complementary and overlapping mechanisms of action, including modulation of detoxification enzymes, stimulation of the immune system, reduction of platelet aggregation, modulation of cholesterol synthesis and hormone metabolism, reduction of blood pressure, and antioxidant, antibacterial, and antiviral effects. Thousands of biologically active phytochemicals have been identified in plant foods, such as grains, nuts, legumes, vegetables, and fruits. Of these plant food groups, vegetables and fruits are the most botanically diverse. Vegetables include roots, leaves, stems, fruits, and seeds from more than 40 botanical families. Thus, they have the potential to contribute significant variety and complexity to the human diet (Sethi and Sethi 2006).

Vitamins and Minerals in Vegetables

Vegetables are important to provide enough vitamins and minerals for health. They are particularly important as a source of vitamin A, vitamin C, and folate (folic acid, folacin). These 3 are the most important ones, but most vegetables are a "good" source of thiamine (B1), potatoes and green leafy vegetables are rated a "good" source of riboflavin (B2), and potatoes, broccoli, cauliflower, and tomatoes are a "good" source of pantothenic acid (B5). Pyridoxine (B6) is important in brain function, immune system function, and as a precursor to several important hormones. All the brassicas are rated a "good" source, as are potatoes, spinach, peas, carrots, watercress, and onions. Many vegetables contain small but useful amounts of vitamin E. Vegetables are generally very good sources of most minerals (with the exception of iron). Tubers and roots are an energy source, besides; it is the protective phytochemicals and the vital vitamin C, vitamin A, and folic acid contents that make vegetables essential to human well-being. Vegetables are generally a good source of

---

MS 20070922 Submitted 12/12/2007, Accepted 3/13/2008. Authors are with Indian Inst. of Vegetable Research, Post Box No.01, P.O. Jakhini (Shahanshahpur), Varanasi-221 305, U.P., India. Direct inquiries to author S. Singh (E-mail: sudhiriivr@gmail.com).

calcium and green beans, in particular, are a good source. The Indian drumstick tree, *M. oleifera*, has the highest calcium level and highest vitamin C level of any tropical vegetable (Shah and Nath 2006).

Carotenes, in general, and β-carotene the most common, are obtained from plant foods (Jones and Porter 1986). β-Carotene is a *precursor* of vitamin A (pro-vitamin A) (Mayne 1996). β-Carotene is converted to vitamin A by the body. Because the rate at which β-carotene is converted to vitamin A in the body is known, most often the vitamin A content of foods are quoted as "actual" vitamin A (retinol)—generally the number of micrograms per 100 gram sample—and the micrograms of β-carotene are converted into international units of vitamin A (by multiplying micrograms of β-carotene by 1.6). β-Carotene is nontoxic under most circumstances. In fact, the body has a mechanism whereby it can regulate the absorption of carotenes (although absorption is generally rather low anyway, may be in the 15% to 35% range). For raw carrots, for example, only around 1% of the carotene present in the carrot ends up being absorbed. This rises, variably, to may be 19% when the carrot is cooked. In spite of the fairly low rate of conversion, carrots alone provide 30% of the vitamin A in the diet.

Fats in a meal improve the conversion of β-carotene to the fat-soluble vitamin A (Brown and others 2004). The amount of β-carotene converted to vitamin A varies, the more finely chewed, or grated, the greater is the availability (Ncube and others 2001). Moderate cooking increases the availability, as it helps break down the cell walls of the vegetable (Rock and others 1998). Repeated cooking at higher temperatures destroys some of the vitamin A. And having adequate vitamin E seems essential to efficient conversion. So, vegetables lightly cooked in oil, for example, are a very good way to maximize the amount of available β-carotene in the diet. Luckily, our liver can "stock up" and store vitamin A (which is why carnivorous animals accumulate such large amounts); in fact, the human liver can store a supply up to 6 mg. Vitamin A is an important antioxidant, vital for healthy skin and cell membranes, and important for the function of the immune system, amongst other things. But regardless of whether they are converted to vitamin A or not, carotenoids protect cells against oxidative damage. There is a definite corelation between intake of β-carotene derived from vegetable and fruit and lower risk of cancer. Vegetables are one of the most important sources of β-carotene.

Health Attributes of Fruits and Vegetables

In India, the production of fruits and vegetables has been growing at compounded annual rates of 5% and 6%, respectively, over the last decade. India is the 2nd largest producer of vegetables and 3rd largest producer of fruits with a production of 113.5 million metric tones of vegetables and 76 million metric tones of fruits, respectively (Indian Horticulture Database 2003). The growing awareness of consumption of fresh fruits and vegetables leads to many health benefits such as reduced incidence of many common forms of cancer and diets rich in plant-based foods also cause reduced risk of heart disease and many chronic diseases of aging. Fruits and vegetables contain phytochemicals that have anticancer and anti-inflammatory properties, which translates to functional properties in foods (Kaur and Kapoor 2001). Tomato contains red pigment as lycopene, which is localized in the prostate gland of males and may be associated with maintaining prostate health, which may further be linked with decreased risk of cardiovascular diseases. Broccoli, Brusssels sprouts, and kale contain glucosinolates, which have also been linked to decreased risk of cancer (Giulano and others 1993; Fraser and others 1994). Garlic and other alliums contain allyl sulfides that may inhibit cancer cell growth. Several studies across the globe have pointed out a close link between dietary phytochemical intake and reduced risk of cardiovascular diseases. Dietary flavonoids have an inverse correlation with mortality from coronary heart diseases, plasma total cholesterol, and low-density lipoprotein (LDL) (Shi and Le Maguer 2000).

Oxidized LDL has been proposed as an atherogenic factor in heart disease, promoting cholesterol ester accumulation and foam cell formation. Dietary antioxidants from vegetables get incorporated into LDL and become oxidized themselves, thus preventing oxidation of polyunsaturated fatty acids. Phytochemicals also reduce platelet aggregation, modulate cholesterol synthesis and absorption, and reduce blood pressure. Systemic inflammation may also be a critical factor in cardiovascular disease, C-reactive protein, anti-inflammatory marker, may be a stronger predictor of cardiovascular disease than LDL cholesterol; and anti-inflammatory activity of phytochemicals may play an important role in improving the health of the heart. Free radicals can cause DNA damage, which in turn can lead to base mutation, DNA cross-linking, and chromosomal breakage and rearrangement. The damage may be controlled by dietary antioxidants from vegetables through modulation of detoxification enzymes, scavenging of oxidative agents, stimulation of the immune system, hormone metabolism, and expression in cell proliferation and apoptosis (Velmurugen and others 2001).

Phytochemicals in Vegetables

Phytochemicals/phytonutrients/phytonutriceuticals are organic compounds derived from plants that have health promoting properties (Prior and Cao 2000). Besides the common nutrients such as carbohydrates and amino acids from protein, there are certain nonnutrient phytochemicals in vegetables that have bio-

Table 1 — Most commonly studied phytochemicals in vegetables.

Food	Phytochemical(s)
Allium vegetables (garlic, onions, chives, leeks)	Allyl sulfides
Cruciferous vegetables (broccoli, cauliflower, cabbage, Brussels sprouts, kale, turnips, bok choy, kohlrabi)	Indoles/glucosinolates Sulfaforaphane Isothiocyanates/thiocyanates Thiols
Solanaceous vegetables (tomatoes, peppers)	Lycopene
Umbelliferous vegetables (carrots, celery, cilantro, parsley, parsnips)	Carotenoids Phthalides Polyacetylenes
Compositae plants (artichoke)	Silymarin
Citrus fruits (lemons)	Monoterpenes (limonene) Carotenoids
Other fruits (grapes, berries, cherries, apples, cantaloupe, watermelon, pomegranate)	Ellagic acid Phenols Flavonoids (quercetin)
Beans, grains, seeds (soybeans, oats, barley, brown rice, whole wheat, flax seed) Protease inhibitors	Flavonoids (isoflavones) Phytic acid Saponins
Herbs, spices (ginger, mint, rosemary, thyme, oregano, sage, basil, tumeric, caraway, fennel)	Gingerols Flavonoids Monoterpenes (limonene)

logical activity against chronic diseases (Table 1) (Craig and Beck 1999). They are low in fat and, like all plant products, contain no cholesterol. Most phytochemicals are found in relatively small quantities in vegetable crops. However, when consumed in sufficient quantities, phytochemicals contribute significantly towards protecting living cells against chronic diseases (Fahey and Talalay 1995). Major phytochemicals have been classified into 10 different classes based on their biological activities including: (1) carotenoids (α-and β-carotene, β-cryptoxanthin, lutein, lycopene, and zeaxanthin), (2) glucosinolates (sulforaphane, indole-3 carbinol), (3) inositol phosphates (phytate, inositol tetra and penta phosphates), (4) cyclic phenolics (chlorogenic acid, ellagic acid, and coumarins) (5) phyto-estrogens (isoflavones, daidzenin, genistein, and lignans), (6) phytosterols (campestrol, β- sitosterol, and stigmasterol), (7) phenols (flavonoids), (8) protease inhibitors, (9) saponins, and (10) sulfides and thiols.

Antioxidant Activity of Fresh Tomato

Tomatoes exhibit antioxidant activity with a good source of immunostimulatory properties and contain moderate amounts of β-carotene, vitamin C, and phenolics. Tomatoes contain vitamin C (160 to 240 mg/kg), lycopene (60 to 90 mg/kg), and phenolic acids such as ferulic, chlorogenic, and caffeic acids (5 to 10 mg/kg fresh weight). The important nutrients in small quantities are vitamin E (5 to 20 mg/kg), flavonoids (quercetin 5 to 50 mg/kg), and trace elements such as copper (0.01 to 0.09 mg), manganese (0.09 to 0.13 mg), and zinc (0.1 to 0.17 mg/kg), which are constituents of several antioxidant enzymes (Hart and Scott 1995; Tonucci and others 1995). The concentration of lycopene is 2-fold higher in the pericarp than in the locular cavity and that of β-carotene is 4-fold higher in the locular cavity than in the pericarp. Flavonoids and phenolic acids seem to be more concentrated in the skin than in the flesh and vitamin E appears to be specifically located in seeds (Shi and Le Maguer 2000). Various factors such as variety, maturity stage, environmental factors, and cultural practices contribute to lycopene distribution in tomatoes. Normally, tomatoes contain about 3 to 5 mg lycopene/100 g of raw material. Higher amounts of lycopene (9 to 15 mg/100 g) are also reported in some deep varieties of tomatoes (Tonucci and others 1995). Among Indian varieties, Indoprocess III and Pusa Ruby are some of the promising varieties in terms of lycopene content. Lycopene content increases with an increase in the maturity stage in tomatoes. At the turning stage, it increases considerably and can reach about 8 to 10 mg/100 g fresh weight at the red stage (Thakur and Lal Kaushal 1995). Lycopene concentrations have been reported to be higher in summer and lower in winter. Fruits picked green and ripened in storage are lower in lycopene than vine-ripened fruits. Relatively high temperature (35 to 40 °C) was found to inhibit lycopene production, while low temperature inhibited both fruit ripening and lycopene production (Lurie and others 1996). The outer pericarp has a maximum quantity of lycopene. Tomato skin contains 12 mg lycopene/100 g wet skin weight, while whole mature tomato contains only 3.4 mg lycopene/100 g wet wt. The concentration of lycopene in tomato skin is about 3 to 5 times higher than in whole mature tomatoes. Further studies also indicate that lycopene is attached to the insoluble fiber portion of the tomatoes (Sharma and Le Maguer 1996).

Effect of Processing of Vegetables on Bioavailability of Phytochemicals

The processed forms of tomatoes are consumed in the form of tomato juice, paste, puree, ketchup, and sauce. Deep red tomato fruits containing high concentrations of lycopene could be processed into products with dark red color. However, the lycopene content in concentrated tomato products is generally lower than expected because of losses during tomato processing (Shi and Le Maguer 2000). The principal causes of lycopene degradation in tomato processing are isomerization and oxidation. It is widely established that lycopene undergoes isomerization on thermal processing. The form of change in trans–cis isomers in lycopene governs the biological properties in tomatoes. The determination of the degree of isomerization may result in better insight into the potential health benefits of the processed tomatoes (Zechmeister 1962).

In processed tomato products, the oxidation process depends on many factors such as moisture, temperature, and the presence of pro- or antioxidants, and lipids. The deterioration in color that occurs during the processing of various tomato products results from exposure to air at high temperatures during processing causing the naturally occurring all trans-lycopene to be isomerized to cis-lycopene. It is generally accepted that the all trans form of lycopene has the highest stability and cis-isomers have the lowest stability (Kaur and others 2004). Coupled with exposure to oxygen and light, heat treatments that disintegrate tomato tissue can also result in the destruction of lycopene. These changes are mainly due to heat stress imposed by the relatively harsh thermal processes required to achieve the shelf stability of processed tomato products (Shi and Le Maguer 2000). Light, acids, and other factors have also been reported to cause isomerization of lycopene (Shi and others 1999). A true assessment of the nutritional quality and health benefits of processed tomato-based food depends not only on the total lycopene content but also on the distribution of lycopene isomers. Controlling lycopene isomerization behavior during production and storage of tomato products can be of benefit in improving processed tomato products and their quality.

The proportion of all trans-lycopene varied from 96% of total lycopene in preserved tomato paste down to 77% in tomato ketchup. It was found that 20% to 30% of the total lycopene consisted of cis-isomers when tomatoes were heated at 100 °C for 1 h (Stahl and Sies 1992). Bioavailability of lycopene from processed tomato juice and paste was significantly higher than that from unprocessed fresh tomatoes (Gartner and others 1997). Microwave processing of tomatoes was found to affect the quality of tomato pulp. Higher retention of lycopene was found in microwave processed tomato pulp in contrast to those processed by conventional methods. Shorter cooking time as compared to longer periods during traditional heating methods might reduce the possibility of isomerization and oxidation allowing for greater lycopene retention with the same bioavailability found in the industrially processed tomato products (Kaur and others 2004).

Drying Effect on Lycopene

The loss of lycopene during dehydration of tomatoes is of important commercial concern. The drying of tomato slices is typically carried out at higher temperatures over an extended period under vacuum. Tomato pulp is manufactured by concentrating in vacuum at lower temperature (50 °C). Tomato powder is generally manufactured by spray- or roller-drying processes. Conventional air-drying decreases lycopene retention in tomato samples due to the influence of heat and oxygen (Shi and others 1999). Formation of cis-isomers is also affected by drying methods. The different methods of dehydration on lycopene degradation show a significant increase in cis-isomers and a simultaneous decrease in all trans-isomers (Kaur and others 2004). Dehydration of tomatoes at mild temperature does not usually cause significant losses in total lycopene content (Nguyen and Schwartz 1998). In the air-drying processes, isomerization and oxidation are 2 factors that simultaneously affect the ideal lycopene content, distribution of trans- and cis-isomers and biological potency. Osmotically dehydrated tomatoes contain fewer cis-isomers when compared with directly air-dried and vacuum-dried tomatoes. The highest amount of cis-isomers was found in processed tomato samples and was increased with temperature and time during dehydration. Osmotic solution remains on the outer layer of tomato, which prevents the penetration of oxygen, thus minimizing the oxidation of lycopene. However, air-drying processes result in isomerization and oxidation, which govern the lycopene content in tomatoes and distribution of trans- and cis-isomers and biological potency (Shi and others 1999). Dried tomatoes are very sensitive to color degradation due to lycopene isomerization, oxidation, and due to nonenzymatic browning. Lycopene degradation in tomato powder was 30% and 60% during 6 wk of storage at 6 and 45 °C, respectively (Anguelova and Warthesen 2000). There has been nearly 17% cis-isomer lycopene formation in foam-mat tomato powder (Lovric and others 1970). Recent reports suggest no significant losses of lycopene in tomato samples dried at 80 °C and a maximum of 12% loss in tomato samples dried at 110 °C (Zanoni and others 1998).

β-carotene

β-carotene is located more in the locular cavity than in the pericarp tissue (Davies and Hobson 1981). Very little information is available on processing effect on β-carotene. The content of β-carotene is much lower with respect to lycopene in tomato paste than in raw and sliced tomatoes (Khachik and others 1992). β-Carotene is more sensitive to oxidation and heat damage than lycopene and is partially isomerized and adversely affected during tomato processing. Different carotenoids have different bond energies and kinetics for isomerization and oxidation reactions.

Carotenoids

Studies have shown that combinations of fatty foods with carotenoid-rich vegetables enhanced carotenoid uptake. Most recent studies have shown that the bioavailability of lycopene from tomato has increased dramatically by heat treatment in the presence of oil (Gartner and others 1997). For example, lycopene was found to be more bio-available from tomato paste than from fresh tomato due to heat treatment and presence of oil content in the paste (Stahl and Sies 1992). It has also been shown that lutein, which has no vitamin A activity, is 5 times more readily available than β-carotene.

Ascorbic Acid

Its content in tomatoes is a function of varietal and technological factors. The mean value of ascorbic acid in different varieties ranges from 150 to 230 mg/kg (Davies and Hobson 1981). Tomato processing with the maintenance of higher levels of ascorbic acid has received considerable attention by food technologists. In the manufacture of tomato juice, ascorbic acid is destroyed mainly by oxidation. Ascorbic acid is oxidized to dehydro-ascorbic acid, which is further oxidized to degradation products with no vitamin C activity. The oxidation may be enzymatic or nonenzymatic and is catalyzed by copper ions. The longer the period for which tomato juice is held at optimum conditions for oxidation the lower will be the retention of ascorbic acid in processed tomato products. The rate of oxidation is dependent on the dissolved copper and temperature of juice. The rate of ascorbic acid destruction increases with increase in the temperature and in the presence of air. It is imperative to the processors to immediately attain the desired temperature as quickly as possible and it should be held for shorter periods at high temperature. Lee and others (1977) reported on the stability of ascorbic acid in tomato, which is a function of temperature and pH. The ascorbic acid degradation follows pseudo first-order kinetics, and the rate of destruction is significantly influenced by pH, reaching a maximum at pH 4.08.Tomatoes lost about 38% of their original ascorbic acid content during hot break extraction (90 °C for 5 to 10 min) and a further 16% loss was caused by concentration (60-70 °C for 4 h). Microwave processing of tomato juice revealed higher retention of ascorbic acid (Kaur and others 1999). Ascorbic acid degradation during storage also followed pseudo first-order kinetics with higher rate constants in tomato paste and puree than in tomato pulp. Ascorbic acid loss was 40% in tomato pulp, 55% in tomato puree, and 60% in tomato paste (Giovanelli and others 2001). Ascorbic acid degradation in tomato paste was highest in tomato paste stored at 40 °C than tomato paste stored at 4 °C during 10 months of storage (Mesic and others 1993).

Phenolics

Phenolics may constitute an important source of dietary phytochemicals. The main phenolic acids are ferulic, chlorogenic, and caffeic acids (Bourne and Rice-Evans 1998). Epidemiological studies indicate that high intake of phenolics and flavonoid is correlated with decreased risk or cardiovascular diseases. Muir and others (2001) advocated that 65% of the flavonoid present in fresh tomatoes were retained in processed tomato paste. During storage, the total phenolics content increased slightly in tomato pulp and puree and was stable in tomato paste, which showed a higher initial content (Giovanelli and others 2001). The possible reason can be correlated that heating at higher temperature may cause an imcrease in total phenolic groups by releasing the bound phenolics.

Antioxidant Activity

Tomatoes have very high antioxidant properties, which attracted the processors to include these properties in various formulated foods. Dietary lycopene and other antioxidant compounds present in tomatoes have potential health benefit properties resulting from their putative antioxidant activity (AOX). Recently the emphasis is laid in evaluating total AOX in foods in terms of the capacity of substance extracted from the food matrix to delay the oxidation processes in a controlled system (Wang and others 1996). Such methods are functional methods to simulate oxidative reactions similar to those occurring *in vivo* and allow for the evaluation of the protective effects against oxidative reactions (Lavelli and others 2000). Thermal processing elevated total AOX and bioaccessible lycopene content in tomatoes and produced no significant changes in the total phenolics and total flavonoids contents (Dewanto and others 2002). Re and others (2002) have reported an improvement in the availability of individual antioxidants (flavonoids and lycopene) upon processing fresh tomatoes into tomato ketchup/sauce. Total AOX along with hydrophilic and lipophilic extracts was increased. These findings strongly support that thermal processing enhances the nutritional value of tomatoes by increasing the bioaccessible lycopene and total AOX content.

Conclusions

Studies in different model systems showed that hydrophilic and lipophilic fractions of all tomato products were able to affect model reactions. Fresh tomato varieties varied considerably in the AOX of their hydrophilic and lipophilic fractions. Processed tomato products showed a significantly lower AOX than fresh tomatoes in their hydrophilic fraction (Lavelli and others 2000). AOX of heat-treated tomato juice (70 or 95 °C for 50 h) revealed a decrease in AOX potential for short heat treatments (Anese and others 1999). This decrease is attributed to both the degradation of natural AOX components and formation of early Maillard reaction products with pro-oxidant properties. However, prolonged heating showed a recovery of the initial AOX and then an increase in the overall antioxidant activity. This was mainly due to the formation of melanoidins, which act as antioxidants during the advanced steps of Maillard reactions. The AOX was measured as peroxyl radical quenching and oxygen scavenging activity.

References

Anese M, Manzocco L, Nicoli MC, Lerci CR.1999. Antioxidant properties of tomato juice as affected by heating. J Sci Food Agric 79:750–4.

Anguelova T, Warthesen J. 2000. Lycopene stability in tomato powders. J Food Sci 65:67–70.

Bourne LC, Rice-Evans C. 1998. Bioavailability of ferulic acid. Biochem Biophys Res Comm 253:70–6.

Brown MJ, Feruzzi MG, Nguyen ML, Cooper DA, Eldridge AL, Schwartz SJ, White WS. 2004. Carotenoid bioavailability is higher from salads ingested with full fat rather than with fat reduced salad dressings as measured with electrochemical detection. Am J Clinical Nutr 80:396–403.

Craig W, Beck L. 1999. Phytochemicals: health protection effects. Can J Diet Pract Res 60:78–84.

Davies JN, Hobson GE. 1981. The constituents of tomato fruit: The influence of environment, nutrition and genotype. Crit Rev Food Sci Nutr 15:205–8.

Dewanto V, Wu X, Adom KK, Liu RH. 2002. Thermal processing enhances the nutritional value of tomatoes by increasing total antioxidant activity. J Agric Food Chem 50: 3010–4.

Fahey J, Talalay P. 1995. The role of crucifers in cancers chemo protection. In: Gustine DL, Flores HE, editors. Phytochemicals and health. Rockville, Md.: American Society of Plant Physiologists.

Fraser PD, Truesdale MR, Bird CR, Schuch W, Bramley PM. 1994. Carotenoid biosynthesis during tomato fruit development. Plant Physiol 105:405–13.

Gartner C, Stahl W, Sies H. 1997. Lycopene is more bioavailable from tomato paste than from fresh tomatoes. Am J Clin Nutr 66:116–22.

Giovanelli G, Lavelli V, Peri C, Pagliarini E, Zanoni B, Spigno P. 2001. The antioxidant activity of tomato III. Effects of processing technologies on oxidative and heat damage. Acta Hort 542:217–20.

Giulano G, Barley GE, Scolnik PA. 1993. Regulation of carotenoid biosynthesis during tomato development. Plant Cell 5:379–87.

Hart DJ, Scott KJ. 1995. Development and evaluation of a HPLC method for analysis of carotenoids in foods and the measurement of the caroptenoid contents of fruits and vegetables commonly consumed in the UK. Food Chem 54:101–11.

Indian Horticulture Database. 2003. National Horticulture Board. Gurgaon, Haryana, India.

Jones BL, Porter JW. 1986. Biosynthesis of carotenoids in higher plants. CRC Crit Rev Plant Sci 3:295–324.

Kaur C, Kapoor HC. 2001. Antioxidants in fruits and vegetables—the Millennium's health. Int J Food Sci Technol 36:703–25.

Kaur C, Khurdiya DS, Pal RK, Kapoor HC. 1999. Effect of microwave heating and conventional processing on the nutritional qualities of tomato juice. J Food Sci Technol 36:331–3.

Kaur C, George B, Deepa N, Singh B, Kapoor HC. 2004. Antioxidant status of fresh and processed tomato—a review. J Food Sci Technol 41:479–86.

Khachik F, Goli MB, Beecher GR. 1992. Effect of food preparations on qualitative and quantitative distribution of major carotenoid constituents of tomatoes and several green vegetables. J Agric Food Chem 40:390–8.

Lavelli V, Peri C, Rizzolo A. 2000. Antioxidant activity of tomato products as studied by model reactions using xanthine oxidase, myeloperoxidase and copper induced lipid peroxidations. J Agric Food Chem 48:1442–8.

Lee YC, Kirk JR, Bedford CL. Heldman DR. 1977. Kinetics and computer simulation of ascorbic acid stability of tomato juice as functions of temperature, pH and metal catalyst. J Food Sci 42:640–8.

Lovric T, Sablek Z, Boskovic M. 1970. Cis-trans isomerization of lycopene and color stability of foam-mat dried tomato powder during storage. J Sci Food Agric 21:641–7.

Lurie S, Handros A, Fallik E, Shapira. 1996. Reversible inhibition of tomato fruit gene expression at high temperarure. Plant Physiol 110:1207–14.

Mayne ST. 1996. β-carotene, carotenoids and disease prevention in humans. FASEB J 10:690–701

Mesic Z, Galic K, Cikovic N. 1993. Redox potential and browning of tomato paste in aluminium tubes during storage at different temperature. R Lebensm Unters Forsch 197:525–30.

Muir SR, Collins GJ, Robinson S, Hughess BA, Vos-CHR-de, Tunen-AJ-van, Verhoeyen ME. 2001. Over expression of petunia chalcone isomerase in tomato results in fruit containing increased levels of flavonoids. Nat Biot 19:470–4.

Ncube TN, Greiner T, Malaba LC, Gebre-Medhin M. 2001. Supplementing lactating woman with pureed papaya and grated carrots improved vitamin A statusin placebo-controlled trial. J Nutr 131:1497–502.

Nguyen ML, Schwartz SJ. 1998. Lycopene stability during food processing. Proc Exp Boil Med 218:101–5.

Prior RL, Cao G. 2000. Antioxidant phytochemicals in fruits and vegetables: diet and health implications. Hort Sci 35:588–92.

Re R, Bramley PM, Rice-Evans C. 2002. Effects of food processing on flavonoids and lycopene in Mediterranean tomato variety. Free Radical Res 36:803–10.

Rock CL, Lovalva JL, Emenhiser C, Ruffin MT, Flatt SW, Schwartz SJ. 1998. Bioavailabilty of β-carotene is lower in raw than in processed carrots and spinach in women. J Nutr 128:913–6.

Sethi S, Sethi V. 2006. Value addition in horticultural crops through diversification. Processed Food Ind 9:43–7.

Shah NS, Nath N. 2006. Minimally processed fruits and vegetables-freshness with convenience (review). J Food Sci Technol 43:561–70.

Sharma SK, Le Maguer M. 1996. Lycopene in tomatoes and tomato pulp fractions. J Food Sci 2:107–13.

Shi J, Le Maguer M. 2000. Lycopene in tomatoes. Chemical and physical properties affected by food processing. CRC Crit Rev Food Sci Nutr 110:1–42.

Shi J, Le Maguer M, Kakuda Y, Liptay A. 1999. Lycopene degradation and isomerisation in tomato degradation. Food Res Int 32:15–21.

Singh S, Singh J, Rai M. 2006. Post harvest processing and value addition in vegetables: current perspective. Ind Food Ind 25:5–58.

Stahl W, Sies H. 1992. Uptake of lycopene and its geometrical isomers is greater from heat processed than from unprocessed tomato juice in humans. J Nutr 122:2161–6.

Thakur NS, Lal Kaushal BB. 1995. Study of quality charactweristics of some commercial varieties and f1 hybrids of tomato grown in Himachal Pradesh in relation to processing. Indian Food Packer 49:25–31.

Tonucci LH, Holden JM, Beecher GR, Khachik F, Davis CS, Mulokozi G.1995. Carotenoid content of thermally processed tomato based food products. J Agric Food Chem 43:579–86.

Velmurugen B, Bhuvaneshwari V, Balasenthi S, Nagini S. 2001. Lycopene, an antioxidant carotenoid modulates glutathione-dependent hepatic biotransformation enzymes during experimental gastric carcinogenesis. Nutr Res 219:1117–24.

Wang H, Cao GH, Prior RL. 1996. Total antioxidant capacity of fruits. J Agric Food Chem 44:701–5.

Zanoni B, Peri C, Nani R, Lave V. 1998. Oxidative heat damage of tomato halves as affected by drying. Food Res Int 31:395–401.

Zechmeister L. 1962. Cis-trans Isomeric carotenoids, vitamin A and arylopolyenes. New York: Academic Press.

COMPREHENSIVE
REVIEWS
IN FOOD SCIENCE AND FOOD SAFETY

Adaptation and Potential Uses of Sorghum and Pearl Millet in Alternative and Health Foods

K.N. Rai, C.L.L. Gowda, B.V.S. Reddy, and S. Sehgal

ABSTRACT: Sorghum (*Sorghum bicolor*) and pearl millet (*Pennisetum glaucum*) are major warm-season cereals largely grown for grain production in the semi-arid tropical regions of Asia and Africa. Under rain-fed farming systems with little external inputs, their grain yield levels are often low ($<$1 t/ha). However, improved hybrid cultivars, when grown under well-irrigated and well-fertilized conditions, have been reported to give 8-9 t/ha of grain yield in sorghum and 4-5 t/ha in summer-season pearl millet, indicating high grain yield potential of these crops and the place they deserve in commercial agriculture. Both crops are highly tolerant to drought and soil salinity and high air temperatures, which enhance their agro-ecological adaptation under increasing severity of these major abiotic production constraints and make them increasingly more relevant in view of climate change. Research shows that sorghum and pearl millet grains are nutritionally comparable or even superior to major cereals such as wheat and rice owing to higher levels of protein with more balanced amino acid profile, dietary energy, vitamins, several minerals (especially micronutrients such as iron and zinc), insoluble dietary fiber leading to lower glycemic index, and phytochemicals with antioxidant properties. Technologies for various processing treatments, such as milling, malting, blanching, acid treatment, dry heating, and fermentation, which reduce antinutritional factors and increase the digestibility and shelf life of various alternative food products such as unleavened flat bread (*roti/chapati*), porridges, noodles, bakery products, and extruded and weaning food products, have been developed and tested at the laboratory scale. These properties and technologies enhance the value of both crops for nutritional security of the undernourished vulnerable population and food-based health management of the elite class. Commercialization of these processing and food product development technologies through public and private partnerships can enhance the pace of large-scale adoption of these products and technologies. This should be supported by a demand-driven grain production, procurement, storage, and handling to ensure the consistency of high-quality grain supplies. The commercial viability would depend on the profitability for all involved in the value chain, from farmers to consumers, which may require policy support and a sustained campaign about the health, nutrition, and ecological sustainability benefits of sorghum and pearl millet.

Introduction

Sorghum (*Sorghum bicolor* L.) and pearl millet (*Pennisetum glaucum* (L.) R. Br.) are major warm-season cereals valued for their food, feed, and fodder uses in various parts of the world. Sorghum is cultivated on more than 42 million ha worldwide with the largest areas in Africa (24.5 million ha) and Asia (10.6 million ha). It is also an important crop in the Americas (6.6 million ha) and Australia (0.7 million ha). India ranks first with the largest sorghum area (9.1 million ha) in the world. While sorghum grain is largely used for food purposes in Africa and south Asia, it is mostly used for nonfood purposes in other parts of the world. Pearl millet, cultivated on more than 29 million ha, has relatively more restricted geographical distribution, with Africa (15 million ha) and Asia (11 million ha) being the largest producers of this crop. India has the largest pearl millet area (9.8 million ha) in the world. In India and Africa, pearl millet grains are mostly used for food purposes. Brazil has recently emerged as a major country, growing pearl millet on more than 3 million ha, mostly as a mulch crop in the soybean system, but recently cultivating it for fodder and experimenting with grain production. Due to its high levels of drought tolerance, pearl millet is gaining importance for feed grain production in the United States. Due to high levels of salinity tolerance, sorghum and pearl millet are also gaining attention as

MS 20080037 Submitted 1/17/2008, Accepted 4/9/2008. Authors Rai, Gowda, and Reddy are with Intl. Crops Research Inst. for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India. Author Sehgal is with CCS Haryana Agricultural Univ., Hisar 125 004, Haryana, India. Direct inquiries to author Rai (E-mail: k.rai@cgiar.org).

feed, food, and fodder crops in the salinity-affected regions of the Middle East and Central Asia.

Sorghum and pearl millet, dubbed as coarse-grain cereals and poor man's crops for long, have remained neglected with respect to their appropriate position in the commercialized food system, and investment in research, development, and commercialization. With the increasing concerns about adverse changes in environmental quality and its consequent negative effects on food and nutritional security, and the perceived need for increasing food production per unit resource investment for an expanding population, these crops along with other underutilized crops have good prospects of entering the food baskets of a wider range of consumers, both rural and urban, poor and rich, and in developing and developed economies. There is a large body of undocumented rural knowledge on the nutritive and health values of these crops and the various types of food products that can be prepared from them. Limited research efforts in grain processing and food product technologies have been made to assess the potential of these crops for alternative and health food uses, especially in the case of pearl millet. Laboratory results point to good prospects of their commercial feasibilities. The objective of this article is to illustrate yield potential as well as adaptation and grain quality attributes of these crops; highlight the processing technologies and alternative food products that can be made; and draw attention to constraints and opportunities for the commercialization of these technologies.

Adaptation and Yield Potential

In the arid and semi-arid tropical regions of Asia and Africa, where much of the sorghum and pearl millet is grown, soil surface temperatures can rise above 60 °C, which can adversely affect germination and seedling survival, leading to poor crop stand and plant vigor. Pearl millet is now increasingly being grown as a summer season crop in parts of Gujarat, Rajasthan, Maharashtra, Tamil Nadu, and Uttar Pradesh states of India. The crop often encounters high air temperatures during flowering and grain filling, often exceeding 42 °C in parts of Gujarat and Rajasthan. In the light of climate change, these situations are not likely to get any milder. Rising temperatures also lead to unpredictable droughts with deficit and erratic rainfall and high evapotranspiration. Associated with drought, high temperatures, and overuse and misuse of irrigation water is the problem of soil salinity (Ashraf 1994; Hollington 1998). Genetic improvement of crops along with the application of efficient crop and natural resource management technologies in an integrated genetic and natural resource management framework provides a sustainable cost-effective approach to address the challenges posed by these existing and emerging stress situations. In this framework, introduction of species already found adapted to these stresses, and their further genetic improvement, is likely to play a significant role in enhancing the resource use-efficient crop productivity and its stability.

Sorghum and pearl millet are traditionally grown as rain-fed crops, mostly in environments characterized by a combination of the above-listed stress factors, which become too marginal and unproductive for maize, another warm-season cereal. Seedlings of some sorghum genotypes surviving at soil surface temperatures as high as 55 °C have been reported (Peacock 1982). Pearl millet is even more heat-tolerant than sorghum with several genotypes surviving at as high as 62 °C of soil surface temperature (Peacock and others 1993). Since more than 90% of the pearl millet area in India is cultivated during the rainy season, pearl millet hybrids developed for adaptation to the rainy season are generally tested for their adaptation in the summer season. It has been observed that most of these hybrids fail to set any seed or have unsatisfactory seed set at higher temperatures exceeding 42 °C during flowering. A few commercial hybrids have, however, been identified that set good seed and give high grain yield when grown under such environments, indicating large variability for the flowering-period heat tolerance.

Sorghum is a highly drought-tolerant species, and pearl millet is even more drought-tolerant with higher water-use efficiency than sorghum. In a comparative study, it was observed that, when frequently irrigated, water-use efficiency of sorghum and pearl millet was comparable to maize, but as the number of irrigation periods decreased and more severe water-stress situations emerged, sorghum became more efficient in producing dry matter for each unit of water applied (Table 1). When the crop growing condition became highly stressful (just 1 irrigation applied), pearl millet became the most water-use-efficient crop. This shows the relevance of these crops in water-scarce situations. Large variability for drought tolerance has been detected in both crops, with the identification of closely linked molecular markers of quantitative trait loci associated with drought tolerance.

Sorghum has been characterized as moderately tolerant to soil salinity (Maas 1985; Igartua and others 1995). It is considered relatively more salt-tolerant than maize (Maas 1985). Also, large genetic variability for tolerance to salinity has been reported in sorghum (Azhar and McNeilly 1988; Maiti and others 1994; Krishnamurthy and others 2007a), offering a good scope for integrating salinity tolerance in breeding programs to improve crop productivity on saline lands. Pearl millet is even more tolerant than sorghum and is the 2nd most salinity-tolerant major cereal after barley. Also, much larger genetic variability for whole-plant response to soil salinity has been reported in pearl millet (Ashraf and McNeilly 1987; Dua 1989; Krishnamurthy and others 2007b). Recent research conducted by the Intl. Crops Research Inst. for the Semi-Arid Tropics (ICRISAT), in collaboration with the Intl. Center for Biosaline Agriculture (ICBA), the Intl. Center for Agricultural Research in Dry Areas (ICARDA), and the Natl. Agricultural Research Systems (NARS) in India, the Middle East, and Central Asia has confirmed the high salinity tolerance levels of sorghum and pearl millet. Large variability for salinity tolerance has been detected and salinity-tolerant germplasm and improved populations and breeding lines have been identified in both crops (Ramesh and others 2005; Kulkarni and others 2006).

Adaptation to the above-mentioned stress environments, where cultivation of other crops such as maize becomes uneconomical, and the dual role of these crops in meeting the food and fodder requirements of local farmers has been of critical importance in their continuing cultivation. In such environments, typical of subsistence agriculture, sorghum grain yields are low (800 to 1000 kg/ha) and pearl millet grain yields are still lower (600 to 800 kg/ha). However, improved cultivars of both crops are highly responsive to improved management. Sorghum hybrids

Table 1 — Water use efficiency (WUE) of sorghum, pearl millet, and maize at different frequencies of irrigation: S0 = 7 irrigations, S1 = 4 irrigations; S2 = 3 irrigations; S3 = 2 irrigations.

	Dry matter (kg/ha/mm water) at irrigation level			
Crop	S0	S1	S2	S3
Sorghum	15.4	16.4	18.5	14.0
Pearl millet	14.6	13.8	16.3	17.9
Maize	15.0	12.8	13.7	11.0

Source: Singh and Singh (1995).

maturing in about 110 to 115 d, when grown as commercial crops with improved crop management technologies (timely sowing and weeding, optimum plant population, irrigation, and fertilizer application) can give 8000 to 9000 kg/ha of grain yield. Similarly, pearl millet hybrids maturing in 80 to 85 d, when grown as an irrigated summer season and at 60 to 80 kg/ha of applied nitrogen, have given 4000 to 5000 kg/ha of grain yield.

Grain Structure and Quality

Sorghum grains are much larger in size (generally 20 to 25 g/1000, but can be as high as 60 g/100) than pearl millet grains (generally, 8 to 11 g/1000, but can be as high as 20 g/1000). Like all other cereals, grains of both crops are composed of pericarp (outer layer or bran), germ (embryo), and endosperm (storage tissues), which account for 6.5%, 9.4%, and 84.2% of the grain weight, respectively, in sorghum (Dahlberg and others 2004). In pearl millet, pericarp mass as a fraction of total grain mass is relatively greater than it is in sorghum (8% of the total grain mass), and germ is relatively much larger than sorghum (17% of the total grain mass). Pericarp has 3 parts: epicarp, mesocarp, and endocarp. Sorghum mesocarp is unique among all the cereals in that it contains small starch granules in grains with thick pericarp. Certain genotypes of sorghum have a pigmented inner integument, usually called testa or subcoat, which is the location of most of the condensed tannins in sorghum grains. Germ consists of 2 major parts: embryonic axis and scutellum. Endosperm is composed of aleurone layer, peripheral, corneous, and floury areas. The aleurone is outer cover adjacent to the testa, which is thicker in sorghum (4 to 40 μm) than in pearl millet (0.4 μm). Peripheral endosperm tissue is composed of several layers of dense cells and it affects the processing quality and the nutrient digestibility. The appearance of the corneous endosperm tissues may be translucent or vitreous. The opaque or floury endosperm is located around the center of the grain.

Pericarp is high in fibre and minerals whereas germ is high in crude protein, fat, and ash. Pericarp also contains tannins in certain sorghum genotypes, but the improved white food sorghums are devoid of it. The highest levels of tannins (almost all condensed type) are found in those sorghums that have 2 dominant genes for pigmented testa and a spreader gene for the presence of brown pigment, producing high tannin-brown grain color sorghums (Dykes and Rooney 2006). Pearl millet pericarp does not contain tannins, but it does contain other phenolics such as phenolic acid, like those in sorghum (many more flavonoids in case of sorghum). Endosperm contains mostly starch and protein with small amount of fat and fibre. Starch granules present in the corneous endosperm tissues are smaller and angular, with no air spaces, which may, in part, lead to hard grain texture. Those present in the floury endosperm are larger and round, with larger air spaces, which may, in part, lead to soft grain texture. Floury endosperm grains are more digestible than the corneous ones and are desirable in some types of food products. However, corneous endosperm types are most appropriate for many traditional food applications, and such grains are less prone to deterioration in quality due to disease and insect attacks and weathering. There is large genetic variation in grain shape in pearl millet (globular, obovate, hexagonal, and elliptical) than in sorghum (mostly spherical). But there is large variability for grain color in sorghum (white, cream, yellow, brown, red, and black) and variable preference for such color. Pearl millet grains are mostly gray color (light gray to dark gray), but plants with white, yellow, brown, and black color can also be found.

Sorghum has 10.4% crude protein, 1.9% fat, 72.6% carbohydrate, 1.6% crude fiber, and 1.6% minerals (Table 2). It is important to note that in both crops there is large genetic variability for these quality traits, and the values reported in the literature depend on the genotypes used. Thus, in sorghum, variability has been reported for starch (63.4% to 72.5%), protein (7.9% to 11.5%), fat (1.9% to 3.0%), amylase (17.8% to 21.9%), and fiber (1.6% to 2.4%) (Ratnavathi and others 2004). Pearl millet has higher levels of protein (9.2% to 13.6%) and fat (3.4% to 7.1%) than sorghum, with large variability also reported for starch (61.0% to 70.3%), ash (1.1% to 2.4%), popping expansion ratio (2.1% to 11.3%), and amylase activity (567 to 3141 maltose units) (Hadimani and others 1995). The biophysical environments from where grain samples are obtained for cross-species quality comparison are also important. For instance, improved varieties of rice, wheat, and maize are normally cultivated in relatively better-endowed environments with higher native soil fertility levels, and managed with higher doses of applied fertilizers (more than 100 kg/ha of nitrogen) and irrigation (which further enhances nutrient uptake). In contrast, sorghum and pearl millet are normally grown as rain-fed crops in drylands with poor soil fertility and at applied fertilizer levels of no more than 60 kg/ha. Sorghum and pearl millet grain samples harvested from the relatively better-endowed environments of Kansas, U.S.A., showed sorghum having 11% protein and pearl millet having 16.9% protein (Malleshi and Klopfenstein 1998).

Amino acid composition has significant effect on the nutritional quality of protein. The amino acid profile of pearl millet is better than that of sorghum and maize and is comparable to wheat, barley, and rice (Ejeta and others 1987; Hadimani and others 1995; Abdalla and others 1998; Malleshi and Klopfenstein 1998) with a less disparate leucine/isoleucine ratio (Hoseney and others 1987; Rooney and McDonough 1987). In general, the protein efficiency ratio of pearl millet is higher than that of sorghum and wheat (Rao and others 1964; Pushpamma and others 1972; Oke 1977). Carbohydrates of sorghum and pearl millet have 65% to 70% starch and 16% to 20% nonstarchy polysaccharides (NSPs). The NSPs make up about 95% of dietary fiber, which is derived from the bran and endosperm cell wall. In a comparison of malts from 16 sorghum varieties for amylase activity, it was found that some sorghum varieties had levels as high as 178 to 183 per μg of α-amylase, which was comparable to that of the commercial barley malt (189 per μg), and β-amylase was slightly less (37 to 41 per μg) as compared to the barely malt (52 per μg) (Beta and others 1995).

Micronutrient malnutrition, especially that associated with vitamin A, iron, and zinc, has recently been reported to be a widespread food-related health problem worldwide, particularly with people in those parts of the developing countries that have little access to fruits, vegetables, and animal products in their diets (Mason and Garcia 1993). Since the biofortification approach provides a sustainable and cost-effective solution to this problem (Bouis 2000), genetic enhancement of grain iron and zinc content in sorghum and pearl millet has been undertaken at ICRISAT. The details of this approach, the likelihood of its successes, and the ensuing consequences are hoped to be presented in another article in this volume. Suffice it to say that genetic

Table 2—Proximate composition of major cereal crops.

Crop	Protein (%)	Fat (%)	Carbo. (%)	Crude fiber (%)	Minerals (%)
Sorghum	10.4	1.9	72.6	1.6	1.6
Pearl millet	11.6	5.0	67.5	1.2	2.3
Maize	11.1	3.6	66.2	2.7	1.5
Wheat	11.8	1.5	71.2	1.2	1.5
Rice	6.8	0.5	78.2	0.2	1.5

Source: Ali SZ, CFTRI, Mysore.

improvement of sorghum and pearl millet in an attempt to develop improved cultivars with elevated levels of iron and zinc has led to the identification of promising germplasm and breeding lines. For instance, preliminary studies at ICRISAT have identified sorghum germplasm and breeding lines having > 75 ppm iron (about 20% more than wheat and maize) and > 50 ppm zinc (comparable to maize and wheat) (Table 3). There are indications of some sorghum germplasm accessions having up to 133 ppm iron and 91 ppm zinc. A pearl millet male-sterile line (863A) involved in 3 commercial hybrids of pearl millet was found to have 73 ppm iron and 56 ppm zinc (Velu and others 2007). An open-pollinated variety (ICTP 8203) of pearl millet, currently grown on about 0.3 million ha in Maharashtra state of India was found to have 80 ppm iron and 47 ppm zinc. Pearl millet breeding lines with > 130 ppm Fe and > 80 ppm zinc have also been identified.

Based on the nutrient composition as mentioned previously, sorghum and pearl millet are considered highly nutritious cereals. Improving their bioavailability can make them even more nutritious. The bioavailability of several nutrients is considerably reduced due to several antinutritional factors such as polyphenols and phytates, although these so-called antinutritional factors have numerous health-related positive attributes and can be used in specialty foods. Polyphenols, occurring largely in the peripheral area of the seed, inhibit the activities of several hydrolytic enzymes such as trypsin, chymotrypsin, amylases, cellulases, and ß-galactosidase (Singh 1984), resulting in reduction in protein and starch utilization (Thompson and Yoon 1984; Pawar and Parlikar 1990). They also reduce the availability of minerals and vitamins (Singh and Nainawatee 1999). Condensed tannins found in brown and red sorghums interfere with protein and starch metabolism in sorghum. These tannins have not been found in white grain food sorghums and most of pearl millet except those with brown color.

Rapid development of rancidity and bitterness, especially in pearl millet flour, has been a major constraint in its commercialization for various food products (Kaced and others 1984). Once the grain is decorticated and ground, the quality of meal deteriorates rapidly due to hydrolytic decomposition and oxidative degradation of lipids of the meals and consequent release of free fatty acids and formation of peroxides (Lai and Varriano-Marston 1980; Varriano-Marston and Hoseney 1983). These changes, as well as a methanol-extractable precursor similar to apigenin, contribute to the objectionable mousy odor of pearl millet flour (Reddy and others 1986).

Grain Processing Technologies

Dehulling

Both whole grains and dehulled (decorticated) grains of sorghum and pearl millet are used for preparing various types of food products. Sorghum and pearl millet grains of globular/elliptical shape, corneous endosperm and thick pericarp are relatively easy to decorticate with little loss of endosperm, and cleaner meal yield. Decortication is generally to the extent of removing 12% to 30% of the outer grain surface. Increased decortication naturally leads to greater loss of fiber, ash, and fat. It also reduces protein, lysine, histidine, and arginine. Phytic acid in monocots is mainly stored in the outer layers of the grain and to a lesser extent in the germ. Thus, milling or decortication greatly reduces the amount of phytates. Decortication also reduces the phenols and thus the antioxidant activity of both tannin-sorghums and nontannin sorghums by 82% to 83% due to removal of pericarp and testa. However, conventionally cooked porridges have higher antioxidant activity than extrusion-cooked products. Retention of antioxidant activity in fermented and unfermented porridges means that whole tannin-sorghum can be processed into specialty foods with potential health benefits (Dlamini and others 2007).

Table 3 — Micronutrient composition of major cereal crops (mg/kg).

Crop	Iron (Fe)	Zinc (Zn)
Sorghum	17 to 76	10 to 55
Pearl millet	30 to 146	25 to 85
Maize	10 to 63	13 to 58
Wheat	29 to 57	25 to 53
Rice	6 to 24	14 to 35

Decorticated grains improve the nutritional quality and sensory properties of various food products, but these also have cost considerations in terms of the time and investments and grain weight losses. Sorghum and pearl millet grains can be decorticated in rice mills or other modified mills. In some villages and urban areas, millet grains are decorticated with abrasive disks in mechanical dehullers. The incipient moist conditioning of the grain facilitates separation of the seed coat matter in the abrasive or friction-type mills to prepare decorticated grains (Desikachar 1975). A dehuller, suitable for sorghum and modifiable for pearl millet, has been manufactured by the Rural Industries Innovation Center (RIIC), Kanye, Botswana, which has a capacity of 400 to 600 kg/h. A significant development with this sorghum dehuller is that it has been combined to a hammer mill by the RIIC to create a dehulling–milling mechanism to ease the milling process and make it more time- and cost-efficient (Rohrbach and Obilana 2004).

Research and development efforts are still needed to develop a dehulling technology that removes the germ without much loss of the grain. To produce a meal of low fat content (< 1.0 g fat per 100 g grain), up to 40% of the grain must be decorticated with a flour yield of 60%. With this, there is also loss of protein, insoluble dietary fiber, fat, ash, lysine, and other amino acids (Serna-Saldivar and others 1994). But decortication of grains significantly reduces the phytic acid, amylase inhibitors, and polyphenols, with a resultant increase in the protein, starch digestibility, and mineral availability (Sharma and Kapoor 1996; Malleshi and Klopfenstein 1998). Excessive decortication reduces extraction rates and lowers the nutritive value of the flour, as protein and vitamin levels are more in the peripheral area of the endosperm, a part of which is lost due to decortication.

Manual decortication of sorghum (flour yield 75% to 80%) causes about 40% loss in lysine, while the mechanical decortication (flour yield 90%) causes about 10% loss in lysine, leading to reductions in nitrogen retention and protein efficiency ratio. The nutrient digestibility of the decorticated grains, however, is slightly higher than that of the whole grains. Decortication of brown sorghum has been shown to significantly reduce the amount of condensed tannins, reducing its adverse effect on the nutritional value (Mvasaru and others 1988). It has been shown that dehulling improves the sensory qualities of flat bread (*chapati*) made with sorghum flour (Vimala and others 1996). Dehulled grain, when used to cook as a boiled rice-like product, needs less cooking time and results in greater volume and weight of the products.

Milling

Grains can be milled either by using a hammer mill or a roller mill. The flour produced using a hammer mill has large particle size and is not uniform, hence it is not suitable for preparing thin and stiff porridge of rough texture and not suitable for preparing baked and steamed food products of smooth texture. Fine flours to prepare the same products can be obtained by using the roller mill. The sorghum dehuller—hammermill developed at RIIC, Botswana, is a practical machine for testing and adaptation by small- and medium-scale millers (Rohrbach and Obilana 2004). Maximill, another milling machine, has been developed in South Africa. One outstanding development in the processing equipment research is the small-scale, double roller mill developed in Namibia. It produces sorghum flour of high quality and it can be modified for adaptation to pearl millet.

Incipient moist conditioning of grains facilitates the separation of seed coats in the abrasive or friction type mills to prepare decorticated grains (Desikachar 1975). A small-capacity mini grain mill using this principle has been developed at the Central Food Technology Research Inst., Mysore, India (Shankara and others 1985) to prepare refined flour from sorghum and millets. This method, however, is not preferred because the germ also gets pulverized and mixed with the milling fractions that affects the shelf life of the product (Hadimani 1994).

Recently, a new method for improving the shelf life of sorghum and millet has been developed at CFTRI (Meera and others 2002); it involves moist heating of the grains followed by drying to about 10% to 12% moisture and decortication to the desired degree or pulverization. This process improves the milling characteristics of sorghum and pearl millet varieties that have high proportions of floury endosperm. Flour from treated and decorticated sorghum could be stored for about 8 to 10 mo, and that from pearl millet for about 3 to 4 mo, during which the free fatty acid (FFA) content remained below 10%, which is the limit of perceptible deteriorative condition. The oxidative rancidity also remained low, as the flours are refined. Another advantage of this process is that the microbial load on the grain surface is drastically reduced.

Malting

This process involves limited germination of cereal in moist air under controlled conditions. For pearl millet, a malting procedure has been developed that involves soaking of grain in 0.1% formaldehyde solution for 6 h, followed by aeration for 3 h, and resteeping in fresh formaldehyde solution for 16 h. The grains are then germinated for variable periods, that is, 12, 24, 36, 48, and 72 h, after which the grains are dried in an oven and vegetative growth is removed by abrasive action. Malting sorghum consists of steeping grain for 20 h in aerated water at 28 to 30 °C and immersing the steeped grain in 2% sodium hypochlorite solution for 10 min and then rinsing with water. The grains are germinated at 28 °C and 95% relative humidity for 5 d in a germinator. The germinated grains are oven-dried at 50 °C for 24 h. The roots and shoots are removed and the dried malt is cleaned (Beta and others 1995).

Malting helps in the mobilization of seed reserves and elaboration of the activity of α- and ß-amylase and protease. Dicko and others (2006) reported malts of some sorghum cultivars having α- and ß-amylase activities comparable to those of barley. Malting reduces protein by 5% to 8% in sorghum, but improves the quality of protein compared to that in the bran, so a small loss in protein in milling of the malted sorghum and pearl millet is compensated for by protein quality (Malleshi and Klopfenstein 1998). The process results in a higher protein efficiency ratio and bioavailability of minerals in cereals (Rao 1987). As compared to the high levels of polyphenols (755 mg/100 g grains) and phytic acid (858 mg/100 g grains) in the untreated controls, malting of pearl millet grains with a 48-h germination reduced polyphenols and phytic acid by more than 40% (Table 4). Malting pearl millet has also been reported to reduce soluble oxalates from 0.502% to 0.068%, and increased soluble calcium from 2.4 to 14.1 mg/100 g grain (Opoku and others 1981). Malting has been reported to reduce tannins in sorghum by 43%. Malting also increases vitamins such as riboflavin, thiamin, ascorbic acid, and vitamin A. There was little effect of malting on increasing the shelf life of flour. It has been found that steeping pearl millet grains for 16 h, followed by germination for 72 h increased *in vitro* starch digestibility by 97%, protein digestibility by 17%, and total sugar by 97% (Chaturvedi and Sarojini 1996).

Malting in sorghum has also been shown to improve the overall physicochemical and nutritional values of the resultant flour. While using sorghum for malting, it is necessary to remove the rootlets completely from the sprouted grains as they contain dhurrin, a cyanogenic compound. Also, since sorghum is more susceptible to mold infestation during germination, it may require application of chemical or natural antimicrobial agents during steeping and germination.

Blanching

This is one of the effective processing technologies to increase the shelf life of pearl millet. Blanching is usually done by boiling water at 98 °C in a container then submerging the grains in the boiling water (1:5 ratio of seeds to boiling water) for 30 s and drying at 50 °C for 60 min. Blanching has been observed to be effective in the retardation of enzymatic activity and thus improve the shelf life of pearl millet flour without much altering the nutrient content (Chavan and Kachare 1994).

Blanching of seeds at 98 °C for 10 s in boiling water before milling has been reported to effectively retard the development of fat acidity in meal and enhance shelf life by 25 d (Kadlag and others 1995). Fat acidity increased about 6-fold in untreated pearl millet flour, whereas it remained almost unchanged in flour obtained from boiling water-blanched grains (98 °C for 30 s) (Chavan and Kachare 1994). As compared to the high levels of polyphenols (755 mg/100 g grains) and phytic acid (858 mg/100 g grains) in the untreated controls, blanching of pearl millet seeds reduced the polyphenol and phytic acid contents by 28% and 38%, respectively. Also, fat acidity was reduced significantly in the case of blanched pearl millet flour as compared to raw flour after 28 d of storage (Rekha 1997).

Acid treatment

The dark-grey grain pearl millet is highly preferred in Maharashtra state of India. Elsewhere in India and most of the world, this grain color is not preferred for food purposes. Treating the decorticated seed with mild organic acids, such as acetic, fumaric, or tartaric, and also with the extracts of natural acidic material such as tamarind (Hadimani and Malleshi 1993) has been found to improve the product quality by reducing polyphenols and other antinutritional factors, thereby also increasing consumer acceptability. Various studies have reported that soaking of pearl millet in acid solutions, like sour milk or tamarind pods, markedly reduced the color of the grain. Dehulled grains decolorized faster than whole grains because the acidic solution penetrates the grain at a faster rate (Reichert and Youngs 1979). Among the various acidic solutions tried, dilute hydrochloric acid was a

Table 4—Effect of malting and blanching on polyphenols, phytic acid, and fat acidity of pearl millet flour.

	Antinutrients (mg/100 g grain)	
Treatment	Polyphenols	Phytic acid
Untreated (control)	755	858
Malting (48 h)	449	481
Blanching	529	565
Acid treatment (24 h)	182	153

Source: Rekha (1997) and Poonam (2002).

Table 5—Changes in fat acidity (mg KOH/100 g), free fatty acids (mg/100 g fat), and lipase activity of acid and heat-treated pearl millet flour during storage.

	Storage period (d)					
Rancidity factor	0	7	14	21	28	CD ($P \leq 0.05$)
Fat acidity (mg KOH/100 g flour)						
Control	30.30	42.40	58.10	83.30	123.70	3.36
Acid treatment	35.10	35.00	36.20	38.60	38.00	1.82
Heat treatment	28.00	30.90	34.40	41.20	50.50	1.27
CD ($P \leq 0.05$)	2.56	2.17	1.26	3.65	2.56	
Free fatty acids (mg/100 g fat)						
Control	282.00	427.30	789.00	942.00	1115.00	4.32
Acid treatment	208.00	210.30	216.00	221.00	230.30	4.27
Heat treatment	67.00	70.00	75.00	80.00	84.00	5.68
CD ($P \leq 0.05$) 3.82	3.94	5.99	6.82	5.20		
Lipase activity (% enzyme activity on % fat)						
Control	3.69	5.60	10.34	12.35	14.61	0.06
Acid treatment	2.90	2.93	3.01	3.08	3.21	0.06
Heat treatment	0.89	0.93	1.00	1.06	1.12	0.08
CD ($P \leq 0.05$) 3.82	0.05	0.05	0.08	0.09	0.07	—

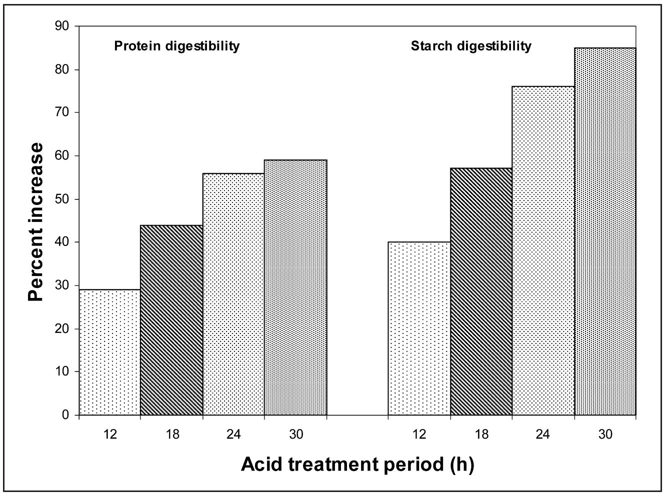

Figure 1—Percent increase in *in vitro* protein and starch digestibility of acid-treated pearl millet flour over untreated (control).

more effective and suitable chemical treatment to remove pigments from whole grain before milling as compared to citric acid and acetic acid (Naikare and others 1986). Soaking grains in dilute HCl for 15 to 24 h reduces a major portion of these pigments and thus helps in the production of creamy white grains.

Soaking of pearl millet in 0.2 N HCl for 24 h reduced polyphenols by 76% and phytic acid by 82% as compared to 755 mg/100 g polyphenol and 858 mg/100 g grains of phytic acid in the untreated control (Table 4). While fat acidity of the flour during 28 d of storage increased 4-fold in the untreated control, there was very marginal increase in the flour produced from the acid-treated grains (Table 5). Similar patterns of changes were observed in the acid-treated and control treatments with respect to free fatty acids and lipase activity. In another study, pearl millet grain samples given acid treatments for 6, 12, 18, and 24 h had *in vitro* protein digestibility increased by 29%, 44%, 56%, and 59%, respectively, and the *in vitro* starch digestibility increased by 40%, 57%, 76%, and 85%, respectively (Figure 1).

Dry heat treatment

Lipase activity is the major cause of spoilage of pearl millet meal, so its inactivation before milling improves the meal quality. The application of dry heat to meal effectively retards lipase activity and minimizes lipid decomposition during storage. It has been observed that when pearl millet grains were given a dry heat treatment in a hot air oven at 100 ± 2 °C for different time periods ranging between 30 and 120 min, and then cooled to room temperature, there was about a 50% increase in fat acidity, free fatty acids, and lipase activity during the 28 d of the storage of flour produced from the acid-treated grains, while there was a 4-fold increase in these parameters in the flour produced from untreated grains (Table 5). Heating grains for 120 min has been found to be most effective for maximum retardation of the lipolytic decomposition of lipids during storage (Kadlag and others 1995). Fat acidity, free fatty acid presence, and lipase activity decrease significantly during storage of 28 d in pearl millet flour given a 18-h acid treatment and a 120-min heat treatment. Results also showed that heat treatment increased the shelf life of pearl millet flour as compared to raw flour (Poonam 2002).

Fermentation

Fermented sorghum and pearl millet products are widely consumed in India and Africa. Fermentation usually involves malting and souring by mixed cultures of yeast and lactobacilli. During the fermentation process, enzymes in the grain and those in the fermenting media cause degradation of starch and soluble sugars. Fermented cereals have better nutritional quality due to increased levels and/or bioavailability of some of the nutrients. For instance, it was observed that during the fermentation process fermenting microorganisms led to synthesis of vitamin B12 in sorghum (Gazzaz and others 1989).

The *in vitro* protein digestibility of pearl millet (74.8%) is higher than of sorghum (59.0%). In a cooked gruel product, called *nasha* in Sudan, when prepared from whole grain fermented flour, the protein digestibility increased to 85.5% in pearl millet and 65.5% in sorghum (Mertz and others 1984). It was observed that *nasha* had more digestible energy and protein than when prepared with the unfermented whole grain (Graham and others 1986). Fermentation in pearl millet has not been found to change protein digestibility. A slight increase in thiamin and a greater increase in niacin, with no appreciable change in riboflavin have been observed in sorghum fermented for making *kisra* (El-Tinay and others 1979). Dhankher and Chauhan (1987a) and Khetrapal and Chauhan (1990) observed improved *in vitro* digestibility of both starch and protein in pearl millet when subjected to germination, and even better when further fermented. Dhankher and Chauhan (1987b) found that fermentation of pearl millet for 9 h for the production of *rabadi* resulted in a 27% to 30% decrease in phytic acid and a 10% to 12% decrease in polyphenols. Fermentation of tannin-sorghum gruel with the addition of wheat phytase and mushroom polyphenol oxidase reduced the total phenols by 57% and phytate by 88% (Towo and others 2006). The *in vitro* accessibility of iron increased from 1.0% in raw sorghum flour to 3.1% when it was fermented with the addition of power flour (flour from germinated tannin-free sorghum) and incubated with phytase and polyphenol oxidase after the fermentation process.

Parboiling

Parboiling is especially beneficial for soft-textured grains, including brown sorghums. Parboiled grains decorticate more efficiently in removing the germ and the pericarp. Parboiled-decorticated grains have slightly lower protein digestibility than the raw grains decorticated to the same extent. In practical terms, however, this detrimental effect is negligible since most traditional food processes involve cooking of flour or decorticated grains. A good-quality parboiled sorghum could be processed by soaking the grains for 24 h in hot water, draining, and steaming it for 10 min in a pressure cooker, drying, and finally grinding into *suji.* The product obtained by this procedure has been found to have a low calorie content and to remain in good condition in vacuumized packs (Naikare 2002). The yield of parboiled *suji* was up to 80% to 82%, while that of the fine flour was 18% to 20% when the resultant meal was sieved through a 40-mesh sieve, whereas no bran was obtained. No microbial spoilage or physical damage was observed up to 6 mo when it was packed in polypropylene flexible bags after vacuumization and storage under ambient conditions.

The parboiled grains can be used for various snack food items, especially for diabetics. (Sehgal and others 2004). The fine flour of parboiled sorghum can be used in gruel preparation; it gives thick consistency with high density in the resultant gruel-like product. Parboiled grains can also be cooked to produce rice-like products. In pearl millet, parboiling can prolong the shelf life of the products such as *milri*.

Alternative Food Products

Processed sorghum and pearl millet grains, and meals from them, are used to prepare various types of traditional and non-traditional food products. Murty and Kumar (1995) summarized and classified these into 9 major food categories (thick porridge, thin porridge, steam-cooked products, fermented breads, unfermented breads, boiled rice-like products, alcoholic beverages, nonalcoholic beverages, and snacks); and they provided the details of their preparations and the various common names in many countries. We highlight these products here (excluding beverages) under 5 broad categories given below.

Traditional food products

The simplest and the most common traditional foods made from sorghum and pearl millet are thin porridge (gruel); thick porridge (fermented and unfermented); flat, unleavened fermented bread such as *kisra, injera,* and *dosa*; and unfermented bread such as *chapati*. These can also be used to make *couscous* (a steamed granulated product) or boiled rice-like products. Fermented breads are prepared by first mixing the flour with water and a starter, and leaving it for 12 to 24 h for fermentation, and then using it for cooking. Flat, unleavened bread or *chapati* prepared from pearl millet flour enriched with soy flour has been reported to have high protein efficiency ratio, minimal thickness, puffing, and uniform color and texture. *Chapati* prepared from pearl millet flour produced after the grains had been bleached or acid-treated or heat-treated has been reported to have enhanced overall acceptability as compared to the *chapati* prepared from the raw untreated grains (Poonam 2002). Use of processed flour, in comparison to raw flour, in the product development has been found to reduce antinutrients and increase the digestibility (Singh 2003).

Various types of snacks are also made from sorghum and pearl millet in India. Products like *laddoo*, *namkeen sev,* and *matari* have been made using blanched and malted pearl millet flour. These products were highly acceptable and have shown to have longer shelf life and stored well up to 3 mo. Rekha (1997) incorporated blanched and malted pearl millet flour in various products like *bhakri*, *suhali*, *khichri*, *churma*, *shakkarpala*, *mathari,* and the products were found to be organoleptically acceptable. An earlier study (Chaudhary 1993) also indicated that the traditional products including *chapati*, *khichri*, *bhakri*, popped grain, *dalia,* and *shakkarpala* prepared from pearl millet were not only acceptable but their protein and starch digestibilities were also better. Similar products as mentioned previously for pearl millet have also been prepared from sorghum. Nutritious *laddoo* and *puttu* can be prepared from sorghum flour by incorporating 30% soy flour. *Chapati* made from sorghum has been shown to be organoleptically acceptable. Sorghum flour has been successfully used for *bhakri* preparation and considerable research in India is underway for increasing the shelf life of acceptable sorghum *bhakri*.

Baked products

Sorghum and pearl millet flour are not good raw materials for the baking industry, since they do not contain gluten and form dough of poor consistency. For instance, cookies made from pearl millet flour do not spread during baking, have a poor top grain character, and are dense and compact (Badi and others 1976). However, pearl millet flour hydrated with water, dried, and supplemented with 0.6% unrefined soy lectin can produce cookies with spread characteristics equal to those made from soft wheat flour. Various types of biscuits and cakes produced using blanched pearl millet have been found to be organoleptically acceptable. Various types of biscuits developed by incorporating different levels of blanched as well as malted pearl millet flour have been found to be acceptable and to store well up to 3 mo (Singh 2003).

Sorghum and wheat flour blends have been used to produce baked products including yeast-leavened breads, cakes, muffins, cookies, and biscuits (Rooney and others 1980; Morad and others 1983; Torres and others 1993; Suhendro and others 1998). Usually 5% to 50% sorghum flour is substituted for wheat flour. In a study on the use of sorghum in composite flour for making bread, it was found that bread made with boiled malt flour (30%) had improved crumb structure, crumb softness, water holding capacity, and resistance to staling, as well as a fine malt flavor compared to the bread made with unmalted sorghum flour composited in the same proportion (Hugo and others 2000). Incorporation of sorghum flour at the 15% level has been shown to produce acceptable breads without affecting loaf volume, crust color, and crumb texture (Iwuoha and others 1997; Rao and Rao 1997). Replacement of up to 20% wheat with sorghum flour gave acceptable bread, while further substitution of up to 55% by sorghum flour gave acceptable biscuits. A blend of 70% sorghum flour and 30% detoxified cassava starch produced acceptable bread and cakes (Olatunji and others 1989). Sorghum and wheat composite flour in the proportion 50:50 led to the production of organoleptically acceptable biscuit (Orewa and Iloh 1989; Priyolkar 1989).

Extruded products

Extrusion is being used increasingly for making ready-to-eat (RTE) foods. In extrusion processes, cereals are cooked at high temperature for a short time. Starch is gelatinized and protein is denatured, which improves their digestibility. Antinutritional factors that are present may be inactivated. High-temperature, high-pressure extrusion and expansion has been shown to change the molecular weight (MW) distribution of tannins in tannin-sorghum (also called brown sorghum) (Rooney and Awika 2004). It causes the high-MW polymers of the proanthocyanidins to break down into lower-MW constituents (monomers to tetramers) that are presumably more readily available for direct absorption and hence enhance their antioxidant properties. Microorganisms are largely destroyed and the product's shelf life is thereby extended. The products are easily fortified with additives. Whole or milled sorghums can be expanded directly by using low-cost friction extruders. Sorghum extrudates have been found to compare favorably with those from rice and corn, depending upon the decortication levels, particle size distribution, and moisture content (Rooney and Awika 2004). With the increase in the decortication level, extrudates become whiter, more expanded, less dense, and more crisp. The extrudates made from coarse-particle-size materials have the most desirable characteristics compared to the other particle sizes used. Some sorghum products have a higher expansion ratio than both rice and corn with similar bulk density and texture characteristics. White sorghums have excellent extrusion properties and could compete with rice and corn for expansion ratio.

Sorghum has been extruded with single- and twin-screw extruders to produce bland-flavored, light-colored, highly expanded extrudates that carry mild flavors and seasonings similar to rice, at lower cost. For example, in some applications, rice does not expand properly without the use of potato starch or other expansive ingredients, but sorghum can expand properly without additives, and the cost of the sorghum is often lower than that of rice. Sorghum and pearl millet grits and flour can be used to prepare RTE products. Such products have crunchy texture and can be coated with traditional ingredients to prepare sweet or savory snacks. Alternatively, the grits could be mixed with spices and condiments prior to extrusion to obtain RTE snacks of desirable taste. The acid-treated pearl millet yields products of better acceptability as compared to that from just decorticated pearl millet. Sorghum and pearl millet, blended with soy or protein-rich ingredients, such as legumes or groundnut (peanut) cake, on extrusion give nutritionally balanced supplementary foods (Malleshi and others 1996). Sumathi and others (2007) showed that extruded pearl millet products prepared from a blend of 30% grain legume flour or 15% defatted soybean had, respectively, 14.7% and 16.0% protein, and 2.0 and 2.1 protein efficiency ratio. The shelf life of the extrudates was about 6 m in different flexible pouches under ambient storage conditions. Noodles, macaroni, and pasta-like extruded products could be prepared from millet flour (Desikachar 1975). Extruded snacks prepared with mixed millet flour containing rice flour and/or corn flour and/or tapioca starch in various proportions have been shown to have acceptable appearance, color, texture, and flavor (Siwawij and Trangwacharakul 1995). Extrusion cooking also enhanced the *in vitro* protein digestibility of foods (Malleshi and others 1996).

Utilization of sorghum and pearl millet for producing soft-cooked products such as vermicelli noodles is very rare, although these grains are unique with respect to taste and aroma, and provide dietary fiber. Research at the Central Food Technological Research Inst. (CFTRI), Mysore, India, has led to a process to prepare noodles (Sowbhaghya and Ali 2001a). The noodles on cooking in water retained the texture of their strands and firmness without disintegration, and the solid loss was less than 6% (Sowbhaghya and Ali 2001b). The noodles from both sorghum and pearl millet were readily acceptable in the savory and sweet formulations.

Flakes and pops

Extensive studies have been carried out on sorghum flaking at CFTRI, Mysore, and various process parameters, such as soaking time, temperature, wet-heat, or dry-heat treatment conditions, have been standardized (CFTRI 1985). The grain soaked to its equilibrium moisture content is steamed or roasted to fully gelatinize the starch, dried to about 18% moisture content, conditioned, decorticated, and then flaked immediately by passing through a pair of heavy-duty rollers. The flakes can also be used for the preparation of traditional snacks like "*uppitu*" after boiling and seasoning. The thicker flakes could be deep-fried or dry-roasted to prepare expanded crunchy snack products. Results of exploratory studies on flaking of pearl millet following the method adopted for sorghum have been promising. Pearl millet flaking would be a new avenue for its widespread utilization. Since stabilization of the oil occurs during flaking, pearl millet flakes will have longer shelf life.

Since popping involves formation of steam and development of pressure inside the grain, the optimum moisture level and popping temperature play important roles in the quality of the popped cereal. Varietal differences exist largely with respect to popping characteristics. The optimum conditions for grain popping, according to the CFTRI process, are equilibrating sorghum and pearl millet to about 16% moisture and subjecting the grains to a high-temperature, short-time treatment (about 230 °C for a fraction of a minute) in an air popper developed at the institute (CFTRI 1985). The machine is highly suitable for value addition to sorghum and pearl millet by popping.

Popping of pearl millet is not very popular, but the popped pearl millet is a good source of energy, fiber, and carbohydrates. Varieties with hard endosperm and medium-thick pericarp exhibit superior popping quality (Hadimani and others 2001). The lipolytic enzymes are denatured during the process of popping. The nutritional advantage of the popped millet is utilized in developing formulations for supplementary foods or weaning foods for children and mothers (Bhaskaran and others 1999). Since sorghum and pearl millet are rich sources of micronutrients and phytochemicals, such products may score over similar products made from rice and wheat.

Health foods

Sorghum and pearl millet can find uses in preparing various types of health foods and food ingredients. Both crops contain a relatively higher proportion of insoluble dietary fiber. This causes slow release of sugar, thus making the food products based on them especially suitable for those suffering from or prone to diabetes. For instance, various pearl millet-based food products were found to have a lower glycemic index (GI) than those based on

Table 6 – Health value of pearl millet-based diabetic products.

	Glycemic index	
Product	Control (wheat flour)	Pearl millet-based products
Biscuit	72.7	58.1
Chapati	69.4	48.0
Dhokla	68.4	38.0
Instant idli	69.8	52.1
Pasta	71.3	54.1

Source: Mani and others (1993).

wheat, with the extent reduction in the GI trait ranging from 20% for biscuits to 45% for *dhokla* (Table 6). Similarly, whole grain sorghum-based products (*chapati*, *upama,* and *dhokla*) have been found to lead to lower glucose levels, lesser percent peak rises and lesser area under the curve in diabetic subjects compared to those prepared from dehulled sorghum and wheat (Lukshmi and Vimla 1996). Various types of cookies and biscuits were prepared for diabetics using malted and unmalted sorghum flour. Cookies prepared from 40% wheat flour blended with 60% malted sorghum flour led to an increase in fiber content. Wet-heat treatment of sorghum is known to lower its digestibility. This characteristic feature could perhaps be made use of to market sorghum flakes as diabetic flakes. During the flaking process, the starch undergoes retrogradation leading to formation of resistant starch or enhancing the dietary fiber contents (Mangala and others 1999). This added advantage in sorghum flakes could be of potential health benefits in the dietary management for diabetics. Tannin sorghums are slow in digestion. Some cultures in Africa prefer tannin sorghums since it contributes to a longer period of satiety or fullness as compared to other cereals. Thus, tannin sorghums have potential applications in foods for diabetics (Awika and Rrooney 2004).

Table 7—Cereal grains and egg composition of n-6 and n-3 fatty acids.

	Diet		
Fatty acid	Corn	Corn + pearl millet	Pearl millet
Diet composition of fatty acid (% of total fatty acids)			
Total n-6	59.3	47.0	40.0
Total n-3	2.4	2.5	3.3
n-6 : n-3 ratio	25.2	19.0	12.8
Egg composition of fatty acid (mg/g yolk)			
Total n-6	66.8	55.6	47.3
Total n-3	5.1	5.5	5.7
n-6 : n-3 ratio	13.1	10.1	8.3

Modified from Collins and others (1997).

Gluten intolerance, leading to protein allergy (specifically gliadin allergy), is a physiological disorder from which about 500000 people suffer in the United States alone (Dahlberg and others 2004). Sorghum and pearl millet are gluten free and, hence, have a good chance of being commercialized for the food-based management of this problem. Sorghum, especially, is a potential source of nutraceuticals such as antioxidant phenolics and cholesterol-reducing waxes (Taylor 2006).

Pearl millet is rich in oil and linoleic acid accounts for 4% of the total fatty acids in this oil, giving it a higher percentage of n-3 fatty acids as compared to maize in which linoleic acid accounts for only 0.9% of the total fatty acids and, hence, is highly deficient in n-3 fatty acids. The n-3 fatty acids play an important role in many physiological functions, including platelet aggregation, LDL cholesterol accumulation, and the immune system. Feed can have a significant effect on the fatty acid composition of hen eggs and, consequently, on human health. In a poultry feeding trial, it was observed that eggs produced from layers fed a pearl millet-based diet had lower n-6 fatty acids and higher n-3 fatty acids and, thus, led to lower n-6:n-3 fatty acid ratios than those fed corn-based diets (Table 7). These eggs are of special health value, especially for those prone to high levels of LDL in the cholesterol.

The bran separated as a by-product during grain processing could serve as a source of the edible oil similar to that of rice bran oil. Deoiled bran from pearl millet has lower ash and silica contents as compared to that of deoiled rice bran. Thus, it could be efficiently used as a source of dietary fiber. Pearl millet bran contains a high proportion of soluble dietary fiber and could be tapped for hypocholesterolemic and hypoglycemic effects. In view of this, fiber-regulated sorghum and millet flakes could be an ideal snack for the obese and for calorie-conscious people (Hadimani and Malleshi 1993).

Oxygen radical absorbance capacity (ORAC) of black sorghum has been found to be comparable to that of the blueberries, and brown sorghum over 3 times more (Figure 2). Flavonoids and

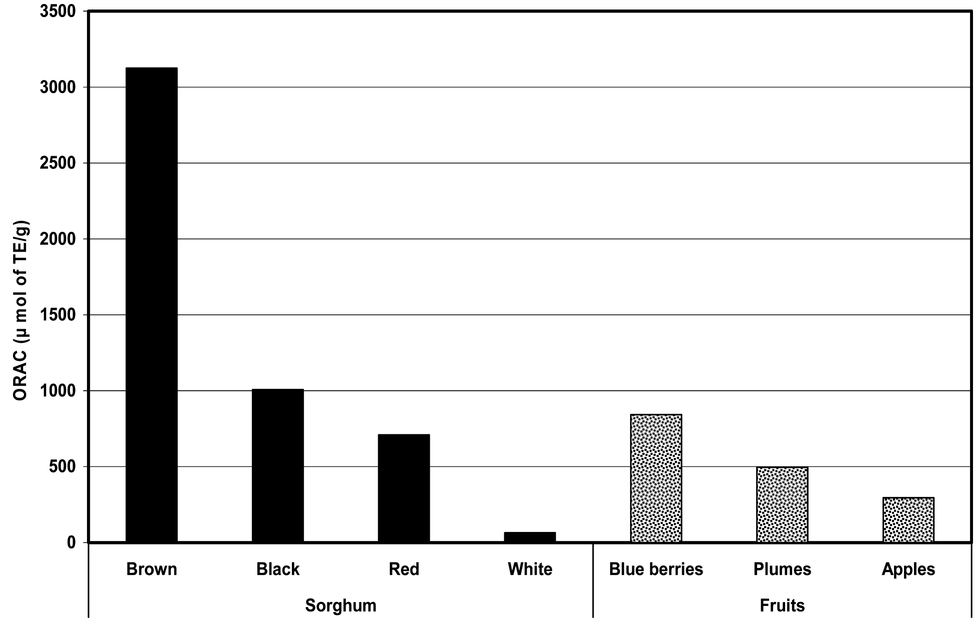

Figure 2—Oxygen radical absorbance capacity (ORAC) in sorghum bran and fruits (dry basis). TE = trolox equivalent (Source: Awika and others 2003; Wu and others 2004).

tannins in these sorghums are concentrated in pericarp and testa, which can be abrasively milled and separated for use as phytonutrients in foods. Good quality breads containing tannin sorghum bran have high phenol, antioxidant activity, and dietary fiber levels with a natural dark color and excellent flavor. Health bread mixes containing tannin sorghum bran, barley flour and flax seed have also been made in the United States (Rudiger 2003). Research shows that addition of 15% brown sorghum bran to wheat flour produces brownish, dark-colored loaves with significant levels of phenols and dietary fiber.

In a recent review, Dykes and Rooney (2007) examined the health value of various grains. Pigmented sorghum and pearl millet grains have anthocyanins located in the pericarp, which is removed with bran during the dehulling. These brans can have special industrial value. For instance, sorghum contains unique anthocyanins (3-deoxyanthocyanins), which are more stable at high pH, thus increasing their values as good natural food colorants. These anthocyanins are more concentrated in black-pericarp than red-pericarp sorghums. Also, flavonoids have antioxidant, anti-allergic, anti-inflammatory, anticarcinogenic, and gastroprotective properties. Pearl millet, especially sorghum, has many of these flavonoids. Similarly, tannins bind to proteins, carbohydrates, and minerals, and thus decrease their bioavailability. However, these can be separated and used in health foods. For instance, condensed tannins found in sorghum with pigmented testa can be separated and used as health food ingredients. In addition, they also have anticarcinogenic, anticardiovascular, gastroprotective, antiulcerogenic, and cholesterol-lowering properties. High-tannin sorghums have the highest antioxidant properties (about 7 times those of pearl millet and 50 times those of white rice). Antioxidant activities of condensed-tannin sorghums approach or even exceed those in fruits and vegetable. Tannin-sorghum bran has 10 times higher antioxidant activity than red delicious apple. Large variability for grain color has been reported in pearl millet. Their beneficial health values need to be investigated.

Constraints and Opportunities for Commercialization

One of the greatest constraints in the commercialization of sorghum and pearl millet grains for food purposes has been a misplaced social stigma dubbing these as poor man's crops. These crops have traditionally been grown in marginal environments, where poverty becomes a correlated outcome. These crops also have an insignificant place in the national and international marketing systems (pearl millet has none) in the regions where they are traditionally grown. Thus, sorghum and pearl millet could not make it to the food basket of the urban elite whose consumption choices play a dominant role in the commercialization of any food product. Grain quality and nutritional studies now show that these grains are more appropriate choices for the nutritional security of the rural and urban poor who have limited access to other sources of dietary components. In addition, these grains could also be more appropriate choices than the fine cereals such as wheat and rice for the elite who will benefit from their high nutraceutical properties. This will require different approaches to commercialize these grains or their by-products to serve these widely different consumer classes.

Coarse fibrous grains and poor shelf life of the flour (especially in the case of pearl millet) are other major constraints to the commercialization of sorghum and pearl millet. Colored pigments and the characteristic astringent flavor in pearl millet and color grain sorghums (brown and red) are additional constraints to commercialization (Desikachar 1975). Decortication of grains overcomes some of these constraints and also improves nutritive quality and consumer acceptability (Reichert 1979; Pawar and Parlikar 1990). The grain utilization for preparing shelf-stable food products will require a processing technology that can remove the germ with little loss in the grain. In the case that heavy decortication is needed to prepare the meal, the decortication by-products should have a market value. For instance, the decorticated by-product that includes germ, bran, and aleurone layer is rich in oil and fiber. This can be used for oil extraction and to prepare dietary fiber, which can be used as specialty food ingredients. But production and the uses of these various components will need to be integrated to derive the full benefits of commercialization. Optimal heat treatment that destroys lipolytic enzymes but does not affect the natural protective oxidant principles may extend shelf life of the flour and food products. By-products such as the kafirin-prolamin protein and pericarp wax have potential as bioplastic films and coatings for food, primarily due to their hydrophobocity and rapid biodegradation property (Taylor 2006).

The various grain processing and food product technologies developed for other crops of major cereals are not directly applicable to sorghum and pearl millet. The modified forms of these technologies or newly developed technologies are available, but they lie with indigenous communities, small enterprises, research institutes, and universities (Rohrbach and Obilana 2004). The major problem has been lack of dissemination, access, retrieval, and consolidation of such information. Further, there is a need to test most of these technologies for their commercial applications, recognizing the scope of and need for commercialization at 3 socio-economic levels: communal/cottage industry, the medium scale/service level, and the large industrial scale. With the increasing application of information and communication technology in agriculture and industry in an increasingly globalized world, and increasing emphasis on public–private–civil society collaboration, further refinement and development of commercially applicable technologies can be rapidly achieved.

Policy support from the governments plays a significant role in product and process commercialization, at least in the initial stages when the food products from grains of new crop species have to compete with those from the established crop species. For instance, subsidy on wheat and rice production almost all over the world plays a big role in their production and marketing. On top of this is the subsidized procurement and supply of wheat and rice through the Public Distribution system in India. Similar support is not available to sorghum and pearl millet in the major areas of South Asia and Africa where these crops are grown. This leaves farmers with little incentive for investment in production as the returns are not economical when increased production leads to a drop in grain prices. The low-resource agriculture, characterized by rain-fed cultivation of these crops with negligible external inputs, leads to low productivity with large variation in production and grain surpluses across the years. The low volume and inconsistency in grain supplies reduce the dependability of producers for grain supplies, which is so essential for commercialization. Opportunities exist to drastically reduce or even eliminate these uncertainties through governmental policy support for increased and stable production and marketing of sorghum and pearl millet grain surpluses.

Most of those involved in commercial grain processing and food manufacturing are not familiar with the possible alternative food uses and health value of sorghum and pearl millet. Food products commonly prepared from other cereals such as wheat and maize can also be prepared from sorghum and pearl millet by using them in a composite flour. The emphasis should, however, be on exploiting the potentially useful intrinsic qualities of these grains to produce unique and alternative value-added products (Rohrbach and Obilana 2004). Trying to produce substitute products using sorghum and pearl millet, for which these cereals have no desirable traits, have been one of the reasons for limited commercial successes. For instance, neither sorghum nor millet grains possesses gluten. Thus, they cannot substitute directly for wheat in bread and other baked goods. However, with good milling technologies (and appropriate handling of amylose and amylopectin in the grains) to produce suitable flours, meals, and grit, a wide range of excellent textured baked and steamed food products can be produced, for example: *couscous*, steamed and deep-fried dumplings, flat breads such as *chapatti* and *tortilla*, and even semileavened breads such as *injera* and *kisra*. One option for successful commercialization of sorghum and pearl millet is to pursue a few premium or niche markets wherein sorghum or pearl millet grains have unique values—for example, the production of malt for malt beverages and drinks, weaning foods, or glucose manufacture. For these ventures to succeed, specialty grains will be required for which both crops can be expected to have large genetic variability. Postharvest handling of the grains during threshing, bulking, and transportation is also important to maintain identity-preserved quality and cleanliness. In these circumstances, traders and processors may be willing to pay a premium price for high-quality grains specially suited to their manufacturing process, thus benefiting both the producers and users, and finally the consumers.

Commercialization of sorghum and pearl millet grains for alternative and health food uses needs to be viewed in a broader context from production to utilization, and emerging challenges and opportunities. These crops have been and will continue to be grown both for food and stover (dry fodder after grain harvest) in most of Asia, Africa, and elsewhere with farmers practicing mixed crop-livestock systems of farming with generally small holdings. Under such situations, production of specialty grains and maintaining their identity through the harvesting and postharvest handling to meet the industry's quantity and quality needs will require a commercial outlook of crop production. This will necessitate organized efforts at all levels. In the developed world, with mechanized farming and large farm holdings, identity-preserved grains have been procured and used through vertical integration of the food value chain and contract farming. In most parts of the developing countries, however, such models may not be appropriate because farmers' holdings are small, fragmented, dispersed, and heterogeneous. So the need may be to bring the power of scale to small farmers rather than displacing them. This is possible through the ITC Limited's eChaupal model that uses information and communication technology for virtual integration of these farmers to enable identity-preserved grain handling (Sivakumar 2004).

The future scenario is one of hotter climate, reduced water availability, frequent droughts, and less arable land, with a substantial part of it affected by soil salinity. Considering the positive attributes of sorghum and pearl millet to address these environmental stress factors, their role in sustainable agriculture should increase worldwide. This could be specially true for pearl millet, which is most tolerant to heat, drought, and soil salinity; it has much fewer of the disease and insect pest problems than other cereals. It has been reported that the global warming and climate change will have an adverse effect on the area under wheat and rice, among many other crops, but it is likely to cause area expansion of pearl millet (31%) and sorghum (8% to 9%) by 2055, most of it in those parts of the countries and the world where sorghum and pearl millet are currently not the traditional crops (Lane and Jarvis 2007). This will open up new challenges and opportunities in their cultivation and utilization for food and other purposes. There are indications that pearl millet in crop rotation also reduces nematode problems in wheat and soybean (Bonamigo 1999), contributing to eco-friendly pest management. Thus, the value of sorghum and pearl millet must be viewed not only in terms of their food and nutritional security for the poor, and health benefits for the elite, but also in terms of natural resource use efficiency and long-term sustainability of the production systems.

Large genetic variability has been detected both in sorghum and pearl millet for various grain quality traits (apparent as well as cryptic traits). Extensive studies, based on a wide range of genotypes, are needed to examine the effects of various processing technologies and food products on these nutrients, and their implications in nutrition and health.

Acknowledgments

This study was partially supported by grants from the HarvestPlus Challenge Program of the Consultative Group on Intl. Agricultural Research (CGIAR) and the Indian Council of Agricultural Research. Several papers on alternative uses of sorghum and pearl millet presented at a CFC-funded Expert Meeting and included in its proceedings proved useful in providing the background information for the preparation of this article.

References

Abdalla AA, El-Tinay AH, Mohamed BE, Abdalla AH. 1998. Proximate composition, starch, phytate and mineral contents of 10 pearl millet genotypes. Food Chem 63(2):243–6.

Ashraf M. 1994. Breeding for salinity tolerance in plants. Crit Rev Plant Sci 13:17–42.

Ashraf M, McNeilly T. 1987. Salinity effects on five cultivars/lines of pearl millet [*Pennisetum americanum* (L) Leeke]. Plant Soil 103:13–9.

Awika JM, Rooney LW. 2004. Sorghum phytochemicals and their potential impact on human health. Phytochemistry 65:1199–221.

Awika JM, Rooney LW, Wu X, Prior RL, Cisneros-Zevallos L. 2003. Screening methods to measure antioxidant activity of sorghum (*Sorghum bicolor*) and sorghum products. J Agric Food Chem 51:6657–62.

Azhar FM, McNeilly T. 1988. The genetic basis of variation for salt tolerance in *Sorghum bicolor* (L.) Moench. seedlings. Plant Breed 101:114–21.

Badi SM, Hoseney RC, Finley PL. 1976. Pearl millet. II. Partial characterization of starch and use of millet flour in bread making. Cereal Chem 53:718–24.

Beta T, Rooney LW, Waniska RD. 1995. Malting characteristics of sorghum cultivars. Cereal Chem 72(6):533–8.

Bhaskaran V, Mahadevamma, Malleshi NG, Shankara R, Lokesh BR. 1999. Acceptability of supplementary food based on popped cereals and legumes suitable for rural mothers and children. Plant Foods Human Nutr 53:237–47.

Bonamigo LA. 1999. Pearl millet crop in Brazil. Implementation and development of the Cerrado Savannahs. In: Neto AL de F, Amabile RF, Netto DAM, Yamashita T, Gocho H, editors. Proceedings of the International Pearl Millet Workshop. 9–10 June 1999, Planaltina, Brazil, Embrapa, Cerrados, Planaltina. P 31–65.

Bouis HE. 2000. Enrichment of food staples through plant breeding: a new strategy for fighting micronutrient malnutrition. Nutrition 16:701–4.

CFTRI. 1985. Annual report 1984–85. Mysore, India: CFTRI. 11 p.

Chaturvedi A, Sarojini G. 1996. Malting of pearl millet (*Pennisetum typhoideum*): its effect on starch and protein digestibilities. J Food Sci Technol 33(4):342–4.

Chaudhary S. 1993. Preparation of nutritional evaluation of some traditional foods from pearl millet [MSc thesis]. Hisar, Haryana, India: CCS Haryana Agricultural Univ. 98 p.

Chavan JK, Kachare DP. 1994. Effect of seed treatment on lipolytic deterioration of pearl millet flour during storage. J Food Sci Technol 31:80–1.

Collins VP, Cantor AH, Pescatore AJ, Straw ML, Ford MJ. 1997. Pearl millet in layer diets enhances egg yolk n-3 fatty acids. Poult Sci 76:326–30.

Dahlberg JA, Wilson JP, Snyder T. 2004. Sorghum and pearl millet: health foods and industrial products in developed countries. In: Alternative uses of sorghum and pearl millet in Asia: proceedings of the expert meeting; 2003 July 1–4. Patancheru, Andhra Pradesh, India: ICRISAT. CFC Technical Paper Nr 34. P 42–59.

Desikachar HSR. 1975. Processing of maize, sorghum and millets for food uses. J Scient Industr Res 34:231–6.

Dhankher N, Chauhan BM. 1987a. Effect of temperature and fermentation time on protein and starch digestibility (*in vitro*) of rabadi—a fermented pearl millet food. J Food Sci 52:489–91.

Dhankher N, Chauhan BM. 1987b. Effect of temperature and fermentation time on phytic acid and polyphenol content of *rabadi*—a fermented pearl millet food. J Food Sci 52:828–9.

Dicko MH, Gruppen H, Traore AS, Voragen AGJ, Berkel WJH van. 2006. Sorghum grain as human food in Africa: relevance of content of starch and amylase activities. Afr J Biotech 5:384–95.

Dlamini NR, Taylor JRN, Rooney LW. 2007. The effect of sorghum type and processing on the antioxidant properties of African sorghum-based foods. Food Chem 105:1412–9.

Dua RP. 1989. Salinity tolerance in pearl millet. Indian J Agric Res 23:9–14.

Dykes L, Rooney LW. 2006. Sorghum and millet phenols and antioxidants. J Cereal Sci 44:236–51.

Dykes L, Rooney LW. 2007. Phenolic compounds in cereal grains and their health benefits. Cereal Food World 52:105–11.

Ejeta G, Hansen MM, Mertz ET. 1987. *In vitro* digestibility and amino acid composition of pearl millets and other cereals. Proc of the Natl Acad Sci, USA 84:6016–9.

El-Tinay AH, Abdel Gadir AM, El-Hidai M. 1979. Sorghum-fermented kisra bread. I. Nutritive value of kisra. J Sci Food Agric 30:859–63.

Gazzaz SS, Rasco BA, Dong FM, Borhan M. 1989. Effects of processing on the thiamine, riboflavin, and vitamin B12 content of fermented whole grain cereal products. J Food Process Preserv 13:321–34.

Graham GC, MacLean WC, Mordes E, Hamaker BR, Kirleis AW, Mertz ET, Axtell JD. 1986. Digestibility and utilization of protein and energy from *nasha*, a traditional Sudanese fermented sorghum weaning food. J Nutr 116:978–84.

Hadimani NA. 1994. Studies on pearl millet grain quality with special emphasis on milling and popping of millet [PhD thesis]. Mysore, India: Univ. of Mysore. P 122–79.

Hadimani NA, Malleshi NG. 1993. Studies on milling, physico-chemical properties, nutrient composition and dietary fibre content of millets. J Food Sci Technol 30(1):193–8.

Hadimani NA, Ali SZ, Malleshi NG. 1995. Physico-chemical composition and processing characteristics of pearl millet varieties. J Food Sci Technol 32(3):193–8.

Hadimani NA, Murali Krishna G, Tharanathan RN, Malleshi NG. 2001. Nature of carbohydrates and proteins in three pearl millet varieties varying in processing characteristics and kernel texture. J Cereal Sci 32:17–25.

Hollington PA. 1998. Technical breakthroughs in screening and breeding wheat varieties for salt tolerance. In: Gupta SK, Sharma SK, Tyagi NK, editors. Proceedings of the National Conference on Salinity Management in Agriculture. Karnal, India: CSSRI. P 273–89.

Hoseney RC, Andrews DJ, Clark H. 1987. Sorghum and pearl millet. Ch. 9. In: Olson RA, Frey K, editors. Nutritional quality and cereal grains: genetic and agronomic improvement. Madison, Wis.: Am Soc Agron.

Hugo LF, Rooney LW, Taylor JRN. 2000. Malted sorghum as a functional ingredient in composite bread. Cereal Chem 77:428–32.

Igartua E, Garcia MP, Lasa JM. 1995. Field responses of grain sorghum to a salinity gradiant. Field Crops Res 42:15–25.

Iwuoha CI, Anyadike AC, Eke OS. 1997. The effect of flour-blending on the physico-chemical and sensory qualities of bread. J Food Sci Technol 34:311–5.

Kaced I, Hoseney RC, Varriano-Marston E. 1984. Factors affecting rancidity in ground pearl millet (*Pennisetum americanum* L. Leeke). Cereal Chem 61(2):187–92.

Kadlag RV, Chavan JK, Kachare DP. 1995. Effects of seed treatments and storage on the changes in lipids of pearl millet meal. Plant Foods Human Nutr 45:279–85.

Khetrapal N, Chauhan BM. 1990. Effect of germination and fermentation on *in vitro* starch and protein digestibility of pearl millet. J Food Sci 55:883–4.

Krishnamurthy L, Serraj R, Hash CT, Dakheel AJ, Reddy BVS. 2007a. Screening sorghum genotypes for salinity tolerant biomass production. Euphytica 156(1/2):15–24.

Krishnamurthy L, Serraj R, Rai KN, Hash CT, Dakheel AJ. 2007b. Identification of pearl millet [*Penniseetum glaucum* (L.) R. Br.] lines tolerant to soil salinity. Euphytica 158:179–88.

Kulkarni VN, Rai KN, Dakheel AJ, Ibrahim M, Hebbara M, Vadez V. 2006. Pearl millet germplasm adapted to saline conditions. Intl Sorghum Millets Newslett 47:103–6.

Lai CC, Varriano-Marston E. 1980. Changes in pearl millet meal during storage. Cereal Chem 57(4):275–7.

Lane A, Jarvis A. 2007. Changes in climate will modify the geography of crop suitability: agricultural biodiversity can help with adaptation. Presented at the symposium on Climate-Proofing Innovation for Poverty Reduction and Food Security; 2007 Nov 23. Patancheru, Andhra Pradesh, India: ICRISAT.

Lukshmi KB, Vimla V. 1996. Hypoglycemic effect of selected sorghum recipes. Nutr Res 16(16):1651–8.

Maas EV. 1985. Crop tolerance to saline sprinkling water. Plant Soil 89:273–84.

Maiti RK, dela Rosa-Ibarra M, Sandowal ND. 1994. Genotypic variability in glossy sorghum lines for resistance to drought, salinity and temperature-stress at seedling stage. J Plant Physiol 143:241–4.

Malleshi NG, Klopfenstein CF. 1998. Nutrient composition and amino acid contents of malted sorghum, pearl millet and finger millet and their milling fractions. J Food Sci Technol 35(3):247–9.

Malleshi NG, Hadimani NA, Chinnaswamy R, Klopfenstein CF. 1996. Physical and nutritional qualities of extruded weaning foods containing sorghum, pearl millet, or finger millet blended with mung beans and non-fat dried milk. Plant Foods Human Nutr 49:181–9.

Mangala SL, Malleshi NG, Mahadevamma, Tharanathan RN. 1999. Resistance starch from differently processed rice and ragi (finger millet). Europ Food Res Technol. 209:32–7.

Mani UV, Prabhu BM, Damle SS, Mani I. 1993. Glycemic index of some commonly consumed foods in western India. Asia Pacific J Clin Nutr 111–4.

Mason JB, Garcia M. 1993. Micronutrient deficiency—the global situation. SCN News 9:11–6.

Meera MS, Ali SZ, Narasimha HV, Bhashyam MK, Srinivas A, Sathyendra Rao BV. 2002. A process for the preparation of sorghum and pearl millet grain-based product having enhanced shelf life. Parent file in India and Egypt. Indian Patent 306/DEL/02.

Mertz ET, Hessen MM, Cairns-Whittern C, Kirleis AW, Tu L, Axtell JD. 1984. Protein digestibility in sorghum and other major cereals. Proc Natl Acad Sci USA 81:1–2.

Morad MM, Doherty CA, Faubion JM, Rooney LW. 1983. Utilization of dried distillers grain from sorghum in basked food systems. Progress Report. College Station, Texas: Rgr Exp Sta.

Mwasaru MA, Reichert RD, Mukuru SZ. 1988. Factors affecting the abrasive dehulling efficiency of high tannin sorghum. Cereal Chem 65(3):171–4.

Murty DS, Kumar KA. 1995. Traditional uses of sorghum and millets. In: Dendy DAV, editor. Sorghum and millets: chemistry and technology. St. Paul, Minn. Am Assoc Cereal Chem. P 185–221.

Naikare SM. 2002. Annual report of NATP submitted to CRIDA. Hyderabad, India. 40 P.

Naikare SM, Chavan JK, Kadam SS. 1986. Depigmentation and utilization of pearl millet in the preparation of cookies and biscuits. J Maharashtra Agric Univ 11:90–3.

Oke OL. 1977. The potential of millet and sorghum as food in Nigeria. In: Dendy DAV, editor. Proceedings of the Symposium on Sorghum and Millets for Human Food, Congress of International Association for Cereal Chemistry, 11–12 May 1976, Vienna. London, U.K.: Tropical Products Inst. P 121–4.

Olatunji O, Adesina AA, Koleoso OA. 1989. Use of sorghum as composite flour in baking. In: Murty DS, editor. Industrial utilization of sorghum: summary proceedings of a Symposium on the Current Status and Potential of Industrial Uses of Sorghum in Nigeria; 1989 Dec 4–6; Kano, Nigeria. Patancheru, Andhra Pradesh, India: ICRISAT. 21 p.

Opoku AR, Ohenhen SO, Ejiofor N. 1981. Nutrient composition of millet (*Pennisetum typhoides*) grains and malt. J Agric Food Chem 29:1247–8.

Orewa GO, Iloh A. 1989. Current status of composite flour technology and prospects with particular reference to the production of biscuits in Nigeria. In: Murty DS, editor. Industrial utilization of sorghum: summary proceedings of a symposium on the current status and potential of industrial uses of sorghum in Nigeria; 1989 Dec 4–6; Kano, Nigeria. Patancheru, Andhra Pradesh, India: ICRISAT. 22 p.

Pawar VD, Parlikar GS. 1990. Reducing the polyphenols and phytate and improving the protein quality of pearl millet by dehulling and soaking. J Food Sci Technol 27(3):140–3.

Peacock JM. 1982. Response and tolerance of sorghum to temperature stress. In: Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum; 1981 Nov 2–7. Patancheru, Andhra Pradesh, India: ICRISAT. P 143–59.

Peacock JM, Soman P, Jayachandran R, Rain AU, Howarth CJ, Thomas A. 1993. Effects of high soil surface temperature on seedling survival in pearl millet. Exptl Agric 29:215–225.

Poonam. 2002. Effect of acid and heat treatment on nutrient composition and shelf life of pearl millet (*Pennisetum glaucum*) flour [MSc thesis]. Hisar, Haryana, India: CCS Haryana Agricultural Univ. 106 p.

Priyolkar VS. 1989. Use of sorghum flour in biscuit and wafer production: the NASCO experience. In: Murty DS, editor. Industrial utilization of sorghum: summary of proceedings of a symposium on the current status and potential of industrial uses of sorghum in Nigeria; 1989 Dec 4-6; Kano, Nigeria. Patancheru, Andhra Pradesh, India: ICRISAT. 23 p.

Pushpamma S, Parrish DB, Deyoe CW. 1972. Improving protein quality of millet, sorghum and maize diets by supplementation. Nutr Report Intl 5:93–100.

Ramesh S, Reddy BVS, Sanjana Reddy P, Hebbar N, Ibrahim M. 2005. Response of selected sorghum lines to salinity-stress under field conditions. Intl Sorghum Millets Newslett 46: 14–7.

Rao JS, Rao VG. 1997. Effect of incorporation of sorghum flour to wheat flour on chemical, rheological and bread characteristics. J Food Sci Technol 34:251–4.

Rao NBS. 1987. Nutritional implications of millets and pseudo millet. Nutr News 8(5):1–3.

Rao SV, Swaminathan M, Parpia HAB. 1964. Mutual supplementation of dietary proteins for meeting protein needs and overcoming proteins shortage in developing countries. J Nutr Dietetics 1:128–36.

Ratnavathi CV, Biswas PK, Pallavi M, Maheswari M, Vijay Kumar BS, Seetharama N. 2004. Alternative uses of sorghum—Methods and feasibility: Indian perspective. In: Alternative Uses of Sorghum and Pearl Millet in Asia: Proceedings of the Expert Meeting; 2003 July 1–4. Patancheru, Andhra Pradesh, India: ICRISAT. CFC Technical Paper Nr 34. P 188–200.

Reddy VP, Faubion JM, Hoseney RC. 1986. Odor generation in ground stored pearl millet. Cereal Chem 63(5):403–6.

Reichert RD. 1979. The pH sensitive pigments in pearl millet. Cereal Chem 63:403–6.

Reichert RD, Youngs CG. 1979. Bleaching effect of acid on pearl millet. Cereal Chem 56:287–90.

Rekha. 1997. Efficacy of processing techniques in the utilization of pearl millet for value added products [MSc thesis]. Hisar, Haryana, India: CCS Haryana Agricultural Univ. 125 p.

Rohrbach DD, Obilana AB. 2004. The commercialization of sorghum and pearl millet in Africa: traditional and alternative foods, products and industrial uses in perspective. In: Alternative Uses of Sorghum and Pearl Millet in Asia: Proceedings of the Expert Meeting; 2003 July 1–4. Patancheru, Andhra Pradesh, India: ICRISAT. CFC Technical Paper Nr 34. P 233–63.

Rooney LW, Awika JM. 2004. Specialty sorghums for healthful foods. In: Abdelaal E, Wood P, editors. Specialty grains for food and feed. St Paul, Minn.: AACC. P 238–312.

Rooney LW, Khan MN, Earp CF. 1980. The technology of sorghum products. In: Inglett E, Munck L, editors. Cereals for food and beverages: recent progress in cereal chemistry. New York: Academic Press. P 551–4.

Rooney LW, McDonough CM. 1987. Food quality and consumer acceptance of pearl millet. In: Witcombe JR, Beckerman SR, editors. Proceedings of the International Pearl Millet Workshop. Andhra Pradesh, India: Intl. Crops Research Inst. for the Semi-Arid Tropics (ICRISAT). P 43–61.

Rudiger C. 2003. The formulation of a nutraceutical bread mix using sorghum, barley and flax seed [MS thesis]. College Station, Tex.: Texas A&M Univ.

Sehgal S, Kawatra A, Singh G. 2004. Recent technologies in pearl millet and food product development. In: Proceedings of the Alternative Uses of Sorghum and Pearl Millet in Asia Workshop; 2003 July 1–4. Patancheru, Andhra Pradesh, India: ICRISAT. P 60–95.

Serna-Saldivar SO, Clegg C, Rooney LW. 1994. Effects of parboiling and decortication on the nutritional value of sorghum (*Sorghum bicolor* L. Moench) and pearl millet (*Pennisetum glaucum* L.). J Cereal Sci 19(1):83–9.

Shankara R, Malleshi NG, Krishnamurthy H, Narayana MN, Desikachar HSR. 1985. Development of mini grain mill for dehusking and grinding of cereals. J Food Sci Technol 22:91–3.

Sharma A, Kapoor AC. 1996. Levels of antinutritional factors in pearl millet as affected by processing treatment and various types of fermentation. Plant Foods Human Nutr 49:241–52.

Singh G. 2003. Development and nutritional evaluation of value added products from pearl millet (*Pennisetum glaucum*) [PhD thesis]. Hisar, Haryana, India: CCS Haryana Agricultural Univ.

Singh U. 1984. The inhibition of digestive enzymes by polyphenols of chickpea and pigeonpea. Nutr Report Intl 29:745–53.

Singh P, Nainawatee HS. 1999. Grain quality traits. In: Khairwal IS, Rai KN, Andrews DJ, Harinarayana G, editors. Pearl millet breeding. New Delhi, India: Oxford & IBH Publishing Co. Pvt. Ltd. P 158–83.

Singh BR, Singh DP. 1995. Agronomic and physiological response of sorghum, maize and pearl millet to irrigations. Field Crops Res 42:57–67.

Sivakumar S. 2004. Cereal grain procurement, storage and handling systems for commercial use. In: Alternative Uses of Sorghum and Pearl Millet in Asia: Proceedings of the Expert Meeting; 2003 July 1–4. Patancheru, Andhra Pradesh, India: ICRISAT. CFC Technical Paper Nr 34. P 141–5.

Siwawij S, Trangwacharakul. 1995. Study on sorghum snack production by extrusion process. Thailand J Agric Sci 28(3):253–61.

Sowbhaghya CM, Ali SZ. 2001a. Vermicelli noodles and their quality characteristics. J Food Sci Technol 38:423–32.

Sowbhaghya CM, Ali SZ. 2001b. A process for manufacturing high fibre low fat vermicelli noodles from millets. Indian Patent 1128/DEL/99.

Suhendro EL, McDonough CM, Rooney LW, Waniska RD, Yetneberk S. 1998. Effects of processing conditions and sorghum cultivar on alkaline-processed snacks. Cereal Chem 75:187–93.

Sumathi A, Ushakumari SR, Malleshi NG. 2007. Physico-chemical characteristics, nutritional quality and shelf-life of pearl millet based extrusion cooked supplementary foods. Int J Food Sci Nutr 58:350–62.

Taylor JRN. 2006. Novel food and non-food uses for sorghum and millets. J Cereal Sci 44:252–71.

Thompson LU, Yoon JH. 1984. Starch digestibility as affected by polyphenol and phytic acid. J Food Sci 49:1228–9.

Torres PI, Ramirez-Wong B, Serna-Saldivar SO, Rooney LW. 1993. Effect of sorghum flour addition on the characteristics of wheat flour tortillas. Cereal Chem 70(1):8–13.

Towo E, Matuschek E, Svanberg U. 2006. Fermentation and enzyme treatment of tannin sorghum gruels: effects on phenolic compounds, phytate and *in vitro* accessible iron. Food Chem 94:359–76.

Varriano-Marston E, Hoseney RC. 1983. Barriers to increased utilization of pearl millet in developing countries. Cereal Food World 28(7):392–5.

Velu G, Rai KN, Muralidharan V, Kulkarni VN, Longvah T, Raveendran TS. 2007. Prospects of breeding biofortified pearl millet with high grain iron and zinc content. Plant Breed 126:182–5.

Vimala V, Geervani P, Umapradeep K, Rama Devi A. 1996. Effect of dehulling and genotypes of sorghum (*Sorghum vulgare*) on roti quality. J Food Sci Technol 33(3):234–6.

Wu X, Beecher GR, Holden JM, Haytowitz DB, Gebhardt SE, Prior RL. 2004. Lipophilic and hydrophilic antioxidant capacities of common foods in the United States. J Agric Food Chem 52:4026–37.

COMPREHENSIVE
REVIEWS
IN FOOD SCIENCE AND FOOD SAFETY

Food Technology for Rural Settings

Mahtab S. Bamji

ABSTRACT: Agro-processing, in particular food processing, is receiving considerable attention now in India. But the emphasis is generally on capital-intensive involvement and large-scale industries. To empower rural women through livelihood, cottage and small-scale food processing based on local raw materials is required. Dangoria Charitable Trust (DCT) has set up a tiny rural food processing and training center in the village of Narspaur, Medak district, Andhra Pradesh, India. Some of the products prepared, like cereal-pulse-based complementary foods, chutney powders from green leafy vegetables (GLV), and more, are of direct nutritional relevance, whereas others like pickles, tomato sauce, "murrabba," and others contribute to nutrition indirectly by preventing wastage and generating employment for rural women. When there is glut production of tomatoes and prices crash, tomatoes are solar-dried or juice is preserved as puree. Solar drying of GLV is done using appropriate blue shielding to cut off the UV radiation. This helps to preserve β-carotene. Some of the problem areas are: microbial contamination due to contaminated chili powder, complex procedures for getting FPO license, developing cost-effective and yet attractive packaging, transportation cost (since markets exist in urban areas), and most importantly establishing market linkages.

Introduction

The food industry is described as the "sunrise industry," particularly in India, a country among the largest producers of milk and among the top 2 in the world for production of vegetables, fruits, and food grains. Unfortunately, what is produced is still insufficient and out of reach of the poor due to their lack of purchasing power. A confounding factor is the wastage that occurs due to inadequate and substandard storage facilities, lack of cold storage, and shortage of food processing for value addition and to improve shelf life. According to one estimate, the annual wastage of agricultural produce in India due to inadequate storage and processing facilities is almost 30% and equivalent to almost 580 million rupees. The wasted food could feed almost 232 million people. The multiplication factor for food processing is 2.4, which means that for every Rs.1 wealth created directly, an additional Rs. 2.4 are earned indirectly through transportation, packaging, cold storage, and so on (DG Rao, lecture on October 16, World Food Day 2007, Hyderabad, India).

Apart from preventing wastage, generating employment, and making foods available off-season (which indirectly helps food security), food technology can directly contribute to food security through enhancement of nutrient density. Increasing protein density of cereal foods by fortifying with protein concentrate or a legume (food–food fortification); increasing micronutrient density by fortifying with 1 or more vitamins and/or minerals are examples. A lesser-tried strategy is fortification with dehydrated fruits and vegetables to increase the micronutrient density of cereal–pulse-based ready-to-cook (RTC) or ready-to-eat (RTE) foods. RTC, ready-to-heat (RTH), and RTE foods contribute to drudgery reduction and easy access. RTE bakery products like biscuits and bread and extruded and fried snacks have become popular even in rural areas. Thus the food industry can help nutrition security in different ways.

Though food processing is receiving considerable attention in India, emphasis is on capital-intensive involvement and large-scale industries. Establishment of tiny and cottage-scale food processing industries in rural areas would help to empower rural women through skill development and livelihood. This study shares the experience of Dangoria Charitable Trust in establishing and running a tiny rural food processing industry.

Preharvest Technologies

Food technology can be preharvest or postharvest. In preharvest technology, the nutrient content of a plant product is enhanced by biofortification (molecular breeding) or genetic engineering. In the former, favorable genes are introduced through their identification in natural varieties and incorporation by traditional marker breeding. In the latter, favorable genes are introduced even from unrelated sources, by genetic engineering. The former being closer to nature is not controversial, whereas the latter has raised controversies regarding environmental and health safety.

Primary processing

Farmers can be trained to do primary processing like washing, cleaning, grading, sorting, and more to fetch better prices by accessing urban markets where good-quality produce can be sold at a higher price. This has become important with the present trend of the corporate sector entering into the marketing of farm produce. However, many farmers who are in a hurry to sell their produce prefer to sell mixed-quality produce (vegetables and fruits) without sorting to middle men. The culture of primary processing for better value is, however, slowly growing.

MS 20070920 Submitted 12/12/2007, Accepted 3/28/2008. Author is with Dangoria Charitable Trust, 1-7-1074, Musheerabad, Hyderabad, 500020, India. Direct inquiries to author Bamji (E-mail: msbamji@gmail.com).

Secondary processing

Most secondary processing technologies, such as drying, preparation of preserves like pickles, jams, jellies, "murabba" (fruits preserved in sugar syrup), sauces, purees, and beverages like juices, squashes, as well as fermentation, de-hulling, malting, roasting, and grinding of food grains, oil extraction, extrusion, and even baking, are relatively simple, inexpensive, and can be set-up in rural areas with the available human resources.

Tertiary processing

This involves continuous processing instead of batch processing, computerization of operations and control mechanisms; automation and robotization are very sophisticated and beyond the competence of a rural entrepreneur or self-help group.

Evolution of Food Processing

Food processing is one of the oldest occupations. It blends science with art. Traditional home skills and grandma's recipes are still very popular. They are, however, subjective. With the introduction of modern science, standardization of processes and products began to occur. Individual art was transformed into science-based technologies, and manual labor began to be replaced by mechanization and automation.

Food processing centers/industry in rural areas

Since most food commodities are produced in rural areas, setting up decentralized food processing units near the production centers in rural areas where there is seasonal glut would help to access fresh produce and reduce wastage as well as cost of handling and transportation. It would also help to generate employment and reduce rural poverty. While this logic makes sense and pilot model food processing centers have been advocated for rural areas, such units face numerous problems.

Problems faced by rural processing units

(1) Erratic power supply.
(2) Lack of skilled labor.
(3) Paucity of artisans for maintenance of equipment.
(4) Only seasonal access to cheap vegetables and fruits, which renders dedicated equipment idle for rest of the year.
(5) Many ingredients and packaging materials have to be brought from the city and that involves transportation cost.
(6) Transportation cost to access urban markets for selling.
(7) Competition from branded products as well as low-end poor-quality cheap products.
(8) High cost of production due to low turnover.

Experience of "mahila udyog," Dangoria Charitable Trust (DCT)

DCT has set up a food processing and training center in the village of Narsapur, Medak district, Andhra Pradesh, India. Financial assistance came from projects funded by government agencies like the Dept. of Science and Technology, Dept. of Biotechnology, and Ministry of Food Processing Industries through the Central Food Technological Research Inst., Mysore, India. A variety of cereal–pulse, vegetable-, and fruit-based products are being made and marketed. Rural women are being trained not only in food processing but also sanitation, hygiene, packaging, principles of HACCP (hazard associated critical control point), and explained nutritional importance. Fruit products order (FPO) license (Prevention of Food Adulteration Act 1954), for the center has been obtained for the fresh fruit and vegetable-based products like pickles, tomato sauce, and beverages. A license to market other products is obtained from the district authorities. The center has been registered as a "tiny food processing center" in the district.

Development of Low-Cost Complementary Foods

Poshana, the cereal–pulse complementary food

Diet surveys show that Indian diets are qualitatively deficient in micronutrients, particularly iron, vitamin A, and riboflavin, perhaps even zinc, folic acid, and vitamin B_{12}. The diets of infants and children are particularly deficient in all nutrients. Rural mothers do not introduce complementary food till 12 mo of age. They do not have time or patience to prepare special foods for infants. The challenge, therefore, is to prepare a low-cost complementary food for infants and children. Most commercial foods are very expensive for the poor. A survey among rural mothers regarding infant feeding practices showed that 18% of mothers had given branded commercial foods, which are very expensive, on doctors' advice. Very often, the food was diluted using not too clean water to make it stretch.

DCT decided to make and promote a low-cost complimentary food. A product called "poshana," containing wheat semolina, Bengal gram "dal," and groundnut, fortified with iron as ferrous sulfate, was developed. The nutrient composition of this product, compared to a commercial food marketed by a multinational company is given in Table 1. Though poshana has a lower-than-required content of micronutrients (except iron, which is added), this deficit can be made up by food–food complementation through supplementing with mother's milk, buffalo/cow milk, and some green leafy vegetable (GLV) (Table 2). Such food–food complementation can meet more than 80% of the requirement of most nutrients (except riboflavin) for a 9-kg child. However, it costs only Rs. 30 to 50 per kg (landing price/maximum retail price (MRP)) against Rs. 272 or more for the commercial product. Fortification with riboflavin besides iron needs to be considered. Since vitamins are unstable on storage, additional amounts would have to be added. The price advantage

Table 1—Comparison of poshana with commercial baby food nutrients from 100 g.

Nutrient	Commercial	Poshana
Calories	417	362
Protein (g)	15	13
Calcium (mg)	750	26
Iron (mg)	7.5	8.2 (fortified)
Vitamin A (μg)	360	7.1
Vitamin B1 (μg)	800	200
Vitamin B-2 (μg)	600	60
Vitamin C (mg)	35	1.0
Price (Rs/kg)	272	30–50

Table 2—Requirement (% recommended dietary allowance [RDA]) of a 9-kg child met through food–food fortification of poshana. Poshana, 100 g; buffalo milk, 100 mL; amaranth, 25 g; breast milk, 600 mL. RDA established by Indian Council of Medical Research (1989).

Nutrient	% RDA
Calories	100
Protein	168
Calcium	85
Iron	100
Vitamin A (as β carotene)	269
Vitamin B1	80
Vitamin B-2	60
Vitamin C	100

however is enormous. Studies are needed to examine the stability of vitamins and bioavailability of micronutrients from processed foods fortified with pharmaceutical products as compared to farm products.

An additional advantage of poshana is that it can make a variety of sweet and savory products like porridge, "upma" (a salty, flavored gruel), idli (salty, fermented dumplings), dosai (salty fermented pancakes), and even egg-less cake. Currently, poshana is being marketed as a protein-rich food for the family and many old people find it convenient and like it. However, greater promotional effort is needed to broaden the market, particularly for children.

Ragi (finger millet) malt

Millets or coarse grains like jowar (sorghum), bajra (pearl millet), and ragi (finger millet) are referred to as nutritious grains, because their micronutrient density is higher than that of rice or wheat. They are also rich sources of fiber. (Table 3). Among the millets, finger millet is unique because of its high content of calcium. Malting improves the availability of micronutrients like iron and zinc (Shankar Rao and Deosthale 1983). (Table 4). Information on the effect of malting on calcium availability in finger millet is not available, but in other grains it is not as marked as for iron and zinc. Thus, hydrothermal treatment and malting of barley improved zinc absorption but not calcium absorption in humans (Fredlund and others 1997). Assimilation of micronutrients depends on the presence of promoters like vitamin C for iron, phosphorus for calcium and inhibitors like phytate and polyphenols.

Table 3—Nutrient content of food grains (per 100 g).

Grain/ nutrient	Bajra	Jowar	Ragi	Rice-milled	Maize	Wheat-flour
Protein (g)	11.6	10.4	7.3	6.8	11.1	12.1
Calcium (mg)	42	25	344	10	10	48
Iron (mg)	8	4.1	3.9	3.2	2.3	4.9
Zinc (mg)	3.1	1.6	2.3	1.4	2.8	2.2
Vitamin B1 (mg)	0.33	0.37	4.2	0.06	0.42	0.49
B2 (mg)	0.25	0.13	0.19	0.06	0.10	0.17
Folic acid (mg)	45.5	20	18.3	8.0	20	36.6
Fibre (mg)	1.2	1.6	3.6	0.2	2.7	1.2

Source: Gopalan and others (2004).

Table 4—Effect of malting on bioavailability of iron from ragi (finger millet).

	Total iron (mg/100g)	Ionisable iron (mg/100g)	% Total iron
Whole grain	3.9	0.29	7.4
Malted	3.4	2.98	88.3

Source: Shankar Rao and Deosthale (1983).

Ragi malt can be consumed in the form of porridge, salty gruel mixed with buttermilk ("ambali"), ragi mudde (thick gruel made into balls), or ragi sangati (ragi added to rice when almost cooked). It is especially recommended for children, as well as for pregnant and lactating women. Among the various products made by DCT ragi malt is the fastest moving.

Ragi laddu

This is a sweet preparation in which ragi is added to sugar syrup, cooked briefly, and made into balls. Sesame seeds and flavoring like cardamom are added.

Ragi "Papad"

Papads are dietary adjuncts generally made from black gram dal. Ragi flour in combination with a small quantity of sago also makes good papads. Dough is cooked, rolled into very thin rounds and dried. It can be fried or microwaved before cooking.

The nutrients of ragi products are given in Table 5.

Dehydration of vegetables and fruits

Dehydration of vegetables and fruits enhances shelf life, reduces bulk, and provides some flexibility in cooking.

Food–food fortification of cereal–pulse products with dehydrated vegetables/fruits, prevents overdosing with mironutrients and may prevent adverse interactions between micronutrients like one micronutrient interfering with the absorption of another. Green leafy vegetable (GLV) powders would also provide health promoting phytochemicals and other micronutrients. Research is, however, needed to study the stability of micronutrients, particularly vitamins during dehydration and their subsequent shelf life. Bioavailability of micronutrients from dehydrated vegetables also needs to be studied.

Methods of dehydration of vegetables and fruits

The commonly used methods for dehydration of vegetables and fruits are:

(1) Hot air driers. They need power, which is erratic in rural areas.

(2) Sun drying (shade drying). There is a considerable loss of nutrients.

(3) Solar drying. A good method, but solar driers with solar panels, which give the best product are expensive. Loss of β-carotene can be reduced by adding a blue shield.

(4) Osmotic dehydration. Used for fruits. Gives a sweet product.

(5) Osmo-air drying. Used for fruits.

Dehydrated green leafy vegetables (GLV) as sprinkles and foodlets

Instead of blending the micronutrients in the processed foods, sprinkles and foodlets have been suggested as an approach that is more empowering for the person who is cooking because she/he can sprinkle the micronutrient mix into the food

Table 5—Nutrient content of finger millet (ragi) products.[a] Values per 100 g.

Item/ nutrient	Protein (g)	Energy (cals)	Ca (mg)	Fe (mg)	B_1 (mg)	B_2 (mg)	Crude fiber (g)
Ragi malt	7.79	350	367	4.2	0.45	0.2	3.84
Ragi papad	6.62	290	271.6	3.7	1.98	0.89	0.91
Ragi laddu (each weighs 10 g)	4.5	444.4	215	2.4	0.3	0.1	0.22
RDA for adult women	50	2000	400	30	1.0	1.2	

[a] Calculated from values given in Gopalan and others (2004); Indian Council of Medical Research (1989).

Table 6 — Nutrient content of dehydrated green leafy vegetables[a] (per 10-g serving).

GLV	Calcium (mg)	Iron (mg)	Beta carotene (μg)	Vitamin C (mg)	Folic acid (mg)	Riboflavin (mg)
Amaranth gangeticus (Totakura)	200	3.9	8340	10	14.9	0.3
Spinach	91	1.4	3288	35	15.4	0.32
Curry leaves	232	0.26	1991	1.12	39.5	.02
Drumstick leaves	185	3.6	8270	92.4	39.4	0.02
RDA-adult woman[b]	400	30	2400[c]	40	100[c]	1.3

[a] Calculated from values given in Gopalan and others (2004).
[b] Indian Council of Medical Research (1989).
[c] Upward revision of RDA is being considered by the Indian Council of Medical Research.

Table 7 — Nutrients from GLV rich in iron[a] (per 10-g serving).

GLV	Ca (mg)	Fe (mg)	Beta carotene (μg)	Vit. C (mg)
Benagal gram leaves	129	9.0	–	–
Knolkhol leaves	555	10.0		
Raddish leaves	282	16.4	2002	96.5
Amaranthus peniculatus — rajakeerai	249	8.7	–	38
Amaranthus. Polygonoidis	251	27.3	–	22
RDA-adult woman[b]	400	30	2400[c]	40

[a] Calculated from values given in Gopalan and others (2004).
[b] Indian Council of Medical Research (1989).
[c] Upward revision of RDA is being considered by the Indian Council of Medical Research.

Table 8 — Nutrients from GLV chutney powders.[a]

Product	Vitamin C (mg)	Beta Carotene (μg)	Antioxidant Vit. E Eq.
Curry leaf chutney powder	7.24	554	4.55
DS leaves chutney powder	6.31	633	3.33
RDA for adult woman[b]	40.0	2,400	8.0

[a] Analysis done at the National Institute of Nutrition, Hyderabad, India, 3 mo after preparation of the powder.
[b] Indian Council of Medical Research (1989).

Table 9 — Vitamin C content of "amla" (Indian gooseberry) "supari" and lime squash.

	Serving	Vitamin C content[a] (mg/serving)
Amala supari	2 g	13.4
Lime squash	50 mL	3.33
RDA for adult woman[b]		40 mg

[a] Analysis done at the National Institute of Nutrition, Hyderabad, India, 2 mo after preparation.
[b] Indian Council of Medical Research (1989).

or use micronutrient spreads (foodlets), a cross between food and tablets. Thus, sprinkles and foodlets can be used without introducing new foods.

In a country like India, where throughout the year a variety of GLVs are available in plenty and are the cheapest vegetables, people should be encouraged to use them for food–food fortification. The next best alternative is to use dehydrated vegetables like GLV, which are rich in micronutrients. Table 6 and 7 show that there is an ample supply of micronutrients such as β- carotene, vitamin C, and calcium in GLVs and GLV powders can be effectively used for food–food fortification to supply these nutrients. Meeting the requirement of iron and some B vitamins like folic acid and riboflavin can be a problem. Some GLVs are also rich in iron (Table 7).

Instead of using pharmaceutical preparations for sprinkles or foodlets, natural foods like the GLV powders, which are rich in micronutrients can be used as food–food supplements (sprinkles) to enrich the diet.

Chutney powders (karap pudi) from solar-dried GLV

In South India, chutney powders made from legumes and spices are used as embellishment with rice, and breakfast foods like "idlis," "dosai," and others. In Andhra Pradesh, India, chutney powders are made from legumes in combination with sun-dried GLV like curry leaves. DCT is marketing "karap pudi" made from curry leaves, drumstick-curry leaf combinations, and "gongura"("ambadi") (Hibiscus cannabinus) leaves. Nutrient compositions of the 1st two, based on analysis, are given in Table 8. These powders are rich sources of β-carotene, vitamin C, and antioxidants, as well as minerals.

Vitamin C–rich products

Apart from citrus fruits, Indian gooseberry or "amla" is rich in vitamin C. A mouth freshener ("supari") is being made from solar-dried amla. Generally, supari is made from areca nut. Table 9 gives the vitamin C content of amla supari and lime squash. The former is a very rich source of vitamin C.

Pickles, murabbas, and relishes. These can be made from many fruits and vegetables. DCT also makes the following products: pickles from solar-dried and fresh tomatoes; pickles from fresh lime, drumstick, and mango; toffee from ginger, murabba (fruit pieces preserved in sugar syrup) from raw mango; and tomato sauce. All these products have some nutritional or medicinal value.

Spices and condiments. A rural food-processing center can make a variety of spices and condiments for which there is a great demand in India. DCT makes coriander powder, "sambhar and rasam" powders, and roasted Bengal gram powder.

Marketing

In today's age of globalization, small industries face tremendous problems of competition both from the larger industries as well as unscrupulous small-time producers who make and market substandard products at low cost. For instance, most bakeries in Hyderabad, India, buy cheap tomato sauce that sells at Rs. 10 per kilogram. These products (tomato sauce and ketchup) do not meet the requirement of Brix, and they contain thickeners like potato, pumpkin, and starch. Thus, the biggest challenge for a rural food processing industry is finding markets.

A Market Survey on Consumer Perception and Purchase Behavior was done through the School of Agri Business Management, College of Agriculture, Acharya N.G. Ranga Agriculture Univ., Hyderabad, India. The salient findings are:

(1) Brand disadvantage.
(2) Packaging not attractive.
(3) Pricing has to be much lower than branded products.
(4) Publicity through medical professionals should be done.
(5) Insufficient margin.
(6) Supply to institutions should be encouraged.

Fancy packaging adds to the cost and is not affordable with products of low turnover. There is vested interest at every level and demand for bribes, which a charitable trust cannot give. Despite difficulties, sale has increased almost 4-fold in the last 5 y. (Table 10).

Conclusions

Rural food processing industry requires much support from government to make it competitive. Entry of large companies even for products like pickles, papads, spices, and condiments limits the sustainability and employment generation capability of rural industries. Rural women have to be trained in costing and marketing skills. They have to be aggressive and attempt to capture at least the rural market.

Table 10—Sale proceeds from processed foods.

Year	Rs.
2002	45128
2003	73305
2004	130006
2005	168102
2006	176190

Acknowledgments

Financial support was received from the Dept. of Science and Technology, Dept. of Biotechnology, and Ministry of Food Processing Industries, Govt. of India, (through the Central Food Technological Research Inst., Mysore-CFTRI, India). Technical advice and help from the Director Dr. V. Prakash and staff of CFTRI (N.G. Malleshi, P. Vijayanand, K. Venkatesh Murty, and Sheila Bhatacharya) with product development and quality control. Analysis of processed foods was done at the Natl. Inst. of Nutrition, Hyderabad, India. Mr. P.V.V.S. Murty, Senior Investigator, DCT, has been associated with this activity throughout. Dr. Devyani Dangoria, Managing Trustee, DCT, and Ms. K. Lakshmi have given encouragement, advice, and support. Ms. V. Nagamani did most of the processing, with help from other women. My sincere gratitude to all the above for their contribution in running this Center.

References

Fredlund K, Bergman EL, Rossander-Hulthén L, Isaksson M, Almgren A, Sandberg AS. 1997. National Board for Industrial and Technical Development (NUTEK), the Nordic Industrial Foundation, Swedish Council for Forestry and Agricultural Research (SJFR, project nr 50.0306/97). PMID: 14647214 [PubMed – indexed for MEDLINE].

Gopalan C, Rama Sastry BV, Balasubramanium SC. Revised and updated by Nrasinga Rao BS, Deosthale YG, Pant KC. 2004. Nutritive value of Indian foods. Hyderabad, India: Natl. Inst. of Nutrition, (ICMR).

Indian Council of Medical Research. 1989. Nutrient requirements and recommended dietary allowances for Indians. A report of the Expert Group of Indian Council of Medical Research, New Delhi, India.

Prevention of Food Adulteration Act. 1954. 22nd edition 2001. Lucknow, India: Eastern Book Co.

Shankar Rao DS, Deosthale YG. 1983. Mineral composition, ionisable iron and soluble zinc in malted grains of pearl millet and ragi. Food Chem 11:217–23.

COMPREHENSIVE
REVIEWS
IN FOOD SCIENCE AND FOOD SAFETY

Food Technology to Meet the Changing Needs of Urban Consumers

H.N. Mishra and V.R. Sinija

ABSTRACT: Food technology involves the application of science and engineering principles to the commercial processing, preparation, packaging, storage, and distribution of foodstuffs. Changes in family lifestyle, especially increased ownership of freezers and microwave ovens, are reflected in demands for foods that are convenient to prepare, suitable for frozen storage, or have a moderate shelf life at ambient temperature. There is also an increased demand for foods that experience fewer changes during processing and, thus, either closely resemble the original material or have a desirable image. New preservation technologies, such as high-pressure processing, pulsed electric fields, and more, offer advantages in meeting consumer demands for freshness, convenience, and safety. In India, processed food products are available in both organized and unorganized sectors. Developments in production technology, emergence of new concepts like ready-to-eat (RTE) foods, enhancement of product shelf life, and modern packaging are driving the shift from nonorganized to organized commercial business. It would be necessary to develop the appropriate technology to produce authentic products with low cost or reusable packaging and an efficient distribution system to market them at an acceptable price. The prime objective is to provide all consumers with increasing levels of convenience.

Introduction

Food is basically energy—a form of solar energy—stored in plant and animal foods in chemical forms. On consumption, this stored form gets converted to physiological energy. Processing and storage of food become imperative because availability of food is mostly seasonal, whereas its consumption goes on throughout the year unfettered by any types of seasonal bounds. Over the last 5 decades, India has made great strides in the production of food grains, milk, fruits and vegetables, and more, and there is a semblance of self-sufficiency, albeit fragile in view of the burgeoning population. Even so, the net amount of the available produce for consumption is unnecessarily reduced due to insufficient storage and processing.

Food technology is the application of scientific methods and engineering principles to the commercial processing, preparation, packaging, storage, and distribution of foodstuffs. It is of great importance in ensuring that the best possible use is made, from a nutritional standpoint, of available food supplies and in developing measures that would reduce losses during the storage, processing, and cooking of food. Advances in food technology have made major contributions to public health over the last century; for example, through better food preservation, a greater variety of safe and nutritious products, and food fortification. However, current progress in our understanding of the interplay between health, diet, and nutrition is opening up exciting opportunities to "use foods to deliver not just improved nutrition but, importantly, a better quality of life for all consumers," according to Jeya Henry, Professor of Human Nutrition at Oxford Brookes Univ., on April 26, 2007.

The food processing industry is one of the largest manufacturing industries worldwide and possesses global strategic importance. With the advancement of science and technology, new food processing technologies are drawing the attention of many scientists in academia and industry. Consumers prefer high-quality foods with longer shelf life and, clearly, some of the new technologies can meet these demands. Newer strategies have been devised to modify the existing food processing techniques and the adoption of novel processing technologies.

In industrialized countries the market for processed foods is changing. Consumers no longer require a shelf life of several months at ambient temperature for the majority of their staple foods. Changes in family lifestyle, and increased ownership of freezers and microwave ovens, are reflected in demands for foods that are convenient to prepare, are suitable for frozen storage, or have a moderate shelf life at ambient temperature. There is also an increased demand by some consumers for foods that have experienced fewer changes during processing and thus either closely resemble the original material or have a desirable image. New preservation technologies, such as high-pressure processing and pulsed electric fields, offer advantages in meeting consumer demands of freshness, convenience, and safety.

MS 20080098 Submitted 2/7/2008, Accepted 3/20/2008. Authors are with Agricultural & Food Engineering Dept., Indian Inst. of Technology, Kharagpur, India. Direct inquiries to author Mishra (E-mail: hnm@agfe.iitkgp.ernet.in).

Minimally Processed Foods

In recent years, consumers have become more health conscious in their food choices but have less time to prepare healthful meals. As a result, the market demand for "minimally processed" or "lightly processed" foods has rapidly increased. Consumers increasingly demand foods that retain their natural flavor, color, and texture and contain fewer additives such as preservatives. In response to the expectations, one of the most important recent developments in the food industry has been the development of minimal processing technologies designed to limit the impact of processing on nutritional and sensory qualities and to preserve food without the use of synthetic additives.

Minimally processed foods have been defined as products that include all the operations that add some value to conventional food preservation processes like washing, selecting, peeling, slicing, chopping, coring, and packaging that cause fewer possible changes in food quality and maintain their quality attributes similar to those of fresh produce, but at the same time provide the food enough useful life to transport it from production site to the consumer. Minimally processed foods may be meant for direct consumption or can be later transformed into the final products by any conventional techniques.

The demand for minimally processed, easily prepared, and ready-to-eat (RTE) "fresh" food products, as well as globalization of food trade and distribution from centralized processing poses major challenges for food safety and quality. Recent foodborne microbial outbreaks are driving a search for innovative ways to inhibit microbial growth in foods while maintaining quality, freshness, and safety. One option is to use packaging to provide an increased margin of safety and quality. The next generation of food packaging may include materials with antimicrobial properties. These packaging technologies could play a role in extending shelf life of foods and reduce the risk from pathogens. Antimicrobial polymers may find use in other food contact applications as well.

Traditional thermal processing techniques can be beneficial to foods in both preservation and flavor formation but be detrimental by damaging other sensory and nutritional properties. Minimizing undesirable changes can be achieved in a number of ways, whether through more effective process control, the use of high temperature short time (HTST) techniques such as aseptic processing or newer technologies such as volume heating methods. The various approaches and the range of technologies such as infrared heating, dielectric methods such as the use of microwaves, and ohmic heating is complemented by the following alternatives to thermal processing, ranging from irradiation to high-pressure processing and the use of pulsed electric fields.

Drying by power ultrasound

Conventional dehydration methods based on hot air drying are widely used but they can deteriorate the quality of the final product. Thus, undesired food flavor, color, composition, vitamin degradation, and the lost of essential amino acids may be caused. Scientists and innovative food centers are looking for emerging food processing technologies to enable the introduction of new, safer, fresher, and better high-quality foods with longer life for local and export markets. Among the emergent new technologies ultrasonic dehydration is very promising because of the special effects of power ultrasound, which is more significant at low temperature and reduces the probability of food degradation. In addition, ultrasound permits the removal of water from solids without producing a liquid phase change. Drying heat-sensitive food materials by power ultrasound is 1 example of the potential use of ultrasound in the food industry. Figure 1 shows an ultrasound set up for crystallization (Ruecroft 2007).

Microwave drying

Microwave (MW)-related (MW-assisted or MW-enhanced) combination drying is a rapid dehydration technique that can be applied to specific foods, particularly to fruits and vegetables. Increasing concerns over product quality and production costs have motivated researchers to investigate and the food industry to adopt combination-drying technologies. The advantages of

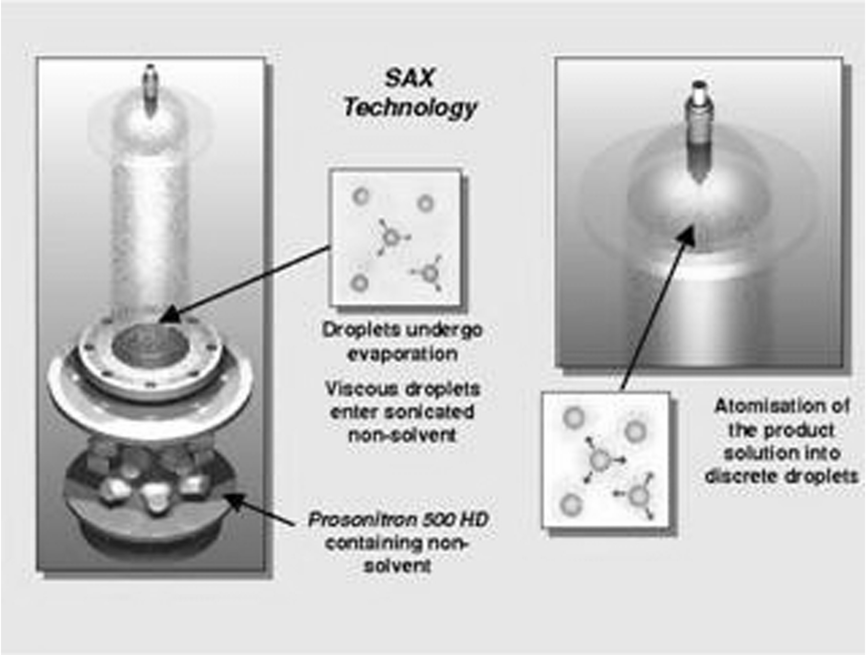

Figure 1 — Ultrasound set up for crystallization (Ruecroft 2007).

MW-related combination drying include the following: shorter drying time, improved product quality, and flexibility in producing a wide variety of dried products. But current applications are limited to small categories of fruits and vegetables due to high start-up costs and a relatively complicated technology as compared to conventional convection drying. MW-related combination drying takes advantages of conventional drying methods and microwave heating, leading to better processes than MW-drying alone.

Many researchers have successfully dried vegetables with high heat-sensitive compositions, and fruits with high sugar contents. In all cases, the drying time is reduced significantly, and in most cases the quality of the dried food products is improved or kept the same as compared with only MW-dried or conventionally dried products (Zhang and Xu 2003). Figure 2 is a schematic representation of a microwave drying system (Feng and others 1999).

Pulse electric fields processing

Pulsed electric fields (PEF) treatment is one of the most important nonthermal processes available for food preservation because of its potential to inactivate microorganisms without altering the organoleptic and nutritional properties of foods. When exposed to high electrical field pulses, microbial cell membranes develop pores either by enlargement of existing pores or by creation of new ones. These pores may be permanent or temporary depending on the condition of treatment. The pores increase membrane permeability, allowing loss of cell contents or intrusion of surrounding media, either of which can cause cell death. The perforation of cell membranes caused by PEF also applies to fruit and vegetable cell walls, so a potentially beneficial side effect of the process is improved extraction of juice from cells. This effect is also applied in another promising use, namely, concentration of sewage sludge, which essentially is a suspension of live and dead cells and organic matter, which can be very hard to filter and concentrate. PEF, by killing live cells and reducing their ability to retain water, greatly improves filtration. Extraction of sugar from beets and starches from potatoes may also be improved by PEF.

Important process variables in PEF include the electric field, which can have various waveforms, strengths, and distribution in the treatment chamber, temperature, pressure, and duration of exposure. Figure 3 shows a simplified design of pulsed electric field scheme and Figure 4 and 5 describe different electrode geometries in the treatment chamber and continuous PEF chamber with baffles, respectively (Barbosa-Cánovas and others 1999).

A PEF unit for treatment of fresh orange juice at a pilot scale was described by Qiu and others (1998). This system consisted of a continuous pilot-scale PEF unit integrated with an aseptic packaging machine. These investigators concluded that the PEF treatment inactivated 99.9% of microbial flora, with the square waves being most effective. Compared with heat pasteurization, the PEF-treated orange juice retained more vitamin C and flavor.

As can be seen in the preceding example, the goal of many studies using PEF treatments is to extend the shelf life of foods by minimizing spoilage caused by microbial growth. In these studies, the level of microbial reduction is a key parameter for evaluating foods treated with PEF against those treated using traditional technologies. Some illustrative examples of foods treated with PEF are shown in Table 1. These applications are still under development stage. Further research is necessary to obtain data on the effects of PEF treatments on the sensory properties as well as nutritional content of foods.

High-pressure processing

High-pressure food processing generally relies on the application of isostatic, hydraulic pressures in the range of 100 to 1000 MPa. The process can be carried out in any type of hydraulic fluid, but water is often preferred for ease of operation and compatibility with food materials. Liquids such as water are relatively incompressible and store much less energy in their compressed state compared with gases; the risk from explosion is thus

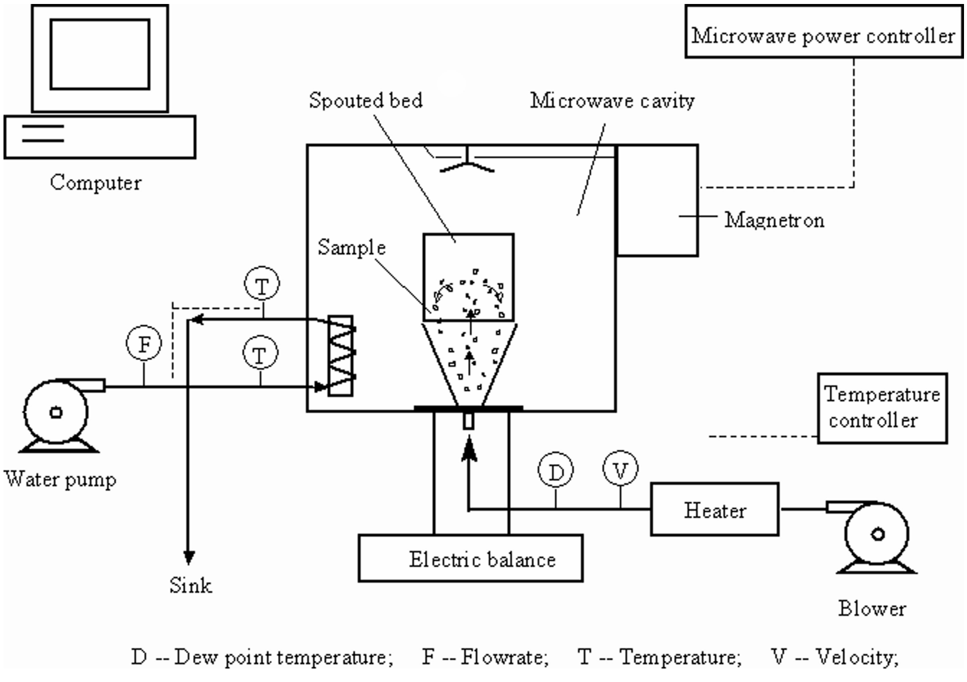

Figure 2—Schematic representation of microwave drying process. (Feng and others 1999).

greatly reduced by the use of incompressible fluids as the pressurizing medium. Liquid foods can be compressed directly in a pressure vessel or liquid and/or solid foods can be contained in flexible containers immersed in the hydraulic fluid for the duration of the pressure process. The principal benefit of high-pressure technology is its relatively minor effect on food composition and hence, sensory and nutritional characteristics. The structure of food proteins and polysaccharides can be changed by high pressure to bring about modifications in rheology and mouthfeel.

The unique physical and sensory properties of pressure-processed foods offer new opportunities for product development. These could include new, long shelf life convenience foods with fresh flavors and colors, minimally processed or raw fish and meat, new types of food gels, and frozen foods with radically improved quality. The key components of a high-pressure system are the pressure vessel, pressurizing system, and ancillary components (Figure 6). A schematic flow diagram of high-pressure processing is also given in Figure 7 (http://www.fao.org/ag/ags/agsi/Nonthermal/nonthermal_1.htm).

Radiation processing

Food irradiation is a physical method of processing food. It has been thoroughly researched over the last 4 decades and is recognized as a safe and wholesome method. It has the potential both of disinfesting dried food to reduce storage losses and disinfesting fruits and vegetables to meet quarantine requirements for export trade. Low doses of irradiation inhibit spoilage losses due to sprouting of root and tuber crops. Foodborne diseases due to contamination by pathogenic microorganisms and parasites of meat, poultry, fish, fishery products, and spices are on

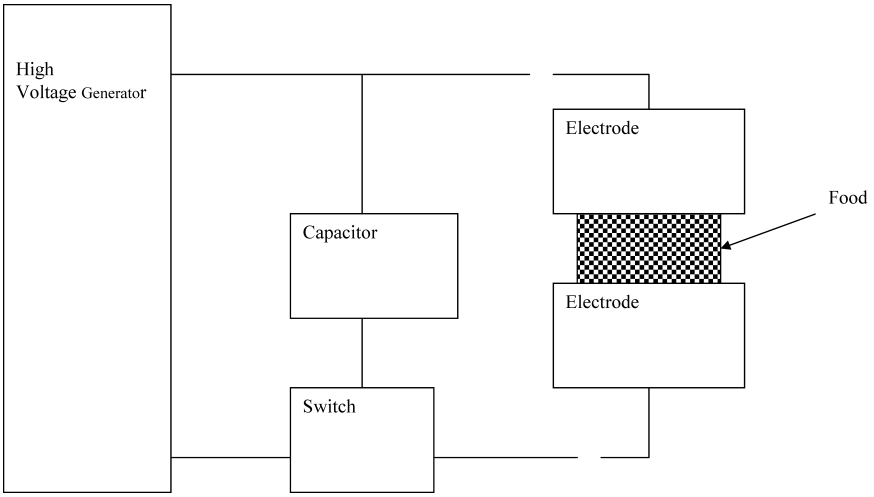

Figure 3—A simplified general design of a pulsed electric field apparatus. (http://www.fao.org/ag/ags/agsi/Nonthermal/nonthermal_1.htm).

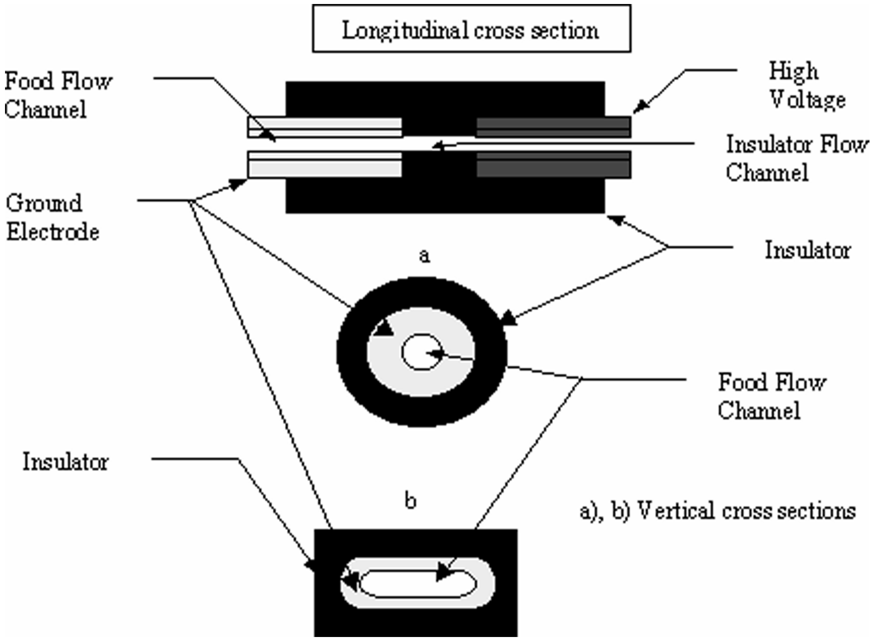

Figure 4—Treatment chamber with different electrode geometries and enhanced electric fields in the insulator channel (Barbosa-Cánovas and others 1999).

the increase. Irradiation of these solid foods can decontaminate them of pathogenic organisms and thus provide safe food to the consumer. It is an energy-efficient food preservation method that has several advantages over traditional thermal processes such as canning. The resulting products are very close to the fresh state in texture, flavor, and color.

Ohmic heating

Ohmic heating is an advanced thermal processing method wherein the food material, which serves as an electrical resistor, is heated by passing electricity through it. Electrical energy is dissipated into heat, which results in rapid and uniform heating. Ohmic heating is also called electrical resistance heating, Joule heating, or electro-heating, and may be used for a variety of applications in the food industry.

Ohmic heating can be used for heating liquid foods containing large particulates, such as soups, stews, and fruit slices in syrups and sauces, and heat-sensitive liquids. The technology is useful for the treatment of proteinaceous foods that tend to denature and coagulate when thermally processed. For example, liquid egg can be ohmically heated in a fraction of a second without coagulating it. Juices can be treated to inactivate enzymes without affecting flavor. Other potential applications of ohmic heating include blanching, thawing, online detection of starch gelatinization, fermentation, peeling, dehydration, and extraction.

Thermal Processing

Heat is the most convenient way of extending the keeping quality of food. Heating food not only destroys microbes but also inactivates enzymes and toxins. While the nutritional quality of foods (especially for some vitamins) may be reduced by heat processing, a judicious combination of high temperature and short time minimizes nutrient losses. The careful selection of time and temperature combination from the thermal death time curve will optimize both the nutritional and sensory properties of food. This highlights the food processors conflict between maintaining food safety and preservation of nutritional quality (Henry and Heppel 2002).

Nonthermal technologies have been advanced to replace conventional heat treatments. These new technologies cannot, however, achieve the broad microbial lethalities that are currently

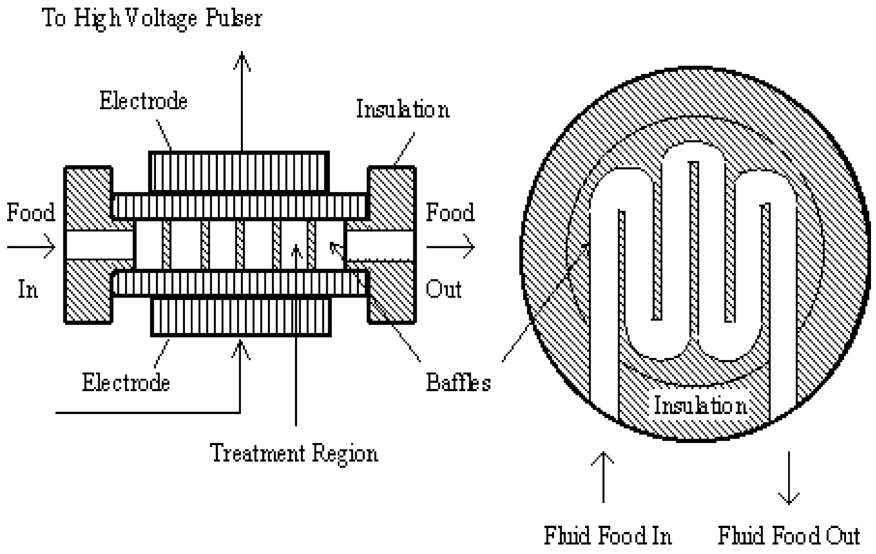

Figure 5 — Continuous PEF chamber with baffles (Barbosa-Cánovas and others 1999).

Table 1 — Examples of foods processed using pulsed electric fields and change in their quality attributes other than microbial.

Product	Process and quality attributes	Reference
Apple juice, fresh, and reconstituted	Pasteurization: No change in solids concentration, pH, and vitamin C. Loss of calcium, magnesium, sodium and potassium. No sensory differences between processed and untreated juices.	Barbosa-Canovas and others (1998)
Commercial cheese sauce, reformulated	Preservation: Better flavor and appearance than comparable products.	Hofmann (1985)
Green pea soup	Cooking: No difference in sensory properties after 4 wk storage at 4 °C.	Barbosa-Canovas and others (1998)
Liquid whole egg	Pasteurization: Prevention of coagulation, superior quality.	Hofmann (1985)
Orange juice	Preservation at pilot-scale: Less than 6% flavor loss, negligible vitamin C and color change.	Hofmann (1985)
Orange juice, fresh-squeezed	Pasteurization: Minimal loss of flavor compounds, color and vitamin C.	Hofmann (1985)
Salsa	Preservation. Better flavor and appearance than comparable products.	Hofmann (1985)
Spaghetti sauce	Aseptic processing: Acceptable after 2 y and 80 °F storage.	Hofmann (1985)

attainable by heat treatment. Current PEF and HPP technologies can only accomplish the equivalent of pasteurization when applied at their maximum lethal doses. The achievement of commercial sterility by these nonthermal technologies is currently not feasible.

The application of nonthermal technologies to foods is more likely to result in stress or injury than to cause the death of microorganisms. An abundance of injured microbial cells in nonthermally processed foods may create new challenges to food processors and regulatory agencies. The detection of low levels of pathogens in food is a difficult task particularly when cells are injured. The safety of the nonthermally processed product is compromised if food and storage conditions favor the recovery of injured cells. Stress of pathogens by nonthermal technologies is a concern and the adaptation of cells to such stress may constitute a microbial hazard. Nonthermal technologies therefore introduce new challenges, and thus warrant the implementation of new safety strategies (www.fao.org).

RTE Convenience Foods

In India, processed food products are available in both organized and unorganized sectors. Developments in production technology, emergence of new products like RTE mixes, enhancement of product shelf life, and packaging are driving the shift from nonorganized to organized commercial business. Due to growing urbanization and changing food habits the demand has been rising at a good pace and there is enough latent market potential waiting to be exploited through developmental efforts. It is high time for the organized sector to take initiative in technology improvement, process modeling and automation, overall improvement in quality, investment in R&D to develop new products and enhance shelf life of existing products, and further improvement in packaging.

The size of the industry might increase substantially if the product portfolio were to include at least one each of the daily staples: ready chapatti from the chapatti–*subzi* staple and precooked or concentrated dal from the dal–*chawal* combination. India is a vast country with different eating habits and, yet, North Indian cuisine is an acceptable restaurant fare and the ubiquitous *idli* and *dosa* are available in every part of country. From dishes consumed throughout the country at different eating occasions of breakfast, lunch, tea time, and dinner, it should be possible to systematically examine similarities and come up with a short list of products that would find a place in the menu of a major part of the country, which could then be developed as processed food. The Western concept of hamburger or a sandwich and its local equivalent chapatti–*subzi* takeaways cooked in perceived hygienic surroundings are a boon for the working women and could be nurtured into big business.

With the increasing dominance of large and technically more sophisticated companies in food processing, attention also should be paid to small operations that do not enjoy the same economies of scale. To this end, an increase in the number of regionally centralized facilities offering the latest processing techniques and advice should be encouraged. It would be necessary to develop the appropriate technology to produce an authentic product, with low cost or reusable packaging and an efficient distribution system to market them at an acceptable price. The prime objective must now be to provide all consumers with increasing levels of convenience.

Change in Nutritional Quality during Processing

While some vitamins are destroyed when foods are processed, most of this loss is not due to heat processing per se. The losses are largely due to the nutrients being sensitive to pH, O_2, moisture,

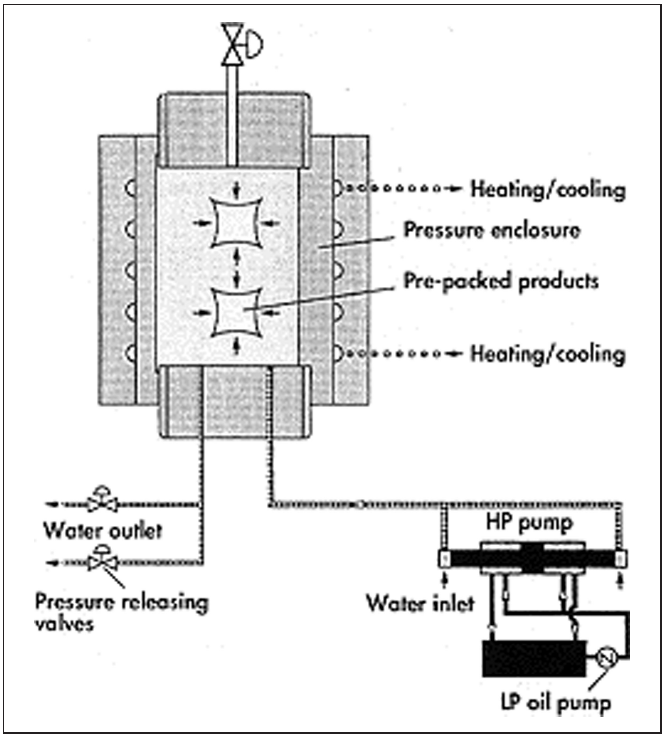

Figure 6—A typical high-pressure processing system for treating pre-packaged foods (From Moreau 1995).

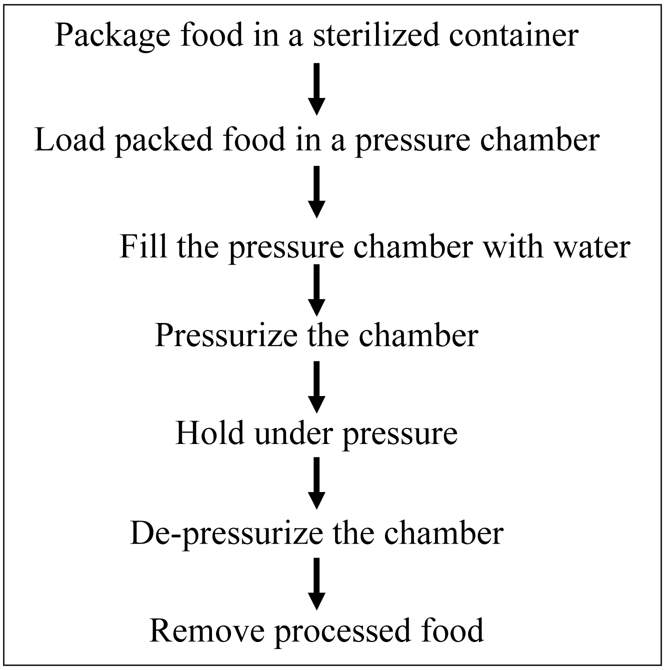

Figure 7—A simplified schematic flow diagram of high-pressure processing. (Source: http://www.fao.org/ag/ags/agsi/Nonthermal/nonthermal_1.htm).

light, heat, or a combination of these. The stability of vitamins varies enormously, ranging from little or no loss to complete destruction. Table 2 summarizes these observations. In general, most food processing technologies in use today do not result in major nutrient losses (Karmas and Harris 1998). More importantly due to the variation in the type of food consumed, the consumption of processed foods is unlikely to influence human micronutrient status.

Bender (1978) succinctly summarized it as "There is general belief that when the housewife buys fresh food and cooks them herself she retains all the nutrients, whereas when the same food passes through the hands of the food processor these nutrients are largely if not completely destroyed. This belief is untrue like so many other popular beliefs in nutrition." Much of the current and future concern related to the role of food processing on nutrient composition of foods is associated with changes in the way the food products are manufactured, social and cultural changes in food consumption and meal pattern and increased demand and interest in low-energy foods that have fat and sugar mimetics.

Food Technology to Improve Nutrition

A desirable development in India in recent years has been the widespread application of science and technology to process and preserve foods in various forms. Better methods of processing and preservation can help increase the effective availability of our food resources. Food fortification can both be a short-term and a long-term approach for achieving nutrition security. Value addition can be through using nutrient-dense foods, underutilized nutritious food materials, increasing the use of healthful byproducts like soy and rice bran, fortification of foods, and so on.

One-half of the world's population, most of them poor and living in developing countries, have diets that are inadequate in protein, calories, and/or micronutrients. Up to one-fifth of deaths and disabilities worldwide are attributed to malnutrition. Micronutrient deficiencies, the hidden hunger that can damage health even when diets are adequate in calories, have increasingly become a focus for concern in the international aid community. Approximately one-third of the world's population is affected by deficiencies in vitamin A, iron, and iodine. Lack of adequate folic acid is also a significant concern, especially during pregnancy. Clinical manifestations of these and other micronutrient deficiencies include birth defects, blindness, mental retardation, anemia, and even death. Those who are marginally deficient in micronutrients are unable to reach their full potential as parents, workers, and citizens. The cycle of poverty thus continues.

One way to break this cycle is by effectively applying food science and technology to nutritional problems and challenges. Better, safer, and more nutritious products can be made available to at-risk populations through food science/technology applications such as micronutrient fortification of widely consumed foods, fortification and other nutritional enhancements of food aid commodities, and direct technical support to industries with the potential to improve the safety and nutritive quality of their products.

Micronutrient fortification

Micronutrient fortification of food staples and food aid commodities can be a relatively cost-effective means of helping to alleviate regional dietary deficiencies of one or more vitamins and minerals critical to good health and development. Adequate consumption of fortified food has been shown to improve micronutrient status in individuals. Correcting micronutrient deficiencies can boost immunological integrity, reduce maternal deaths, decrease infant and childhood mortality, strengthen cognitive development in children, and boost adult work capacity. Well-nourished mothers are more likely to give birth to well-nourished children who grow and learn better, ultimately earn more, and are less likely to suffer from childhood diseases and diet-related chronic disease in midlife.

Effective nutrition interventions can sustain themselves when they are integrated with industrial processes and the food market system. The addition of micronutrients to the government specifications for food aid commodities beginning in the 1980s represented the most significant change in the nutritional requirements for food aid since the program's inception. It also reflected the growing awareness among health professionals and the international aid community of the vital role minerals and vitamins play in human health and development. For example, the most common nutritional disorder worldwide is iron deficiency anemia (IDA), which lowers resistance to disease, impairs development, reduces stamina, and increases the risk of neonatal, infant, and maternal mortality. Clinical vitamin A deficiency also presents a chronic problem for developing country populations.

Table 2—Stability of Nutrients (adapted from Karmas and Harris 1998).

	Effect of pH					
Nutrient	Neutral (pH 7)	Acid ($<$pH 7)	Alkaline ($>$pH 7)	Air or O_2	Light	Heat
Vitamin A	S	U	S	U	U	U
Ascorbic acid (C)	U	S	U	U	U	U
Biotin	S	S	S	S	S	U
Carotene (provitamine A)	S	U	S	U	U	U
Choline	S	S	S	U	S	S
Cobalamin (vitamin B_{12})	S	S	S	U	U	S
Vitamin D	S		U	U	U	U
Folic acid	U	U	S	U	U	U
Vitamin K	S	U	U	S	U	S
Niacin	S	S	S	S	S	S
Pantothenic acid	S	U	U	S	S	U
Pyridoxine	S	S	S	S	U	U
Riboflavin	S	S	U	S	U	U
Thiamin	U	S	U	U	S	U
Tocopherol (vitamin E)	S	S	S	U	U	U

S = stable (no important destruction); U = unstable (substantial destruction).

Essential nutrients

The nutrients known to be essential for human beings are proteins, carbohydrates, fats and oils, minerals, vitamins, and water.

Proteins are made of amino acids, small units necessary for growth and tissue repair. Starches and sugars are carbohydrates, the main source of the body's energy. Sugars are not essential foods. They provide energy (calories) but no nutrients. For that reason sugar is called an "empty calorie" food. Fats and oils (which are liquid fats) are a concentrated source of energy. Fats in the diet in adequate amount are necessary for good health. They make certain vitamins available for use in the body, they cushion vital organs, they make up part of all body cells, and they help to maintain body temperature.

Almost all foods contribute to a varied intake of essential minerals. Most minerals are easy to obtain in quantities required by the body. A major exception is iron for children under age 4 and adolescent girls and women in the childbearing years. These groups need more iron than a normal diet may provide. Iron helps to build red blood cells. It also helps the blood carry oxygen from the lungs to each body cell. Rich sources of iron are meat, especially liver, egg yolks, and dark green vegetables. This mineral builds bones and teeth, and it is also necessary for blood clotting. The best sources are milk and hard cheese. Others are leafy greens, nuts, and small fishes–such as sardines–with bones that can be eaten. Phosphorus works with calcium to make strong bones and teeth. A diet that furnishes enough protein and calcium also provides enough phosphorus. Other important minerals are sodium, potassium, iodine, magnesium, zinc, and copper. So diet may strongly influence an individual's risk of obesity, cardiovascular diseases, cancer, and other lifestyle-related diseases.

Innovative Food Processing Technologies

Several innovative state-of-the-art food process technologies have been developed keeping in view the strategic operational requirements of the military. These include:

- Retort processing of foods in flexible pouches
- Food additives technology
- Cold shock dehydration technology
- High-temperature, short-time (HTST) pneumatic drying
- Flaking technology
- Fluidized beds for drying of cereals, pulses, and vegetables
- Spraydrying
- Technology of hurdle processing and preservation
- Intermediate moisture (IM) foods technology
- Micro-encapsulation technology
- High-temperature, short-time extrusion technology
- Compressed foods technology
- Thermal processing of foods in aluminum containers
- Reverse osmosis and ultrafiltration technology
- Stack encapsulation technology
- Technology for the extension of shelf life of fresh fruits and vegetables

Some of these technologies have become commercial. Some recently developed technologies with vast potential in both defense and civil sectors are briefly discussed here. Figure 8 shows the evolution of preservation techniques.

Food chain approach

The Food and Agriculture Organization (FAO) has adopted this approach, defined as recognition that the responsibility for the supply of food that is safe, healthy, and nutritious is shared by all involved from primary production to final preparation and consumption. Compositional changes, for better or for worse, can be introduced at each and every link in the food chain. Genetic enrichment of nutritional quality of foods such as high-quality-protein maize, beta-carotene-enriched rice, rich breeding lines of rice high in iron and zinc, designer potatoes (transgenic potato with genetic enrichment of protein quality and quantity), are a few examples of food products that could make a difference in the nutrition of future generations to assure nutrition security (Chandrasekhar 2004).

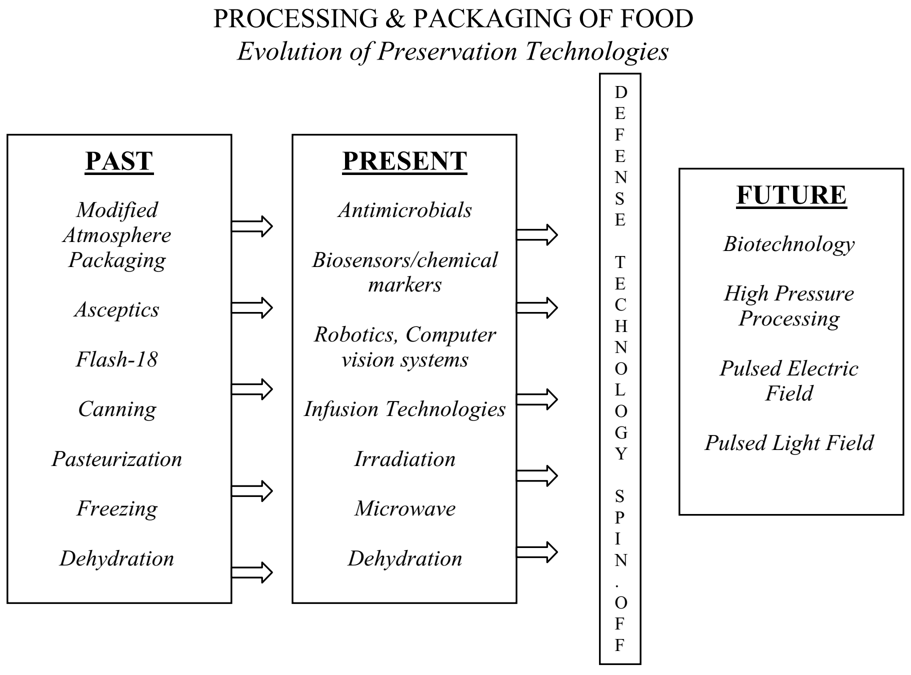

Figure 8 — Evolution of preservation techniques.

Antimicrobial packaging can play an important role in reducing the risk of pathogen contamination, as well as extending the shelf life of foods; it should never substitute for good-quality raw materials, properly processed foods, and good manufacturing practices. It should be considered as a hurdle technology that, in addition with other nonthermal processes such as pulsed light, high pressure, and irradiation could reduce the risk of pathogen contamination and extend the shelf life of perishable food products. Participation and collaboration of research institutions, industry, and government regulatory agencies will be the keys to the success of antimicrobial packaging technologies for food applications.

Food Safety and Quality Assurance

Food safety is receiving more attention worldwide with a rising incidence of foodborne diseases, concern over new potential hazards, and growth in agricultural trade. The concept of food safety in the past excluded elements of nutrition such as known risk factors for certain chronic diseases and nutrients in the form of fortificants and supplements. Concerns about genetically modified foods, functional foods, high levels of nutrient additives, and nutritional supplements are now being taken into consideration in the risk and safety activities of both the FAO and the World Health Organization (WHO).

In this world of plenty, more than 850 million people are undernourished and about 170 million infants and young children are underweight. More than 5 million children die each year as a result of undernutrition. Furthermore, billions of people suffer from vitamin and mineral deficiencies, especially of iron, iodine, vitamin A, and zinc. Good nutrition is also constrained by inadequate safe drinking water and sanitation. At the same time, obesity and other nutrition related chronic disease are becoming a serious problem, even in low-income countries (www.fao.org).

Food safety generally refers to the content of various chemical and microbiological elements in food. More intense consumer awareness of food safety and quality issues, along with government and industry action, is bringing about a more holistic and preventive, food chain approach—sometimes called ''from farm to table''—in many countries, so as to improve traditional food safety systems. FAO has adopted this food-chain approach and defines it as recognition that the responsibility for the supply of safe, healthy, and nutritious food is shared by all stakeholders involved, from primary production to final preparation and consumption.

Hazard analysis and critical control point

Hazard analysis and critical control point (HACCP) is an important quality assurance system. This system ensures that the products are of good quality and safe. The system is extremely desirable in view of the changing scenario in international trade. HACCP is an important requirement for ensuring the quality of products from health and safety aspects and is crucial for exports. Figure 9 shows the importance of HACCP in food processing (http://foodsafetyindia.nic.in).

India has its own standards for the level of contaminants and toxins in food. This standard contains the main principles and procedures that are used and recommended by the Codex Alimentarius in dealing with contaminants and toxins in foods and feeds, and lists the maximum levels of contaminants and natural toxicants in foods and feeds that are recommended by the CAC to be applied to commodities moving in international trade. Codex standards are also available for the analysis of pesticide residues in food items (http://foodsafetyindia.nic.in).

Quality control

Quality control is defined as to maintain the natural identity in the original state without change in its characters, appearance, size, and shape. Food quality is of considerable importance in public health and the national economy. Consumption of improper or substandard quality food grains caused at the time of harvesting, processing, and storage and at the time of distribution may lead to acute and chronic illness to humans and animals. It also reduces the availability of food besides affecting national and international trade and thereby the economy. Besides processing, consumers associations also play a major role in maintaining food quality and safety.

The main objectives of the proposal are to provide quality assurance and analytical services to the food processing industries, to undertake microbiological determinations of various pathogens and mycotoxins and to estimate nutritional parameters including minerals, vitamins, food value in calories, protein carbohydrates, fats, and so on.

Quality assurance

The definition of quality is part of a polemic discussion, since it depends on both subjective and objective factors. The subjective

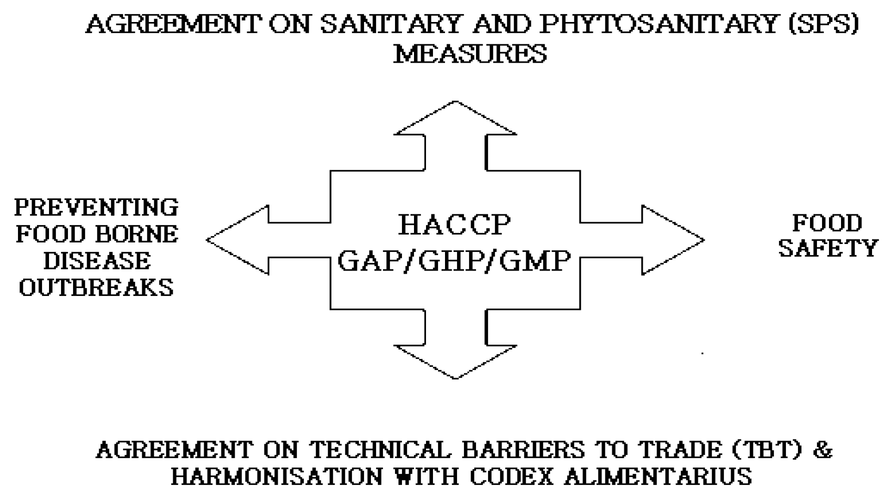

Figure 9 – Importance of HACCP in food processing.

factors include cultural, economic, psychological, religious, and ethical aspects, creating a wide range of quality concepts. The objective factors include standardization of the organoleptic and physicochemical characteristics and food safety assurance (Ilbery and Kneafsey 2000). Quality assurance is included in a preventative approach dealing with all hazards involved in the food processing steps, acting as a control of quality in each step of the process, decreasing the responsibility of the microbial death step, and increasing confidence in the final product, and involving the application of written procedures associated with specific and necessary verifications (Gonçalo 2003). New preservation technologies, such as high-pressure processing and pulsed electric fields offer advantages in meeting consumer demands of freshness, convenience, and safety.

Food Technology and Its Role on Food Prices

Global food consumption currently exceeds production, resulting in the depletion of global stocks of grains, such as wheat and rice, and increasing market uncertainty and price variability. Without a dramatic boost in agricultural productivity, prices will continue to increase. Climate change will also have a negative impact on food production, compounding the challenge of meeting global food demand and potentially worsening hunger and malnutrition among the world's poorest people.

Many regions of the developing world, especially China and India, have seen high economic growth in recent years. Together with an expanding urban population, income growth is altering spending and consumer preferences. Global food demand is shifting from grains and other staple crops to processed foods and high-value agricultural products, such as vegetables, fruits, and meat. Here comes the importance of food technology to minimize the postharvest losses and produce nutritious products at affordable cost to the consumers. Even though the processing operations may cause an increase in the prize of the food items, the increased shelf life and nutritional values can compensate this hike. Although many small farmers would like to take advantage of the new opportunities that such products offer for increasing income, they face serious obstacles to entering markets, including a limited capacity to meet safety and quality standards and produce large quantities for food processors and retailers.

According to the IFPRI report, poor people in developing countries will be adversely affected by both higher prices for food and greater volatility of food prices. Subsidies for biofuels, which are common, increase the negative impact on poor households, as they implicitly act as a tax on basic food. As biofuels become increasingly profitable, more land, water, and capital will be diverted to their production, and the world will face more difficult trade-offs between food and fuel. Second-generation technologies may help cope with these trade-offs, as they utilize biomass waste and in some cases put less pressure on land and water resources. Overall, the majority of poor people, who live in households that are net buyers of food, will be worse off, and increased food prices will make it even more difficult for them to eat healthy, well-balanced diets. The prime aim of new processing techniques should be to provide all consumers with increasing levels of satisfaction and convenience at affordable prices. (CGIAR News 2007)

Food Technology and Future Foods

Recent advances in emerging food-processing technologies, such as high hydrostatic pressure or high-intensity electric field pulses, allow targeted and sophisticated modification and preservation of foods. Today, India is not only self-sufficient but also exports foods and has a reserve because of advances in food technology. Natural food colors, bioactive molecules from plant sources, value addition to the byproducts from various food processing industries, environmentally accepted technologies, and water conservation in processing are the newer areas of development taking place in food technology. Food processing is generally as traditional industry but advances in microelectronics, instrumentation and control, new materials, bioprocessing, and biotechnology are beginning to propel the industry at a faster rate.

Biotechnology in food

Biotechnology is multidisciplinary in approach, involving chemical engineering, modern biochemistry, microbiology, fermentation technology, and genetic enzyme engineering in which the tasks are complex and the benefits are immense. The important area of biotechnology application is the quantitative improvement in foods with nutritionally superior proteins and less or no antinutritional constituents and raw material suitable for processing and preservation. For example, the solids content of tomato has been improved by somaclonal variations. The toxin content of Lathyrus sativus and related peas and beans can now be reduced or eliminated by somaclonal variation. Genetics in baking, wine making, and the production of microbial polysaccharides, enzymes, sweeteners, and flavors is very crucial in food processing and preservation.

Optimal utilization of agricultural resources by agro-based industries through biotechnology will add substantial value to the primary produce, enhance gainful employment, conserve and preserve food, raise nutritional standards, earn more foreign exchange, and better the quality of life and self-reliance of the country.

Biofortification

Biofortification can provide ongoing benefits throughout the developing world at a fraction of the recurring cost of either supplementation or postproduction fortification. The introduction of biofortified crops, varieties bred for increased mineral and vitamin contents would complement existing nutrition approaches. It offers a sustainable and low-cost way to reach people with poor access to formal markets or health care systems. Biofortification makes sense as part of an integrated food systems approach to reducing malnutrition. It addresses the root causes of micronutrient malnutrition, targets the poorest people, uses built-in delivery mechanisms, is scientifically feasible and cost-effective and complements other ongoing methods of dealing with the micronutrient deficiencies.

Nutraceuticals

The word combines "nutrition" and "pharmaceuticals" to mean that food extracts can be used as preventive drugs or food supplements. Science has added knowledge about the disease-preventing phytonutrients present in foodstuffs. The major phytonutrients identified to have neutraceutical properties include terpenes, phytosteroles, phenols, and thiols. A nutraceutical is any substance that is a food or a part of a food and provides medical or health benefits, including the prevention and treatment of diseases. Such products may range from isolated nutrients, dietary supplements, and specific diets to genetically engineered designer foods, herbal products, and processed foods such as cereals, soups, and beverages. These natural substances are found in food and have medicinal properties to treat or prevent certain diseases. These natural substances can be added to the diet by increasing your consumption of certain foods, or they can be taken as nutritional supplements. Nutraceuticals must not only supplement the diet, but should also aid in the prevention and/or treatment of diseases and/or disorders.

Space foods

Space foods should be nutritious, appealing, and palatable. They should be light in weight, low in volume, and possess the property of resistance to crumbling. Any crumbs or liquid that might get loose in a spacecraft would float and could become a hazard. Bite-sized particles solve the problem of crumbling. At zero gravity, water will not pour out of a container, it has to be forced. When an astronaut is thirsty, use must be made of a plastic tube containing soup, tea, coffee, milk, cocoa, or fruit juice all reconstituted from dehydrated food.

A water dispenser is used for rehydrating foods and the galley oven is used for warming foods. Rehydrated items reduce the weight of the substance. Foods packaged in rehydratable containers include soups like chicken consommé, cream of mushroom, casseroles like macaroni and cheese or chicken and rice, and breakfast foods like scrambled eggs and cereals. Breakfast cereals are prepared by packaging the cereal in a rehydratable package with nonfat dry milk and sugar if needed.

Conclusions

Improving food technology not only improves health but also reduces poverty. When food products are safe, nutritious, well marketed, and competitively priced, thanks to efficient manufacturing, they attract consumers. Rising consumer demand, in turn, expands a nation’s entrepreneurial base in food products, creating jobs, and raising family incomes. Larger family food budgets then contribute to a further drop in malnutrition. New preservation technologies, such as high-pressure processing and pulsed electric fields offer advantages in meeting consumer demands of freshness, convenience, and safety. There is no single process that will allow the high-quality production of every food product while ensuring safety; all of these processes as well as thermal processing have their own set of limitations and advantages.

References

Barbosa-Canovas GV, Pothakamury UR, Palou E, Swanson BG. 1998. Nonthermal preservation of foods. New York: Marcel Dekker, Inc.

Barbosa-Cánovas GV, Gongora-Nieto MM, Pothakamury UR, Swanson BG. 1999. Preservation of foods with pulsed electric fields. London, U.K.: Academic Press Ltd. p 1–9, 76–107, 108–55.

Bender AE. 1978. Food processing and nutrition. London, U.K.: Academic Press.

CGIAR News. (2007). Nourishing the future through scientific excellence, December 2007.

Chandrasekhar U. 2004. Soy proteins—an ideal functional food for growth promotion. Proc Nutr Soc Aust, Vol. 28. Asia Pac J Clin Nutr 13(Suppl):S118.

Directorate General of Health Services, Ministry of Health and Family Welfare, Government of India, New Delhi. 2008. Food Safety India. New Delhi, India: Government of India. Available from: http://foodsafetyindia.nic.in.

Feng H, Tang J, Cavalien RP. 1999. Combined microwave and spouted bed drying of diced apples: effect of drying conditions on drying kinetics and product temperature. Drying Technol 17(10):1981–98.

[FAO] Food and Agriculture Organization. 2001. Technical elements of new and emerging non-thermal food technologies. Available from: <http://www.fao.org/ag/ags/agsi/Nonthermal/nonthermal 1.htm>.

Gonçalo EB. 2003. Certificação de sistemas de qualidade na indústria de laticínios. Revista Inst. Laticinios Cândido Tostes 58(333):9–14.

Henry CJK, Heppell N. 2002. Nutritional losses and gains during processing: future problems and issues. Proc Nutr Soc. 61:145–8.

Hofmann GA, inventor; Maxwell Lab., Inc., assignee. 1985 Jun 18. Deactivation of microorganisms by an oscillating magnetic field. U.S. patent 4,524,079.

Ilbery B, Kneafsey M. 2000. Producer constructions of quality in regional speciality food production: a case study from South West England. J Rural Stud 16(2):217–30.

Karmas E, Harris RS. 1998. Nutritional evaluation of food processing. 3rd ed. New York: Van Nostrand Reinholfd.

Moreau C. 1995. In: Ledward DA, Johnston DE, Earnshaw RG, Hasting APM, editors. High pressure processing of foods. Loughborough, Leicestershire, U.K.: Nottingham Univ. Press. p 181–97.

Qiu X, Sharna S, Tuhela L, Jia M, Zhang QH. 1998. Unpublished data. An integrated PEF pilot plant for continuous nonthermal pasteurization of fresh orange juice. Columbus, Ohio: Food Science and Technology Dept., Ohio State Univ.

Ruecroft G. 2007. Power ultrasound, crystals and particle engineering, Paper presented at “Chemsource Symposium 2007” during 27th & 28th June, at RAI, Amsterdam.

Zhang M, Xu YY. 2003. Research developments of combination drying technology for fruits and vegetables at home and abroad. J Wuxi Univ Light Ind 22(6):103–6.

COMPREHENSIVE
REVIEWS
IN FOOD SCIENCE AND FOOD SAFETY

Millet as "Religious Offering" for Nutritional, Ecological, and Economical Security

Anil Joshi, Kiran Rawat, and Bhawana Karki

ABSTRACT: The initiative denoted "offering" for nutritional, ecological, and economic security was taken to utilize local crops as a source of employment for the local community. This was started in the state of Uttarakhand, India. The initiative targeted the shrines in the state and across the country for utilizing the value-added products made from local crops in the form of offerings in places of worship. A market was developed for the products made from local millets and coarse grains through value addition. This created a market for the products and provided a source of income to the local community. There was a gradual change in localities as local products replaced shrines urban products. The better market encouraged people to grow the traditional crops and thus the ecology of the region was also sustained. Considering the fact that India is a religious country and "offering" is a huge market, the link between the shrine's offering and local products from producers was promoted. In a population of more than a billion, the market is extremely huge and still untapped. Thus, the approach is unique in its own way. This was also a solution to meet the nutritional requirements of the people of a region which otherwise was taken care of by the traditional crops in the region. The traditional farming, which is considered ecologically more sound, was promoted under the "ecological food security mission" of HESCO. The revival of traditional agro-practices was done based on science and technology and the ecological balance in the region was maintained.

Introduction

Local produce has everything to do with local human metabolism. Buck wheat and *amaranthus* in higher altitudes meet the higher body energy requirements in the cold. Changes from the traditional diet in past decades have developed several nutrient and energy deficiencies in local rural communities. It should not be ignored that local environment is the ultimate governing factor. And since local agriculture and consumption needs are also governed by this single factor, the understanding of these intricacies must be reflected in agricultural policy and food security initiatives and should not be limited to a couple of grains only.

Millets are important as far as ecological security is concerned. They are suited well for regions under environmental stress. Millets occupy a lower position in food crops, but they are important ecological food security crops for different agro-climatic conditions. They are known for their nutritional quality and can be an immediate subsistence food for a nutrient-scarce community. For the last 5000 y, millets have been grown worldwide up to the beginning of modern agriculture; millets were the only dry-land crops. India is a major millet-producing country in the world. Millets are also called coarse grains and because of their higher nutritive values are also called nutri-cereals. India grows mainly *jowar, bajra, ragi, kodo* (finger millet), foxtail millet, and proso millet among other varieties.

Millets are also called ecological crops as they can withstand severe environmental stresses. They are grown in diverse soils, under varying rainfall, and in areas where thermo- photoperiods may vary greatly. They can be grown in different ecological niches and whenever crop substitution is difficult, one can always grow millets. These groups of plants secure food and nutritional security. Of course, these millets are grown for human consumption, but their straw is also important as fodder.

Millets in the mountain systems

All mountain systems are fragile, vulnerable, and marginal; only eco-friendly crops are important. Besides several local resources, ecological food is also on the brink of disappearance.

MS 20080191 Submitted 3/13/2008, Accepted 6/2/2008. Authors are with Himalayan Environmental Studies and Conservation Studies (HESCO), Shuklapur, Ambiwala, Premnagar, Dehradun, Uttarakahand 248001, India. Direct inquiries to author Joshi (E-mail: dranilpjoshi@yahoomail.com, dranilpjoshi@gmail.com).

Agriculture has been replaced with agri-commerce in most parts of the world. An increasing population necessitates high production of grains to cater to the food needs of the masses, but at the same time we must produce more and more from a limited piece of land. This fact has also been a prevalent feature in global farming resulting in ecological misbalances. Important developments have occurred recently to change the farming pattern traditional to commercial crops, or from millets to cereals or other economic crops. The local culture of farming has changed to nonecological commercial farming, which has led to several anomalies. Ecological balance was much more needed with the agro-farming systems, but attention to such a balance in regional ecological processes has been totally neglected. Unfortunately, tradition and local culture in agriculture, which was an essential part of ecological balance created through ages, has given way to commercial ventures.

Commercial farming has also penetrated into rural India where age-old agriculture is considered backward and unproductive. Traditional food/grains/millets have been loosing their importance. The Green Revolution in India has been diverse and ecologically suitable. It has been mainly commercial and it has turned out most useful to big farmers only. It was never thought that besides total farm productivity of the country, ecological quality was equally significant. Farmers of an area are dependent on locally produced seeds and produce such crops that are life-support crops for self-consumption suiting their own body chemistry in view of the peculiar geographic and climatic conditions. Can there be grains/cereals to cover food scarcity over the globe? Why should there not be regional specific food millet initiatives to cover national food security? It is because a few countries or farmers produce a particular grain crop and their surpluses become outlets for food security initiatives.

Keeping this view in mind, the "offering" initiative was taken because it involved tapping resources in the form of coarse grains and millets that are grown in the mountainous regions and also generate local employment "offering" in its simplest meaning is the "Gift That a Devotee Offers to God. People have the deepest regard and faith in it. It is regarded as God's blessing, so the devotee offers it to God and takes a bit back home. The fact that India is a religious country and "offering" is a huge market; the link between a shrine's offering and local products from local produce was promoted. Assuming that on average a person spends around a minimum of 100 rupees in a year for the purpose of offering, in a population of more than a billion, the market is extremely huge and still untapped. Thus, the approach is unique in its own way. Thus a country like India where offering is an integral part of religion, a local employment can be planned by generating offering from local resources.

Methodology/Approach

Some important things were considered before introducing the concept among people and this led to a very unique and successful initiative "offering" for the people. Some of the facts taken into account were:

- The mountains are rich in coarse grains and millets.
- Due to commercial agriculture replacing traditional agriculture ecological faming was close to disappearance.
- Traditional crops meet the nutritional requirements of the people specific to a region.
- The mountains have numerous places of religious importance.

An attempt was made to link the production of traditional crops to local needs in a way that the nutritional requirements are met and the community is improved economically.

Nutri- cereals-specific to the state of Uttarakhand

Small millets are highly nutritious and even superior to rice and wheat in certain constituents (Table 1). Finger millet is the richest source of calcium (300 to 350 mg/100 g grain).

Small millets are a good source of phosphorus and iron. The protein content ranges from 7% to 12% and fat content from 1.12% to 5.0%. Millet protein has a well-balanced amino acid profile and is a good source of methionine, cystine, and lysine (Table 2). These essential amino acids are of special benefit to those who look upon plant foods for their sole protein nourishment.

The rate of increase in the production of millets has been low as compared to the rate at which wheat and rice production has increased in India (Table 3). There are reasons for it. People started considering millet as a poor man's crop and the Green Revolution made farmers to favor crops that fetch good returns.

The need of value addition

The possible nutria-combination of millets that HESCO has initiated for different recipes is on the way. HESCO with the help of the Central Food Technology Research Inst. (CFTRI, Mysore, India) has developed many protocols in this regard. It has made snacks mainly as the immediate option for children. Calcium, vitamins, and protein appear in these products that also contain minerals and other micronutrients used in the combinations are amaranthus, foxtail millet, finger millet, local wheat, soybeans, and other local crops in various proportions. There are 3 major combinations initially proposed to cover nutritional security. The method was kept simple and emphasis was laid on making the product last for a long time and to be good in taste.

One such protocol developed was Sweet Ball (Laddoo)—Figure 1. Under this protocol, the flour is toasted in a pan until it turns light brown. In 100 g of toasted flour, 40 g sugar

Table 1 — Nutrient composition of millets and cereals (per 100 g).

Food grain	Protein (g)	Carbo-hydrates (g)	Fat (g)	Crude fibre	Mineral matter (g)	Calcium (mg)	Phosporus (mg)	Fe (mg)
Millets								
Finger millet	7.3	72.0	1.3	3.6	2.7	344	283	3.9
Kodo millet	8.3	62.0	1.4	9.0	2.6	27	188	12.0
Proso millet	12.5	70.4	3.1	7.2	1.9	14	206	10.0
Foxtail millet	12.3	60.9	4.3	8.0	3.3	31	290	5.0
Little millet	7.7	67.0	4.7	7.6	1.5	17	220	6.0
Barnyard millet	6.2	65.5	2.2	9.8	4.4	11	280	15.0
Cereals								
Wheat	11.8	71.2	1.5	1.2	1.5	41	306	5.3
Rice	6.8	78.2	0.5	0.2	0.6	45	160	—

Source: FAO. 1970, Rome, Italy, Nutritive value of Indian foods, 1998, NIN, Hyderabad, India.

in powder form is mixed in an open pan. The mixed powder is mould to *laddoo* with the help of the ghee.

The approach was a stepwise procedure mentioned as under.

- The 1st step was identification of the available crops, their status, along with the economic condition of people, and location of the nearest shrine. A general socio economic and market survey and talks with farmers helped in selection of the site. Secondary data were also used for the purpose.
- The next step was interaction with the community, which involved motivating them and explaining to them the concept. This involved a number of exercises like frequent meetings, discussions, and formation of groups in the selected site area.
- The villagers agreed on starting with the idea, and later on local authorities were approached. The authorities included the Temple committee and the Shrine Board, which take care of their respective places of worship. This was important for providing the Groups a market. An agreement between the authorities and the groups was made.
- Once the deal was made, the respective Board or authority asked for a set number of products in a specific time period. They decided to launch the "offering" made by the locals, with the local produce along with the usual offering.
- The groups were trained accordingly and initially HESCO remained with them for support.
- In due course, the "offering" made in the form of *laddoo* (or "sweet ball") became popular because:

Table 2—Essential amino acids in millets and cereals (g/100 g of protein).

Amino acids	Finger millet	Kodo millet	Proso millet	Foxtail millet	Barnyard millet	Wheat	Rice
Isoleucin	4.4	3.0	8.1	7.6	8.8	3.3	3.8
Leucine	9.5	6.7	12.2	16.7	16.6	6.7	8.2
Lysine	2.9	3.0	3.0	2.2	2.9	2.8	3.8
Methionine	3.1	1.5	2.6	2.8	1.9	1.5	2.3
Cystine	2.2	2.6	1.0	1.6	2.8	2.2	1.4
Phenyl alanine	5.2	6.0	4.9	6.7	2.2	4.5	5.2
Tyrosine	3.6	3.5	4.0	2.2	2.4	3.0	3.9
Threonine	3.8	3.2	3.2	2.7	2.2	2.8	4.1
Tryptophan	1.6	0.8	0.8	1.0	1.0	1.5	1.4
Valine	6.6	3.8	6.5	6.9	6.4	4.4	5.5
Histidine	2.2	1.5	1.9	2.1	1.9	2.3	2.4

Source: FAO. 1970, Rome, Italy, Nutritive value of Indian foods, 1998, NIN, Hyderabad, India.

Table 3—Annual production of rice, wheat, and millets in India, 1951–1979 (million metric tons).

	1951	1961	1971	1976	1979
Rice	20.6	34.6	42.2	48.7	53.8
Wheat	6.4	11.0	23.8	28.9	35.0
Millets[a]	12.9	20.7	27.8	26.2	27.1

[a] Bajra, barley, jowar, maize, ragi, and small millets.
Source: Agricultural Situation in India, 1980.

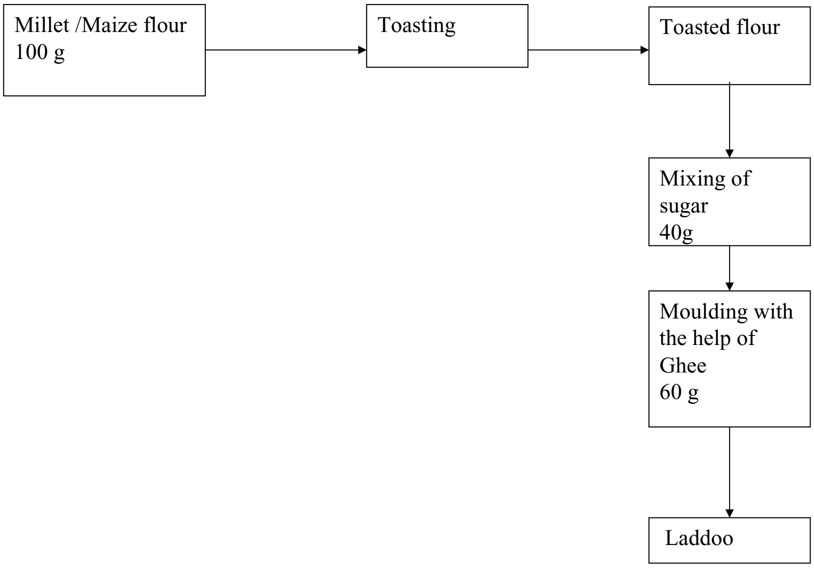

Figure 1—Sweet Ball (Laddoo).

    - It was unique and different from the usual offering
    - It gave the region an identity
    - The offering had longer shelf life and was
    - Good in taste
- After it flourished, HESCO stepped back and the groups started dealing with the authorities directly.

After the initiative was successful in 1st place, it was replicated in other places as well.

Case Studies

The initiative of "offering" started at several places. Village Parthal is located at the bottom of shrine Vaishnav devi in Jammu & Kashmir state of India. This village is economically independent today as it has an annual turnover of Rs 3.6 million ($84033.73). The village was dependent on local agriculture and maize was the principal crop grown in the region. The maize did not give them a good return in the market and this made it difficult for farmers to continue with it and were looking for an alternative. When approached with the idea of utilization of the crop in making of a value-added product, which could be offered in the shrine, the locals were a bit skeptical about it in the beginning. However, HESCO with the help of CFTRI developed a protocol for making sweet balls from the maize. Locally, it is called "*laddoo*." After the protocol was ready and people agreed with the idea, the Shrine Board was approached and a deal between the Board and locals was finalized according to which the Board agreed to take a fixed number of packages from the locals to sell to the pilgrims. This started 5 y ago and a group was formed in the village with the name "Vaishanavi Mahila Dal" as women were the partner.

The village today stands as an example and many other villages have followed its footsteps. Starting with supplying the product to just 1 shrine, today the group supplies other places and has targeted local consumption as well. The group is more organized today and is able to give employment to numerous needy, unemployed persons.

Village Saldhar of state Uttarakhand is located in Joshimath block. The main population is of tribals. The great temple Badrinath is about 60 km from this village. The local offering has attained a turnover of Rs 0.1 million ($2334.27).

Buck wheat and Foxtail millet has been the staple diet of this community. They make chapati, *halwa*, and delicious sweets out of it. The knowledge and training on value addition have brought a difference in their lives in terms of health, economics, and well-being. The women group "Mahila Mangal Dal" formed in the village also started preparing the "offering" for Badrinath, one of the most important shrines of Hindus. The temple committee was approached for marketing inputs that followed with the production. In spite of poor local support, the women launched the new offering in the temple. A shop has been allotted to women at shrine premises. This has helped women to fetch a turnover of Rs 0.1 million ($2334.27).

Table 4—Other case studies.

Name of shrine	State	Crop use	Turnover
Kedarnath	Uttarakhand	Amaranthus	0.1 million ($2334.27)
Shahadra Sharif	Jammu & Kashmir	Maize	0.9 million ($42100.84)
Kalihar Sharif	Uttarakhand	Maize and wheat	0.5 million ($1167.14)

There are many other villages that have started offering as an employment as well nutritional security initiative. Table 4 describes in details, the villages, state, crop use, and turnover.

Results

- Similar initiatives have been taken in other places all over India and in all kinds of shrines: temple, mosque, church, and monastery.
- Fifteen hundred families of 38 villages of the district Chamoli, Rudraprayag, and Tehri of Uttarakhand are back on millet production. These communities grow 7 species with 40 varieties. They have revived their age-old agriculture.
- The economic condition of the local people has improved.
- The traditional farming practices have improved due to a better market for the value-added products made from the local produce.

Discussion

Millets and other crops are less known for technology development due to lower importance and recognition by development agencies. These technologies have been limited and there is a vast untapped potential or productivity potential in these crops.

There are 2 major steps that warrant immediate attention. Every agro-climatic zone has its agro-produce that also suits the local human needs and tastes. The agro-produce here has an age-old link with climate, soil, and microenvironment. The distortion in agri-patterns in many places has ruptured ecological sustainability. The local agriculture pattern otherwise has strong environmental relations both with nature and humans for such an ecosystem. Encouraging such crops means sustaining ecological functioning. Nutritionally, these millets are not less than any crop and are richer in certain aspects. For utilizing them properly, value addition was important and much needed, because this we thought would develop a better market for the products. The already available products gave a tough fight and to replace them involvement of the locals was important, as they were the best judge and knew the market scenario well. The "offering" initiative was not that easy as it may seem because this involved religion, which is directly related to the people. Initially the opposition came from all spheres of society and because of different reasons. The opposition came from the local shopkeepers who were selling the old offering coming from the urban area. Opposition came from the temple committees. There was a difficulty in convincing the people of villages as some agreed, but a larger group stood firm against the idea.

The value addition in the local produce gave a good alternative to the urban products. It also revived the traditional cropping system. Farmers began to grow the traditional crops because now they have a better market for the produce. Selling the value-added products in the form of "offering" also provided people with a steady source of income, and the products were nutritionally rich as well.

The good thing that came up was that with the passage of time the initiative was a great success and was disseminated to other places as well, and now it is being tried all over the country.

Acknowledgment

The authors are grateful for technology and financial support forwarded by CFTRI, Mysore, India and Dept. of Biotechnology, New Delhi, India. They are also indebted to senior scientists, team of HESCO, and shrine committee for their support and guidance.

COMPREHENSIVE
REVIEWS
IN FOOD SCIENCE AND FOOD SAFETY

Food-Based Approaches for Ensuring Adequate Vitamin A Nutrition

Sherry A. Tanumihardjo

ABSTRACT: Efforts to improve vitamin A (VA) status globally have included supplementation and food fortification. Periodic supplementation results in a cyclic pattern of changing liver VA reserves. Fortification causes a gradual increase in VA liver reserves, but the potential for hypervitaminosis A is present because it is delivered as the preformed vitamin. Programmatically, food-based approaches to improve VA status are often overlooked. In part, this is due to perceived poor bioavailability of provitamin A carotenoids from fruits and vegetables and to costs associated with program implementation. However, the bioconversion rate of β-carotene to VA decreases when liver reserves are adequate, mitigating the potential for hypervitaminosis A with food-based approaches. Biofortification of staple crops with β-carotene is an emerging strategy to improve VA status in groups at risk of deficiency. Extrapolations from published human and animal studies estimated the potential of biofortified sweet potato and maize to improve VA status of a model boy and adolescent girl compared with supplementation or fortification. A male child (age 0.5 to 4 y) at the 50th percentile of weight-for-age and an adolescent girl (age 13 to 19 y, body weight 35 to 45 kg) were used to calculate liver size and VA accumulation in response to an intervention. In these simulations, a daily sweet potato portion results in a higher relative increase in liver VA concentrations of infants than daily supplements. Biofortified maize consumption caused a steady increase in VA liver concentrations in both model children. In conclusion, provitamin A sources from multiple foods can improve VA status without the potential for hypervitaminosis A.

Introduction

Efforts to improve vitamin A (VA) status globally have included supplementation (Sommer and Davidson 2002) and food fortification (Dary and Mora 2002). Less emphasis has been placed on diet diversification. This is due, in part, to the perceived belief that provitamin A carotenoids from fruits and vegetables are not very bioavailable (de Pee and others 1995). Many factors affect the bioavailability of provitamin A carotenoids (Tanumihardjo 2002). Over 600 carotenoids have been identified in nature and about 50 provide VA. The major provitamin A carotenoids found in fruits and vegetables are α-carotene, β-carotene, and β-cryptoxanthin (Figure 1). Recent studies in humans using sensitive methodology to determine total VA stores demonstrate that inclusion of orange fruit and vegetables will maintain (Tang and others 1999) or improve VA status (Ribaya-Mercado and others 2007). As little as ½ cup of sweet potato on school days improved liver VA reserves in school-aged children in South Africa (van Jaarsveld and others 2005).

Over 250 million children in the world under the age of 5 y have VA deficiency (WHO 2003) and supplementation programs are a common and effective approach to address this issue (Ross 2002; Sommer and Davidson 2002). However, supplementation programs involve recurrent costs each year that include not only the VA supplements, but also human resources for distribution and monitoring of the programs (Neidecker-Gonzales and others 2007). Food fortification with preformed VA has been successful in Central America (Dary and Mora 2002) and is being adopted in other parts of the world. For food fortification to succeed, the food or condiment needs to be widely consumed and manufactured in only a few factories or distributed centrally. Issues with VA fortificants include stability, continued quality control (Dary and Mora 2002), and monitoring of population status to ensure adequate and not excessive levels of total body VA (Ribaya-Mercado and others 2004; Vitamin A Tracer Task Force 2004).

Biofortification of staple crops with β-carotene has emerged rather recently and is a potential long-term, sustainable approach to improve VA status in humans (Howe and Tanumihardjo 2006a, 2006b). While biofortification of staple crops could be considered a form of dietary diversification, it differs in that it nutritionally

---

MS 20070903 Submitted 12/5/2007, Accepted 2/13/2008. Author is with Dept. of Nutritional Sciences, Univ. of Wisconsin-Madison, 1415 Linden Drive, Madison, WI 53706, U.S.A. Direct inquiries to author Tanumihardjo (E-mail: sherry@nutrisci.wisc.edu).

improves the main energy sources of the diet without the addition of complementary foods. Nutritionists do not dispute the benefits of a diversified diet, but it is often difficult to achieve this idealized diet in resource-poor areas of the world (Tanumihardjo and others 2007). Crops that have been targeted for biofortification with provitamin A carotenoids include sweet potato (van Jaarsveld and others 2005), maize (Howe and Tanumihardjo 2006a, 2006b), cassava, and rice. Traditional breeding methods have been used for sweet potato, maize, and cassava; and efforts with rice have focused on genetic engineering (Yonekura-Sakakibara and Saito 2006). Substantial levels of β-carotene are present in many varieties of sweet potato and regular consumption does improve VA status (Haskell and others 2004; van Jaarsveld and others 2005). Current efforts include finding sweet potato varieties that are well accepted by target groups and educating individuals to purchase and consume orange varieties (Low and others 2007). Provitamin A levels in maize have reached 15 μg β-carotene equivalents (βCE) per gram dry weight and varieties are being adapted to tropical climates that have 10 μg/g dry weight (Harjes and others 2008). Animal studies show that the biofortified "orange maize" is efficacious in maintaining VA status (Howe and Tanumihardjo 2006a; Davis and others 2008).

Preschool-age children are at the highest risk for having inadequate diets mainly due to lack of dietary diversity (Allen 2006). The objectives of this review were, first, to summarize studies with animals and humans fed provitamin A sources and then to apply this study to models to predict changes in liver VA concentrations of preschool and adolescent children after various VA interventions. The 1st evaluation compared potential increases in VA liver reserves of a model infant fed micronutrient tablets (Nestel and others 2003) or sachets such as "Sprinkles" (Sharieff and others 2006; Sprinkles Global Health Initiative 2007) with a daily serving of orange-fleshed sweet potato (van Jaarsveld and others 2005). The 2nd evaluation determined the change in liver VA concentration in a boy, 1 to 4 y old, who had eaten biofortified maize, received twice yearly 200000 IU supplements, or consumed fortified sugar for a 3-y period. Finally, fortified sugar and biofortified maize consumption were compared in an adolescent girl from age 13 to 19 y using maize with 2 provitamin A concentrations at different dietary intakes.

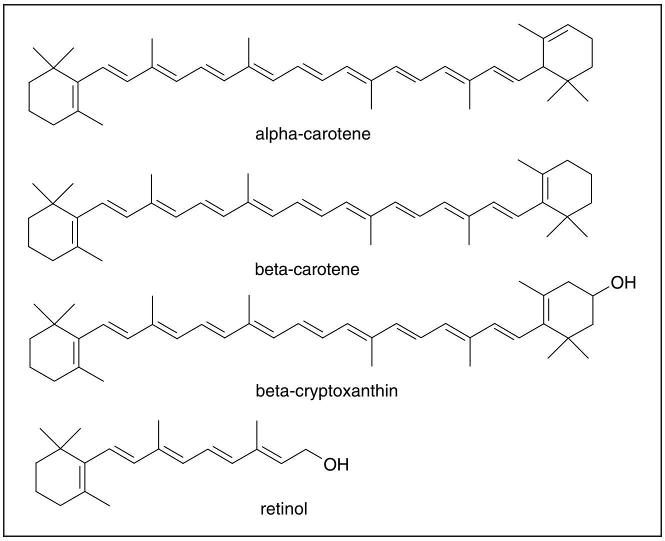

Figure 1 — Chemical structures of the 3 main provitamin A carotenoids found in fruits and vegetables compared with vitamin A (retinol).

Animal Models to Study Provitamin A Activity

Most mammals will model VA metabolism; however, animal models to study provitamin A carotenoids are few. The closest animals to model the carotenoid metabolism of humans are perhaps chimpanzees or orangutans with the exception of the hydrocarbon carotenoid lycopene (García and others 2006). Studies such as these are rare because of the high cost of implementation. Other monkeys have been used to study VA metabolism, but many monkeys in primate centers suffer from hypervitaminosis A induced by fortified feed (Penniston and Tanumihardjo 2001, 2006; Penniston and others 2003; Mills and others 2005; Mills and Tanumihardjo 2006). Such a model is not appropriate because interest in use of provitamin A food sources is aimed at improving VA status in countries at risk of VA deficiency. Other models that have been proposed include the ferret (Lee and others 1999), preruminant calf (Poor and others 1992; Hoppe and others 1996), and Mongolian gerbils (Lee and others 1998). Mongolian gerbils are not useful for studying the bioavailability of the xanthophyll carotenoids lutein and zeaxanthin (Molldrem and Tanumihardjo 2004; Escaron and Tanumihardjo 2006), but they have great utility in the study of provitamin A carotenoids (Tanumihardjo and Howe 2005; Porter Dosti and others 2006; Davis and others 2008). Each model has its advantages and disadvantages. In contrast to humans, Mongolian gerbils are useful models because liver VA reserves can be measured directly. In humans, liver sampling is only justifiable in certain cases. Indirect methods exist to determine total body reserves of VA but the methods are costly and often prohibitively sophisticated (Vitamin A Tracer Task Force 2004).

A series of studies was performed in Mongolian gerbils to assess the relative bioavailability of provitamin A carotenoids and determine bioconversion factors for several foods. Bioconversion factors are usually expressed as μg β-carotene to 1 μg retinol. Current bioconversion factors used for a mixed diet are 12 μg β-carotene and 24 μg α-carotene or β-cryptoxanthin to 1 μg retinol (Inst. of Medicine 2001). The foods tested in gerbils included orange, purple, and red carrots (Porter Dosti and others 2006; Mills and others 2007); kale, spinach, and brussels sprouts (Arscott and others 2007); orange maize (Howe and Tanumihardjo 2006a); yellow cassava (Howe and Tanumihardjo 2007); and orange sweet potato (unpublished observation). Most gerbil studies are comprised of a negative control group and 1 or 2 positive control groups that may include a VA and/or β-carotene supplement. By compiling the data from these gerbil studies, the bioconversion factor was highly correlated to the total liver VA reserves (Figure 2, $R = 0.885$). Therefore, it seemed quite clear that VA status was driving conversion of β-carotene to VA from the foods tested (Tanumihardjo and Howe 2007). This was further supported by the fact that as liver reserves increased, more β-carotene was detected in the gerbils (Howe and Tanumihardjo 2006a; Porter Dosti and others 2006). From these studies, it was demonstrated that provitamin A carotenoids were absorbed and converted to VA as needed, mitigating the potential for hypervitaminosis A from provitamin A food sources. Even when provitamin A carotenoids were fed from high-carotene carrots at more than double the amount, VA liver reserves were only 10% higher than regular orange carrots (Porter Dosti and others 2006).

Human Studies to Determine Bioconversion of Provitamin A Carotenoids to VA

A green leafy vegetable feeding study in Indonesian lactating women did not show improvement in VA status (de Pee and others 1995). Another trial in Ghana using indigenous African eggplant leaves did show a continuous improvement in liver reserves with feeding (Tchum and others 2006). Both interventions used the modified relative dose response test to indirectly evaluate liver VA reserves (Vitamin A Tracer Task Force 2004). Two major differences between the Indonesian and the Ghanaian postpartum women were that the Indonesian women had poorer VA status at baseline and they were fed less vegetable per day, that is, 100 to 150 g compared to 200 g. Therefore, an overall change to adequate VA status may not be expected, especially when the intervention group is considered VA-deficient and lactating (Tanumihardjo 2001). The modified relative dose response test distinguishes between subclinical VA deficiency and adequate VA status, but it does not distinguish between different degrees of VA adequacy and toxicity (Tanumihardjo 2004).

Since the time of the study by de Pee and others (1995), several studies have been performed with vegetables that have used very sensitive indicators of VA status (Furr and others 2005). One of these indicators is termed the "paired stable isotope dilution technique" where total body VA reserves are measured before and after an intervention (Haskell and others 2005b). Tang and others (1999) measured the VA pool size of Chinese school-aged children with low VA status before and after a food-based intervention using either green and yellow vegetables or light-colored vegetables. In this study, the total body VA pools decreased in children who were fed light-colored vegetables but remained constant in children who were fed green and yellow vegetables. The calculated equivalence was 26.7 μg β-carotene:1 μg retinol (range 19:1 to 48:1). Haskell and others (2004) compared the relative change in total body VA to estimate the VA equivalency of carotenoids from several food sources in Bangladeshi men with low to adequate VA status. The β-carotene to retinol equivalency factors were estimated as 13.4 μg beta-carotene:1 μg retinol for sweet potato, 9.5:1 for Indian spinach (*Basella alba*), and 6.3:1 for pure β-carotene in oil.

Parker and others (1999) measured the dilution of deuterium-labeled retinol by carotenoids from raw carrot in individuals with adequate pool sizes and estimated 13 μg β-carotene:1 μg retinol. Tang and others (2005) used carrots or spinach grown hydroponically in deuterated water and compared the isotope ratio of carotenoid-derived retinol with that of an extrinsically labeled retinol tracer in adult human subjects. They estimated 29 μg β-carotene:1 μg retinol from spinach and 19:1 for carrots. The findings in humans, as well as animals, are further supported by a study in Filipino school children that found conversion of provitamin A carotenoids to VA varies inversely with VA status as measured by a 3-d paired stable isotope dilution test (Ribaya-Mercado and others 2000). The variation in the estimated bioconversion factors may further be explained by localization of the β-carotene in the plant matrix, food preparation techniques, or the presence of intestinal parasites (Furr and others 2005). Although some fat is needed for absorption of provitamin A carotenoids, fat does not seem to be a limiting factor for general meal composition (Ribaya-Mercado and others 2007).

Edwards and others (2001) used deuterium-labeled retinyl acetate as an extrinsic reference to estimate bioefficacy of conversion of food β-carotene to retinol. Van Lieshout and others (2003) analyzed the feces of children who were given an extrinsic isotopic label at the same time as pumpkin or spinach and concluded that β-carotene from pumpkin was more bioavailable than that from spinach. Parker and others (1997) used uniformly labeled ^{13}C-β-carotene isolated from algae grown in a $^{13}CO_2$ environment. Kelm and others (2001) and Kurilich and others (2003) have studied absorption and metabolism of lutein and β-carotene derived from kale labeled with $^{13}CO_2$. Therefore, sophisticated methodology has improved our ability to assess the VA value of provitamin A carotenoids in a variety of systems.

Application of Animal and Human Data to Extrapolate Improvement of VA Status with Food Sources of Provitamin A Carotenoids

Results from several human and animal studies (described above) were applied to models to evaluate and compare changes in liver VA concentrations of children in response to a provitamin A-containing food, food fortification, or supplement interventions. Microsoft office Excel (2003; Microsoft Corporation, Redmond, Wash., U.S.A.) was used for all calculations and simulations with specific assumptions unique to each model (described subsequently). The graphs were constructed using 1- or 3-mo

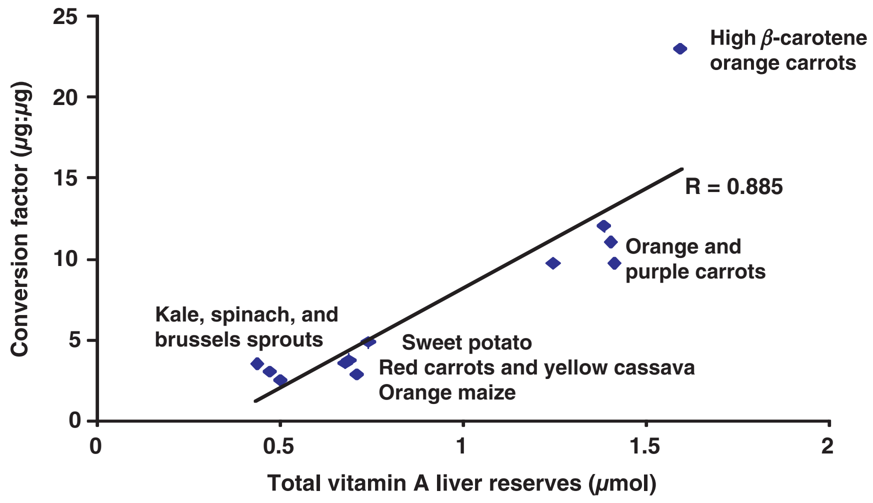

Figure 2—The linear relationship of total vitamin A liver reserves from multiple studies in Mongolian gerbils to the conversion factor of μg β-carotene to μg vitamin A. As vitamin A status improves, less provitamin A carotenoids are cleaved into vitamin A and more β-carotene is stored intact in the liver.

intervals. In all models presented, the assumption is that the liver VA reserves of the model undergoing the intervention are low and liver reserves increase or decrease from a normalized level. Furthermore, the hypothesis is that the daily β-carotene consumed from the food will first meet the VA needs of the model and excess β-carotene above this requirement will be converted at different rates depending on the liver reserves of the person. Calculations were performed in μg quantities and liver VA concentrations are presented using the formula weight of retinol, which is 286 μg = 1 μmol. The model child used for the first 2 analyses was a male and his age ranged from 6 mo to 4 y depending on the simulation. The body weight at each age interval chosen for extrapolation of liver weight (Table 1) was the 50th percentile of the WHO weight-for-age for boys (WHO 2007). Liver weight was calculated to be 4% of body weight (Tanumihardjo 2001). The 3rd and 4th analyses used an adolescent girl, aged 13 to 19 y. Her initial body weight was 35 kg and increased 2 kg/y to 45 kg at 19 y of age. Liver weight (Table 1) was calculated to be 2.4% of body weight (Tanumihardjo 2001). The adequate intake (AI) for infants and the estimated average requirement (EAR) for children and adolescents were used as the VA reference needs (Inst. of Medicine 2001).

Comparison of micronutrient sachets or crushable tablets with sweet potato

Micronutrient sachets used in research studies contain 300 μg (Sharieff and others 2006) to 400 μg VA (Menon and others 2007). The value used for this simulation was 375 μg, which is the amount contained in the sachets that were part of the Tsunami relief efforts in Indonesia (Helen Keller Intl. 2005) and the amount found in UNICEF crushable tablets (Nestel and others 2003). The AI for VA is 400 μg for infants 0 to 6 mo and 500 μg for infants 7 to 12 mo (Inst. of Medicine 2001). The VA AI for infants is based upon human milk intake and is much higher than the recommended dietary allowance for young children (Inst. of Medicine 2001). Although the AI is probably higher than the average requirement for infants of this age, it was used in this comparison to determine relative differences. The portion size used for this simulation was 100 g cooked orange-fleshed sweet potato that contained on average 9980 μg β-carotene. This β-carotene value was based on a prior study in South Africa (van Jaarsveld and others 2005). Using a conversion factor of 12 μg β-carotene:1 μg retinol, 830 μg retinol activity equivalents would be fed each day to a child from 6 mo of age through 12 mo of age. This estimated conversion factor for sweet potato is supported experimentally, that is, 13.4 μg β-carotene:1 μg retinol was calculated when 80 g sweet potato was fed daily to men (Haskell and others 2004). This simulation does not include the VA contribution from breast milk which should continue to be promoted to children of this age (WHO 2002). Equation 1 was used for estimation of the monthly increase in liver VA concentrations in response to sweet potato feeding:

$$\left(\frac{\text{Vitamin A from sweet potato} - \text{adequate intake}}{\text{Liver weight}}\right) \times 30\text{ d} \qquad (1)$$

Table 1 — Parameters for a reference male child using the 50th percentile WHO weight-for-age and liver weight as 4% of body weight and an adolescent girl using 2.4% of body weight for liver weight.

	Age (mo)	Body weight (kg)	Liver weight (g)
Boy	6	7.9	316
	7	8.3	332
	8	8.6	344
	9	8.9	356
	10	9.15	366
	11	9.4	376
	12	9.65	386
Boy	2	12.15	486
	3	14.35	574
	4	16.35	654
Girl	13	35	840
	14	37	888
	15	39	936
	16	41	984
	17	43	1032
	18	45	1080

In the 1st simulation, the difference in liver reserves over time between mixing a VA-containing sachet or tablet in the meal compared with feeding a 100-g serving of cooked and mashed orange-fleshed sweet potato to an infant each day were plotted in micromols per gram liver (Figure 3). It is clear that feeding a daily serving of sweet potato to infants will improve VA status using a conservative conversion factor for β-carotene to retinol. The differences noted in the simulation are relative to each treatment and the published values for AI are subtracted from each day's intake. Other intake of VA, such as breast milk or formula, is not considered in this simulation and therefore a net decrease in liver VA concentrations occurred for the sachets or tablets in relationship to the sweet potato feeding (Figure 3).

Comparison of VA supplements, food fortification, and biofortified maize

In a 2nd analysis, the potential of biofortified maize intake to improve VA status in a male child age 1 to 4 y was compared with biannual supplementation (200000 IU capsules) or sugar fortification. The potential for VA toxicity with repeated supplementation to children was elegantly modeled (Allen and Haskell 2002). For this comparison, a simplified model was used based on the observation that 40% of the supplement is stored in the liver (Haskell and others 1997; Tanumihardjo 2001). This number, however, may be much less in children from VA-depleted mothers. A range of 11% to 17% was stored in piglets given moderate doses of VA (Surles and others 2007) whose mothers were VA-depleted for 3 gestation and lactation cycles. We have observed VA liver-reserve depletion over 4 mo in Indonesian children given supplements (Tanumihardjo and others 1996, 2004). This is similar to the data that were modeled (Allen and Haskell 2002).

Sugar fortification's impact on liver VA concentrations has been evaluated in Nicaraguan children (Ribaya-Mercado and others 2004). The extrapolated data for this analysis assumes that sugar consumption will increase as age and body weight increase and therefore relative increases in liver VA concentration occur as children age. The measured increase in liver VA concentrations was 0.28 μmol/g liver in the year that was evaluated. Sugar fortification has been estimated to provide 45% to 180% of the recommended dietary intake for VA in Central America (Dary and Mora 2002).

For biofortified maize in this analysis, the provitamin A value used was 10 μg βCE/g maize. We assumed losses in cooking of 25% (Li and others 2007), which has been supported experimentally using an African method of maize preparation that included fermentation (Annan and others 2003). Reported cooked maize porridge daily intakes for children have ranged from 250 g in South African children (Faber and others 2001) to 400 g in

Namibia (Vahatalo and others 2005). A child's intake of this staple food would increase as age increased. The potential increase in liver reserves of VA that might occur in a male child after a day's consumption of maize meal is presented in Table 2. The extra VA that would be stored each 3-mo quarter was determined using Eq. 2 until liver VA concentrations reached 0.4 μmol/g liver:

$$\frac{\left[\frac{(\mu g\beta - \text{carotene})}{3} - \text{estimated average requirement}\right]}{\text{Liver weight}} \times 91\text{ d} \qquad (2)$$

After liver reserves reached 0.4 μmol/g liver, Eq. 2 was written as:

$$\frac{\left[\frac{\mu g\beta - \text{carotene in maize} - (\text{estimated average requirement}\times 3)}{12}\right]}{\text{Liver weight}} \times 91\text{ d} \qquad (3)$$

In the expanded analysis, repeated feeding with this staple food was compared with sugar fortification and biannual supplementation in micromols per gram liver (Figure 4). The child transitions from eating 100 to 150 g maize meal at 2 y of age and from 150 to 200 g at 3 y of age. The EAR for this age group (Inst. of Medicine 2001) is 210 μg retinol/d for children 1 through 2 y and 275 μg/d for 3 to 4 y. The estimated improvement in liver concentration of VA used a combination of changes in liver size and bioconversion rate. A bioconversion rate of 3 μg β-carotene:1 μg retinol has been published for biofortified maize when fed as a staple food to Mongolian gerbils (Howe and Tanumihardjo 2006a). The conversion rate decreases when liver reserves of VA increase (Tanumihardjo and Howe 2007). This occurs in Mongolian gerbils at approximately 0.4 μmol retinol/g liver (Porter Dosti and others 2006; Howe and Tanumihardjo 2006a). Therefore, when accumulated liver VA concentrations of 0.4 μmol/g were achieved the model was adjusted (Eq. 3) and "extra" provitamin A carotenoids above the EAR were calculated to convert to VA using the published, generally accepted 12:1 conversion factor (Inst. of Medicine 2001).

The accrual with time reveals that biofortified maize may be as effective as a fortified food at improving VA concentrations in the liver (Figure 4). Moreover, when liver reserves are adequate, conversion rates of provitamin A to retinol decrease. This results in the slope of the line decreasing. In Filipino school-aged children,

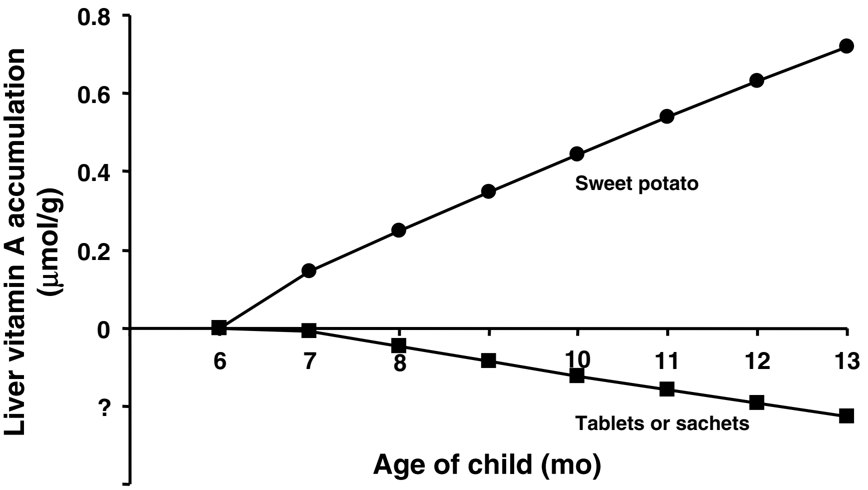

Figure 3—The relative change in liver vitamin A concentrations over time of an infant boy given either a daily supplement of 375 μg retinyl ester in the form of "sprinkles" or a crushed tablet in the weaning food (■) or a daily portion of 100 g boiled and mashed orange-fleshed sweet potato containing 830 retinol activity equivalents (●). The analysis used the adequate intake for infants, which is higher than the amount in the supplement, that is, 400 mg for a 6-mo-old and 500 μg for an infant age 7 to 12 mo, resulting in a net decrease. The simulation does not include other dietary sources of vitamin A such as breast milk.

Table 2—The amount of vitamin A estimated to be stored from provitamin A carotenoids in a vitamin A-depleted preschool boy or adolescent girl who had consumed biofortified maize for a day.

Age (y)	Maize meal (g)	Provitamin A (βCE)[a] (μg/g)	Total βCE (μg)	Retained after cooking (μg)	Conversion to vitamin A (μg)	Estimated average requirement (μg)	Extra vitamin A stored (μg)
Boy							
1	100	10	1000	750	250	210	40
2	150	10	1500	1125	375	210	165
3	200	10	2000	1500	500	275	225
Girl							
13	200	10	2000	1500	500	420	80
15	200	10	2000	1500	500	485	15
17	200	10	2000	1500	500	485	15
Girl							
13	300	15	4500	3375	1125	420	700
15	300	15	4500	3375	1125	485	640
17	300	15	4500	3375	1125	485	640

[a] β-carotene equivalents (βCE) = μg β-carotene + $\frac{1}{2}$ μg α-carotene + $\frac{1}{2}$ μg β-cryptoxanthin.

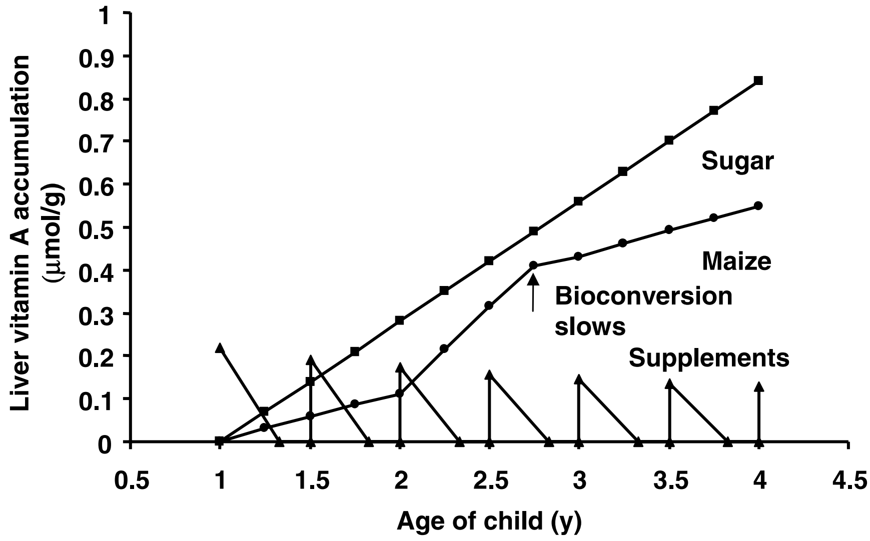

Figure 4—The relative change in liver vitamin A concentrations over time of a male child age 1 to 4 y given either a biannual dose of 200000 IU vitamin A (▲), fortified sugar (■), or maize meal each day (●). In the model, maize meal intake increases from 100 to 150 g at 2 y of age and to 200 g at 3 y of age. At 0.4 μmol/g liver the bioconversion of provitamin A carotenoids to retinol slows resulting in less accrual.

bioconversion of plant carotenoids was inversely related to VA status (Ribaya-Mercado and others 2000). This is in contrast to fortification with preformed VA where stores of VA would continue to increase at the same rate as long as intake is maintained or increased (Ribaya-Mercado and others 2004) and could potentially reach subtoxic levels (Vitamin A Tracer Task Force 2004), defined as 1.05 μmol VA/g liver. With no other sources of dietary VA in children given biannual supplementation, the liver VA concentration fluctuates (Allen and Haskell 2002).

Comparison of sugar fortification with biofortified maize in adolescent girls

Currently, no VA intervention programs are targeted at adolescent-age children, except fortified foods. Yet, many women are not able to meet the nutritional demands of pregnancy and lactation. In the 3rd analysis, an adolescent girl was used with both a high and low intake of fortified sugar and biofortified maize. We used 45% and 180% of the recommended dietary intake (600 μg retinol equivalents) as reported in Guatemala from fortified sugar intake (Dary and Mora 2002). High and low maize meal intake was 200 and 300 g, respectively. The EAR for this age group is 420 μg retinol/d for a 13-y-old girl and 485 μg/d for 14 to 19 y. The estimated improvement in liver concentration of VA used a combination of changes in liver size (Table 1) and bioconversion rate, similar to the young boy in the 2nd analysis. However, the conversion rate decreased twice during this 6-y period when liver VA concentrations reached approximately 0.4 and 0.6 μmol retinol/g liver (Howe and Tanumihardjo 2006a; Porter Dosti 2006). When accumulated liver VA concentrations of 0.4 μmol/g were achieved, the model shifted and "extra" provitamin A carotenoids above the EAR were calculated to convert to VA using the 12:1 conversion factor (Eq. 3) (Inst. of Medicine 2001) and at 0.6 μmol/g the extra provitamin A carotenoids converted at 23:1 (Eq. 4) as shown in Mongolian gerbils (Tanumihardjo and Howe 2007; Simon and others 2008).

After liver reserves reached 0.6 μmol/g liver, Eq. 3 was written as:

$$\frac{\left[\frac{\mu g\beta\text{-carotene in maize} - (\text{estimated average requirement} \times 3)}{23}\right] \times 91\text{d}}{\text{Liver weight}} \qquad (4)$$

Using published intakes for VA from fortified sugar in Guatemala and El Salvador (Dary and Mora 2002), the extremes were plotted for an adolescent girl (Figure 5). From this simulation, it is clear that at the upper level of intake, the girl will have excessive liver reserves 1 y after starting to consume VA-fortified sugar. This is similar to what was observed in captive Old World monkeys after consuming VA-fortified feed for as little as 2 y (Penniston and Tanumihardjo 2001; Mills and Tanumihardjo 2006). On the other hand, the lower level of intake does not meet the average girl's need and a negative liver reserve occurs. Under these conditions of low intake, the utilization rate of the girl probably decreases (Allen and Haskell 2002) and liver reserves will not become as depleted as simulated. In comparison, biofortified maize at low and high intakes results in continued accrual of VA liver reserves. The higher maize intake results in adequate liver reserves very rapidly. The conversion factor was adjusted twice during the simulation (Eq. 3 and 4), ensuring that hypervitaminosis A does not occur. The low maize intake is enough to result in a slow, gradual increase in liver reserves, but may not be able to prevent VA depletion during future pregnancy and lactation.

In another simulation, we determined which level of provitamin A in maize would act most like sugar fortification in an adolescent girl. When biofortified maize with 15 μg βCE/g maize is consumed at 3 different dietary levels (that is, 200, 250, and 300 g of ground maize per day), liver values are very similar to sugar fortification at 100% of the recommended dietary intake (600 μg retinol equivalents) for Guatemala (Figure 6). Moreover, 250 and 300 g maize meal intake result in similar liver VA reserves because of estimated slower conversion at higher liver concentrations. Conversion rates were estimated to be 3 μg βCE:1 μg retinol up to 0.4 μmol retinol/g liver (Eq. 2), 12:1 up to 0.6 μmol/g (Eq. 3), 23:1 up to 0.8 μmol/g (Eq. 4), and 50:1 above 0.8 μmol/g (Eq. 5).

After liver reserves reached 0.8 μmol/g liver, Eq. 3 was written as:

$$\frac{\left[\frac{\mu g\beta\text{-carotene in maize} - (\text{estimated average requirement} \times 3)}{50}\right] \times 91\text{d}}{\text{Liver weight}} \qquad (5)$$

In summary, the simulations set forth in this review used staple crops as the provitamin A source. However, data now exist in

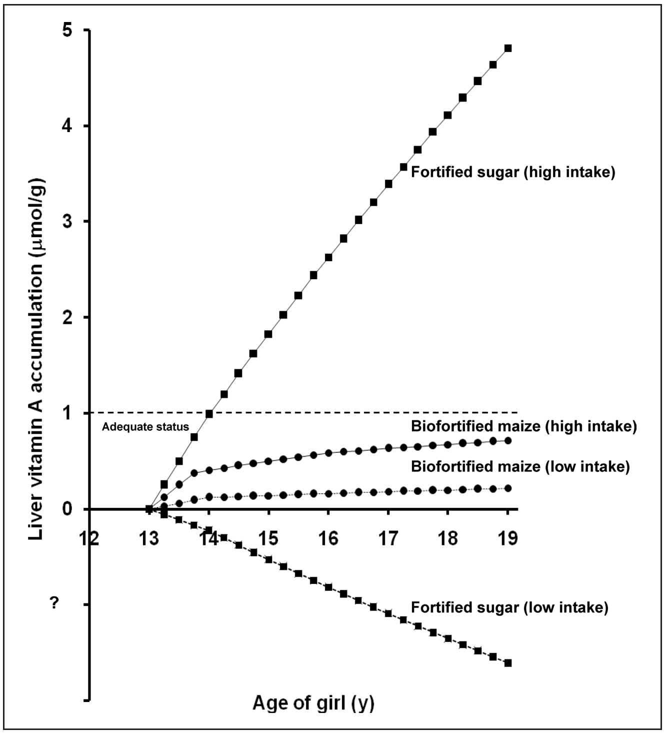

Figure 5—The relative change in liver vitamin A concentrations over time of an adolescent girl age 13 to 19 y consuming either fortified sugar (■) or maize meal each day (●) at low (dashed line) and high (solid line) intakes. Fortified sugar intakes were 45% and 180% of the recommended dietary intake for Guatemala (600 mg retinol equivalents per day). Maize meal (10 μg β-carotene equivalents per gram maize) intakes were 200 and 300 g for low and high intakes, respectively. At approximately 0.4 and 0.6 μmol/g liver, the bioconversion of provitamin A carotenoids to retinol slows resulting in less accrual which mitigates the potential for hypervitaminosis A.

several human studies that show that provitamin A carotenoids from a variety of fruits and vegetables can improve VA status (Ribaya-Mercado and others 2000, 2007; Haskell and others 2004). The same analysis could be done by using carrot or spinach as the provitamin A source. We chose staple foods because poor populations usually eat a staple food every day and therefore it is more conducive to a continuous simulation with time. As shown in Figure 2, even green vegetables resulted in favorable conversion factors when liver reserves of VA are low (Arscott and others 2007).

VA status of the population is the main driving force on whether provitamin A carotenoids are converted to VA. Not only does this mean that a little provitamin A in the diet can alleviate symptoms of VA deficiency such as that shown in night-blind Nepalese women fed vegetables (Haskell and others 2005a), but a natural protection against hypervitaminosis A with provitamin A-containing foods is present when liver reserves of VA are high. Furthermore, high intakes of fruits and vegetables are associated with reduced risk of several chronic diseases, including cardiovascular disease, type 2 diabetes, and certain cancers. Specific carotenoids have also been associated with reduced risk of certain diseases (Tanumihardjo and Yang 2005).

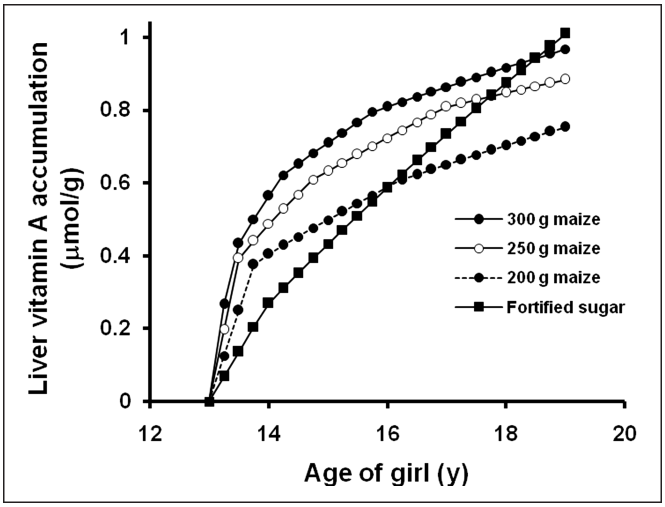

Figure 6—The relative change in liver vitamin A concentrations over time of an adolescent girl, age 13 to 19 y, consuming either fortified sugar (■) or maize meal each day at low (●, dashed line), medium (●, solid line) and high (●, solid line) intakes. Fortified sugar intake was 100% of the recommended dietary intake for Guatemala (600 μg retinol equivalents per day). Maize meal (15 μg β-carotene equivalents per gram maize) intakes were 200, 250, and 300 g for low, medium, and high intakes, respectively. At approximately 0.4, 0.6, and 0.8 μmol/g liver, the bioconversion of provitamin A carotenoids to retinol slows resulting in less accrual, which mitigates the potential for hypervitaminosis A.

Conclusions

Although recent efforts in developing countries have focused on supplementation and fortification, focusing on the inclusion of more provitamin A food sources in the diet is a viable approach to improve VA status. It may take a generation of nutrition education to either get people to change the color of the staple food they are eating or to include more provitamin A vegetables and fruits in the diet, but it can change VA status.

Acknowledgments

Work by the Tanumihardjo lab in this review was sponsored by HarvestPlus contract numbers 2005 × 217.UWM, 8029, and 8037; NIH-NIDDK 061973; the Natl. Research Initiative of the USDA Cooperative State Research, Education, and Extension Service, grant nr 2003-35200-05377; USDA–IFAFS grant nr 2000-4258; Hatch Wisconsin Agricultural Experiment Station WIS04975; and Standard Process Inc.

References

Allen LH. 2006. Causes of nutrition-related public health problems of preschool children: available diet. J Pediatr Gastroenterol Nutr 43:8S–12S.

Allen LH, Haskell M. 2002. Estimating the potential for vitamin A toxicity in women and young children. J Nutr 132:2907S–19S.

Annan NT, Poll L, Sefa-Dedeh S, Plahar WA, Jakobsen M. 2003. Volatile compounds produced by Lactobacillus fermentum, Saccharomyces cerevisiae and Candida krusei in single starter culture fermentations of Ghanaian maize dough. J Appl Microbiol 94:462–74.

Arscott SA, Howe JA, Tanumihardjo SA. 2007. Provitamin A carotenoid profiles of whole food supplements and the various components. FASEB J 21:A351. (Abstract 546.10).

Dary O, Mora JO. 2002. Food fortification to reduce vitamin A deficiency: international vitamin A consultative group recommendations. J Nutr 132:2927S–33S.

Davis CR, Jing H, Howe JA, Rocheford T, Tanumihardjo SA. 2008. β-Cryptoxanthin from supplements or carotenoid enhanced maize maintains liver vitamin A in Mongolian gerbils (*Meriones unguiculatus*) better than or equal to β-carotene supplements. Br J Nutr Forthcoming.

de Pee S, West CE, Muhilal, Karyadi D, Hautvast JG. 1995. Lack of improvement in vitamin A status with increased consumption of dark-green leafy vegetables. Lancet 346:75–81.

Edwards AJ, You CS, Swanson JE, Parker RS. 2001. A novel extrinsic reference method for assessing the vitamin A value of plant foods. Am J Clin Nutr 74:348–55.

Escaron AL, Tanumihardjo SA. 2006. Absorption and transit of lutein and β-carotene supplements in the Mongolian gerbil (*Meriones unguiculatus*). Int J Vitam Nutr Res 76:315–23.

Faber M, Jogessar VB, Benade AJS. 2001. Nutritional status and dietary intakes of children aged 2–5 years and their caregivers in a rural South African community. Int J Food Sci Nutr 52:401–11.

Furr HC, Green M, Haskell M, Mokhtar N, Nestel P, Newton S, Ribaya-Mercado J, Tang G, Tanumihardjo SA, Wasantwisut E. 2005. Stable isotope dilution techniques for assessing of vitamin A status and bioefficacy of provitamin A carotenoids in humans. Public Health Nutr 8:596–607.

García AL, Raila J, Koebnick C, Eulenberger K, Schweigert FJ. 2006. Great apes show highly selective plasma carotenoids and have physiologically high plasma retinyl esters compared to humans. Am J Phys Anthropol 131:236–42.

Harjes CE, Rocheford TR, Bai L, Brutnell TP, Kandianis CB, Sowinski SG, Stapleton AE, Vallabhaneni R, Williams M, Wurtzel ET, Yan J, Buckler ES. 2008. Natural genetic variation in lycopene epsilon cyclase tapped for maize biofortification. Science 319:330–3.

Haskell M, Handelman G, Peerson J, Jones AD, Rabbi MA, Awal MA, Wahed MA, Mahalanabis D, Brown KH. 1997. Assessment of vitamin A status by the deuterated-retinol-dilution technique and comparison with hepatic vitamin A concentration in Bangladeshi surgical patients. Am J Clin Nutr 66:67–74.

Haskell MJ, Jamil KM, Hassan F, Peerson JM, Hossain MI, Fuchs GJ, Brown KH. 2004. Daily consumption of Indian spinach (*Basella alba*) or sweet potatoes has a positive effect on total-body vitamin A stores in Bangladeshi men. Am J Clin Nutr 80:705–14.

Haskell MJ, Pandey P, Graham JM, Peerson JM, Shrestha RK, Brown KH. 2005a. Recovery from impaired dark adaptation in nightblind pregnant Nepali women who receive small daily doses of vitamin A as amaranth leaves, carrots, goat liver, vitamin A-fortified rice, or retinyl palmitate. Am J Clin Nutr 81:461–71.

Haskell MJ, Ribaya-Mercado JD, the Vitamin A Tracer Task Force. 2005b. Handbook on vitamin A tracer dilution methods to assess status and evaluate intervention programs. (Members: Furr HC, Green M, Haskell M, Mokhtar N, Nestel P, Ribaya-Mercado J, Tanumihardjo SA, Wasantwisut E). Washington, D.C.: HarvestPlus Technical Monograph nr 5.

Helen Keller International. 2005. Tsunami relief bulletin year 1, issue 1. Available from: http://www.hki.org/research/tsunami_bulletins/tsunami_relief_1.pdf. Accessed Nov 13, 2007.

Hoppe PP, Chew BP, Safer A, Stegemann I, Biesalski HK. 1996. Dietary beta-carotene elevates plasma steady-state and tissue concentrations of beta-carotene and enhances vitamin A balance in preruminant calves. J Nutr 126(1):202–8.

Howe JA, Tanumihardjo SA. 2006a. Carotenoid-biofortified maize maintains adequate vitamin A status in Mongolian gerbils. J Nutr 136:2562–7.

Howe JA, Tanumihardjo SA. 2006b. Evaluation of analytical methods for carotenoid extraction from biofortified maize (*Zea mays* sp.). J Agric Food Chem 54:7992–7.

Howe JA, Tanumihardjo SA. 2007. Bioefficacy of carotenoid-biofortified cassava. In: Agronomy Abstracts. [CD-ROM]. Madison, Wis.: American Society for Agronomy.

Inst. of Medicine, Food and Nutrition Board. 2001. Dietary reference intakes for vitamin A, vitamin K, arsenic, boron, chromium, copper, iodine, iron, molybdenum, nickel, silicon, vanadium, and zinc. Washington, D.C.: National Academy Press. p 65–126.

Kelm MA, Flanagan VP, Pawlosky RJ, Novotny JA, Clevidence BA, Britz SJ. 2001. Quantitative determination of 13C-labeled and endogenous beta-carotene, lutein, and vitamin A in human plasma. Lipids 36:1277–82.

Kurilich AC, Britz S, Clevidence BA, Novotny JA. 2003. Isotopic labeling and LC-APCI-MS quantification for investigating absorption of carotenoids and phylloquinone from kale (*Brassica oleracea*). J Agric Food Chem 51:4877–83.

Lee CM, Lederman JD, Hofman NE, Erdman JW Jr. 1998. The Mongolian gerbil (*Meriones unguiculatus*) is an appropriate animal for evaluation of the conversion of carotene to vitamin A. J Nutr 128:280–6.

Lee CM, Boileau AC, Boileau TW, Williams AW, Swanson KS, Heintz KA, Erdman JW Jr. 1999. Review of animal models in carotenoid research. J Nutr 129:2271–7.

Li S, Tayie FAK, Young MF, Rocheford T, White WS. 2007. Retention of provitamin A carotenoids in high β-carotene maize (*Zea mays*) during traditional African household processing. J Agric Food Chem 55:10744–50.

Low JW, Arimond M, Osman N, Cunguara B, Zano F, Tschirley D. 2007. A food-based approach introducing orange-fleshed sweet potatoes increased vitamin A intake and serum retinol concentrations in young children in rural Mozambique. J Nutr 137:1320–7.

Menon P, Ruel M, Loechl CU, Arimond M, Habicht JP, Pelto G, Michaud L. 2007. Micronutrient sprinkles reduce anemia among 9- to 24-mo-old children when delivered through an integrated health and nutrition program in rural Haiti. J Nutr 137:1023–30.

Mills JP, Tanumihardjo SA. 2006. Vitamin A toxicity is biochemically evident in wild-caught African green vervet monkeys (*Chlorocebus aethiops*) after two years in captivity. Comp Med 56:421–5.

Mills JP, Penniston KL, Tanumihardjo SA. 2005. Extra-hepatic vitamin A concentrations in captive rhesus (*Macaca mulatta*) and marmoset (*Callithrix jacchus*) monkeys fed excess vitamin A. Int J Vit Nutr Res 75:126–32.

Mills JP, Simon PW, Tanumihardjo SA. 2007. β-Carotene from red carrot maintains vitamin A status but lycopene bioavailability is lower relative to tomato paste in Mongolian gerbils. J Nutr 137:1395–400.

Molldrem KL, Tanumihardjo SA. 2004. Lutein supplements are not bioavailable in the Mongolian gerbil while consuming a diet with or without cranberries. Int J Vitam Nutr Res 74:153–60.

Neidecker-Gonzales O, Nestel P, Bouis H. 2007. Estimating the global costs of vitamin A capsule supplementation: a review of the literature. Food Nutr Bull 28(3):307–16.

Nestel P, Briend A, de Benoist B, Decker E, Ferguson E, Fontaine O, Micardi A, Nalubola R. 2003. Complementary food supplements to achieve micronutrient adequacy for infants and young children. J Pediatr Gastroenterol Nutr 36:316–28.

Parker RS, Brenna JT, Swanson JE, Goodman KJ, Marmor B. 1997. Assessing metabolism of beta-[^{13}C]carotene using high-precision isotope ratio mass spectrometry. Methods Enzymol 282:130–40.

Parker RS, Swanson JE, You CS, Edwards AJ, Huang T. 1999. Bioavailability of carotenoids in human subjects. Proc Nutr Soc 58:155–62.

Penniston KL, Tanumihardjo SA. 2001. Subtoxic hepatic vitamin A concentrations in captive rhesus monkeys (*Macaca mulatta*). J Nutr 131:2904–9.

Penniston KL, Tanumihardjo SA. 2006. Vitamin A intake of captive rhesus monkeys exceeds National Research Council recommendations. Am J Primatol 68:1114–9.

Penniston KL, Thayer JC, Tanumihardjo SA. 2003. Serum vitamin A esters are high in captive rhesus (*Macaca mulatta*) and marmoset (*Callithrix jacchus*) monkeys. J Nutr 133:4202–6.

Poor CL, Bierer TL, Merchen NR, Fahey GC Jr, Murphy MR, Erdman JW Jr. 1992. Evaluation of the preruminant calf as a model for the study of human carotenoid metabolism. J Nutr 122:262–8.

Porter Dosti M, Mills JP, Simon PW, Tanumihardjo SA. 2006. Bioavailability of β-carotene (βC) from purple carrots is the same as typical orange carrots while high-βC carrots increase βC stores in Mongolian gerbils (*Meriones unguiculatus*). Br J Nutr 96:258–67.

Ribaya-Mercado JD, Solon FS, Solon MA, Cabal-Barza MA, Perfecto CS, Tang G, Solon JAA, Fjeld CR, Russell RM. 2000. Bioconversion of plant carotenoids to vitamin A in Filipino school-aged children varies inversely with vitamin A status. Am J Clin Nutr 72:455–65.

Ribaya-Mercado JD, Solomons NW, Medrano Y, Bulux J, Dolnikowski GG, Russell RM, Wallace CB. 2004. Use of the deuterated-retinol-dilution technique to monitor the vitamin A status of Nicaraguan schoolchildren 1 y after initiation of the Nicaraguan national program of sugar fortification with vitamin A. Am J Clin Nutr 80:1291–8.

Ribaya-Mercado JD, Maramag CC, Tengco LW, Dolnikowski GG, Blumberg JB, Solon FS. 2007. Carotene-rich plant foods ingested with minimal dietary fat enhance the total-body vitamin A pool size in Filipino schoolchildren as assessed by stable-isotope-dilution methodology. Am J Clin Nutr 85:1041–9.

Ross DA. 2002. Recommendations for vitamin A supplementation. J Nutr 131:2902S–6S.

Sharieff W, Yin SA, Wu M, Yang Q, Schauer C, Tomlinson G, Zlotkin S. 2006. Short-term daily or weekly administration of micronutrient Sprinkles has high compliance and does not cause iron overload in Chinese schoolchildren: a cluster-randomised trial. Public Health Nutr 9:336–44.

Simon PW, Tanumihardjo SA, Clevidence BA, Novotny JA. 2008. Role of color and pigments in breeding, genetics, and nutritional improvement of carrots. In: Culver C, Wrolstad R, editors. Color quality of fresh and processed foods. Washington, D.C.: ACS Books.

Sommer A, Davidson FR. 2002. Assessment and control of vitamin A deficiency: the Annecy Accords. J Nutr 132:2845S–50S.

Sprinkles Global Health Initiative. 2007. About Sprinkles. Available from: http://sghi.org/about_sprinkles/about_sprinkles.pdf. Accessed Nov 13, 2007.

Surles RL, Mills JP, Valentine AR, Tanumihardjo SA. 2007. One-time graded doses of vitamin A to weanling piglets enhance hepatic retinol but do not always prevent a deficient vitamin A status. Am J Clin Nutr 86:1045–53.

Tang G, Gu X, Hu S, Xu Q-M, Qin J, Dolnikowski GG, Fjeld CR, Gao X, Russell RM, Yin S-A. 1999. Green and yellow vegetables can maintain body stores of vitamin A in Chinese children. Am J Clin Nutr 70:1069–76.

Tang G, Qin J, Dolnikowski GG, Russell RM, Grusak M. 2005. Spinach or carrots can supply significant amounts of vitamin A as assessed by feeding with intrinsically deuterated vegetables. Am J Clin Nutr 82:821–8.

Tanumihardjo SA. 2001. Can lack of improvement in vitamin A status indicators be explained by little or no overall change in vitamin A status of humans? J Nutr 131:3316–8.

Tanumihardjo SA. 2002. Factors influencing the conversion of carotenoids to retinol: bioavailability to bioconversion to bioefficacy. Int J Vitam Nutr Res 72:40–5.

Tanumihardjo SA. 2004. Assessing vitamin A status: past, present and future. J Nutr 134:290S–3S.

Tanumihardjo SA, Howe JA. 2005. Twice the amount of α-carotene isolated from carrots is as effective as β-carotene in maintaining the vitamin A status of Mongolian gerbils. J Nutr 135:2622–6.

Tanumihardjo SA, Yang Z. 2005. Carotenoids: Epidemiology of health effects. In: Caballero B, Allen L, Prentice A, editors. Encyclopedia of human nutrition. 2nd ed. Oxford: Elsevier Ltd. p 339–45.

Tanumihardjo S, Howe J. 2007. Provitamin A carotenoids from foods and supplements provide vitamin A based on need and one conversion factor does not fit all. In: Consequences and control of micronutrient deficiencies: Science, policy, and programs—Defining the issues. Istanbul, Turkey: Micronutrient Forum. 55 p. (Abstract M34).

Tanumihardjo SA, Permaesih D, Muherdiyantiningsih, Rustan E, Rusmil K, Fatah AC, Wilbur S, Muhilal, Karyadi D, Olson JA. 1996. Vitamin A status of Indonesian children infected with *Ascaris lumbricoides* after dosing with vitamin A supplements and albendazole. J Nutr 126:451–7.

Tanumihardjo SA, Permaesih D, Muhilal. 2004. Vitamin A status and hemoglobin concentrations are improved in Indonesian children with vitamin A and deworming interventions. Eur J Clin Nutr 58:1223–30.

Tanumihardjo SA, Anderson C, Kaufer-Horwitz M, Bode L, Emenaker NJ, Haqq AM, Satia JA, Silver HJ, Stadler DD. 2007. Poverty, obesity and malnutrition: an international perspective recognizing the paradox. J Am Diet Assn 107:1966–72.

Tchum K, Newton S, Tanumihardjo S, de Benoist B, Owusu-Agyei S, Arthur F, Tetteh A. 2006. Evaluation of the indigenous leafy vegetable supplementation for Ghanaian postpartum mothers using MRDR assay. In: Kalambaheti Y, Charoenkiatkul S, editors. Bioavailability 2006: optimizing dietary strategies for better health in developing countries. Thailand. 35 p. Abstract O3.2.

Vahatalo L, Mikkila V, Rasanen L. 2005. Schoolchildren's food consumption and dietary intake during the dry season in north-west Namibia. Int J Food Sci Nutr 56:367–75.

van Jaarsveld PJ, Faber M, Tanumihardjo SA, Nestel P, Lombard CJ, Benade AJ. 2005. Beta-carotene-rich orange-fleshed sweet potato improves the vitamin A status of primary school children assessed with the modified-relative-dose-response test. Am J Clin Nutr 81: 1080–7.

van Lieshout M, West CE, van de Bovenkamp P, Wang Y, Sun Y, van Breemen RB, Permaesih D, Muhilal, Verhoeven MA, Creemers AFL, Lugtenburg J. 2003. Extraction of carotenoids from feces, enabling the bioavailability of β-carotene to be studied in Indonesian children. J Agric Food Chem 51:5123–30.

Vitamin A Tracer Task Force. 2004. Appropriate uses of vitamin A tracer (stable isotope) methodology. Washington, D.C.: ILSI Human Nutrition Institute.

[WHO] World Health Organization. 2002. Infant and young child nutrition: Global strategy on infant and young child feeding. Available from: http://www.who.int/gb/ebwha/pdf_files/WHA55/ea5515.pdf. Accessed Jan 23, 2008.

[WHO] World Health Organization. 2003. Immunizations, vaccines, and biologicals. Vitamin A supplementation. Available from: http://www.who.int/vaccines/en/vitamina.shtml. Accessed Nov 13, 2007.

World Health Organization Child Growth Standards. 2007. Available from: http://www.who.int/childgrowth/standards/chts_wfa_boys_p/en/index.html. Accessed Nov 13, 2007.

Yonekura-Sakakibara K, Saito K. 2006. Review: genetically modified plants for the promotion of human health. Biotechnol Lett 28:1983–91.

COMPREHENSIVE
REVIEWS
IN FOOD SCIENCE AND FOOD SAFETY

Keys to Sustainable Food Fortification Programs in Developing Countries

Visith Chavasit

ABSTRACT: This article serves as a guide for developing countries that are considering implementing, or improving upon, large-scale food fortification programs. Food fortification is one of the most economical and practical strategies for combating micronutrient deficiency among people in developing countries. While fortification technologies usually are not complicated and are readily available, several factors must be carefully considered before initiating a food fortification program. These factors include the micronutrient deficiency problems of the country, the target population, the food vehicle, the fortificant, a quality monitoring system, bioavailability of the fortified nutrient, and the impact on people's health. The primary success of a food fortification program must be a fortified product that is sensory-acceptable, affordable, and accessible to the target population. The fortification cost should not be a burden to industry or government but must be shared among consumers. Success also requires an efficient quality monitoring system. The impact of the fortified nutrients should be significant and measurable in terms of efficacy and cost-effectiveness. However, program sustainability must be based on the mutual benefits of industry, consumers, and the government. A successful food fortification program requires inputs from several sectors that are responsible for promotion, enforcement, technical support, taxation, and so on.

Introduction

Micronutrient deficiency, or so-called "hidden hunger," damages the health, learning ability, and work performance of a population, thus impeding people's quality of life and a nation's social and economic status. For decades, food fortification has been used to combat micronutrient deficiencies in developed and developing countries (World Bank 1993). Salt iodization was the very first food fortification program that was sustainable in many countries throughout the world (WHO/UNICEF/ICCIDD 2001). Currently, several foods have been fortified with various nutrients, while many food fortification programs are being launched, especially in developing countries, and for either commercial or social purposes. Compared to dietary diversification and supplementation, which involve changing eating patterns and providing micronutrient capsules, respectively, fortification is the most economical strategy since cost per person per year is normally lower than for other strategies (Phillips and others 1994). For developing countries where micronutrient deficiencies are still major nutrition challenges, food fortification can be one of the best choices. However, the success and sustainability of a food fortification program does not rely on cost alone, but rather on many other factors that involve the participation of the food industry, the government and consumers.

National Micronutrient Deficiency

The micronutrient fortification of foods can be a good tool for food manufacturers or even micronutrient producers as they work together to control major micronutrient challenges. However, without a clear understanding of a nation's and its population's specific micronutrient situation, food products can easily be insufficiently fortified with essential nutrients and may not be suitable for, nor reach, their target population. Such practices are very deleterious for developing countries where resources are quite limited. Consequently, countries need to clearly identify their target population and problem nutrients before initiating any food fortification program.

Information that can indicate specific micronutrient deficiency problems in a country can be obtained from several sources. Initially, the situation of a country can be comparatively assessed by looking at the deficiency problems in other countries with similar backgrounds in terms of geographic conditions, national and local economic systems, race, the eating culture, way of life, and so on. Clinical reports from local health offices, hospitals and research studies, though often sporadic, can sometimes be combined to create a larger picture of a region, subregion,

---

MS 20070914 Submitted 12/10/2007, Accepted 5/19/2008. Author is with Inst. of Nutrition, Mahidol Univ. at Salaya, Phutthamonthon, Nakhon Pathom73170, Thailand. Direct inquiries to author Chavasit (E-mail: nuvca@mahidol.ac.th).

or even a country. In addition, a cross-sectional survey to assess the prevalence and magnitude of a certain nutrient is the best method for confirming the occurrence of a problem. A national nutrition survey, which is normally performed on a regular basis, can provide overall information on the extent of a suspected micronutrient deficiency problem in a country. Important data, such as clinical signs, results of simple biochemical tests, and nutrient consumption patterns, are normally obtained from a national nutrition survey. However, the accuracy of the data depends on the suitability of selected indicators and the methodology used. In some cases, other factors, such as changes in life styles and different working environments, should also be considered. For example, under normal conditions, vitamin D deficiency should not be found in countries where the population is exposed to sunlight all year. However, in these same countries there may be persons who are at risk of vitamin D deficiency because they live or work in sunlight-protected conditions or who regularly use sun-block cream out of a fear of contracting skin cancer.

Food Vehicles

Selecting the right food vehicles for fortification is a major challenge for national fortification programs in developing countries. The types of foods to be fortified must be suitable for the target population, which means that they must be readily acceptable, affordable, and accessible. An appropriate food vehicle should be consumed by the target population all year round. Normally, staple foods and condiments are potential food vehicles since they are consumed regularly. However, the amount consumed should not differ among individuals or groups in the target population, since the consumption amount is the basic information needed to determine the amount of fortificant to be used in the fortification process. Accurate information is essential to reduce the chance of using too much or too little fortificant in the fortified products. In addition, identifying the right vehicle is equally important, since usually a limited number of food vehicles can be fortified at a national level. To guarantee fortification quality (use of the right fortificant at the right dosage) and an affordable price, preferred food vehicles should be ones that are already produced by large industries that have more efficient and reliable production and quality assurance systems. In addition, large companies normally have good distribution systems that can reach even the most remote areas of a country (FAO 1996; Lotfi and others 1996; Blum 1997).

Although industrialized food products should be ideal food vehicles for developing countries, this is not always true. For example, there are 8 large modern wheat flour millers in Thailand that can fortify and control quality very well. However, the consumption amount of wheat flour in Thailand varies greatly among different populations, such as from less than 20 g per person per day among low-income families to over 100 g per person per day in high-income families (National Food Fortification Committee of the Ministry of Public Health Thailand 2003). While rice should be a better food vehicle, since the amount consumed by different populations is similar, persons who are at risk of micronutrient deficiencies usually do not buy rice from large millers. Instead, they purchase rice from village millers that are widely distributed throughout the country. In China, moreover, variation in the amount of wheat flour consumed should not be as much as in Thailand. However, once again, vulnerable groups use only the service of village millers. The major limitations in choosing a food vehicle produced by small producers mainly rest on the nonavailability of appropriate fortification and self-quality monitoring systems at the production sites. In addition, large numbers of small producers can cause the government problems in terms of product quality control.

Fortificants

Various chemicals that can be used as food fortificants are available from different companies all over the world. Although these chemicals provide the same nutrient, they can differ in physical and chemical properties, price, and bioavailability in the human body.

Differences in physical and chemical properties can directly affect a fortificant's feasibility for use, as well as the shelf stability and the sensory quality of the fortified products. For example, only elementary iron can be used to fortify instant noodles in Thailand, since water-soluble iron fortificants, such as ferrous sulfate, ferrous fumarate, and NaFeEDTA, can react with herbs and spices in the seasoning powder and result in undesirable black-colored soups (Chavasit and Tontisirin 1998). On the other hand, rice fortification requires water-soluble fortificants, since they need to be prepared as a solution before being absorbed into the rice matrix (Chitpan and others 2005). Their study showed that NaFeEDTA was the best iron source, since it could prevent rice fat oxidation during storage. Furthermore, the size of elemental iron is very important in wheat flour fortification because it needs to be fine enough to homogeneously disperse into the flour (Motzok and others 1975; Verma and others 1977). Fat-soluble vitamin A is required for fortifying oil-based products, such as cooking oil, while the less stable water-soluble form is required in water-based products, such as fruit juice and milk (Nilson 1994).

Fortification can result in a shorter product shelf life, since certain nutrients can catalyze the rate of qualitative changes, especially physical, chemical, and sensory. In addition to physical, chemical, microbial, and sensory qualities, the shelf life of a fortified food product also depends on the retention of fortified nutrients. Studies on fortified nutrient losses during processing and normal storage conditions of the vehicle are required to compensate for such losses with an appropriate additional amount (Nilson and Piza 1998). Attempts to prevent such problems also include using a coated or encapsulated fortificant or using chelating agents, such as citric acid or sodium citrate (Chavasit and others 2003; Watanapaisantrakul and others 2006). In addition, some fortificants cannot be used for persons in certain age groups. For example, NaFeEDTA is not allowed to be used at more than 0.2 mg/kg body weight per day in children (WHO 1999). Use of appropriate packaging is another alternative for prolonging the shelf life of fortified products, such as light-protected containers for vitamin A-fortified cooking oil or aluminum foil-laminated plastic bags for iron-fortified rice (Chitpan and others 2005; Puysuwan and others 2007). However, changes in packaging normally affect the cost of the fortified products.

The price differences of fortificants may not significantly affect the fortification cost if a small amount is required. For example, potassium iodide and potassium iodate differ in iodine content (76% compared to 59%) and have different prices ($29/kg compared to $25/kg). However, the difference in final cost is not a major concern since they are used in very small amounts (micrograms). Concerns should be on cases where costs per unit of nutrient are very different and a large amount of nutrient is required, such as iron fortification with NaFeEDTA as opposed to $FeSO_4$. Cost per unit of nutrient, therefore, needs to be evaluated. However, the final answer is not always dependent on cost, since the same nutrient in different physical and chemical characteristics can be absorbed and utilized in the human body differently (OMNI/Roche/USAID 1997). Such a difference in bioavailability can be due to several factors, such as particle size and the solubility of the fortificant in the gastrointestinal tract, the food environment, and even the individual consumer. Elemental iron has lower bioavailability due to its low solubility, therefore it is recommended to fortify at a double dosage of the requirement.

NaFeEDTA is recommended for fortifying high-extracted wheat flour, which contains high phytate (Hurrell and Egli 2007). Other factors, such as nutrient interaction, should also be considered since they can affect the bioavailability of the fortified nutrient. Such an interaction can be with either natural nutrients or other fortified nutrients (Sandström 2001). Although in the real world the ideal fortificant may not be found, the most appropriate ones are normally a compromise.

Fortification Process

Various food fortification techniques are available, varying from the simple to the more complicated, such as dry mixing, dissolution in oil, dissolution in water, adhesion, coating, extrusion, and spraying. In developing countries where resources are quite limited, the steps required for fortification should be able to be merged smoothly in the normal production process of the food vehicle. Ideally, there should not be any additional equipment required, and the fortification step should not interrupt or slow down the food vehicle's normal production process. For example, fortifying cooking oil with vitamin A for bulk transportation can be done by adding vitamin A into the truck's tank before pumping in the oil. The turbulence from pumping can homogeneously mix the fortified product without the need for additional equipment (Puysuwan and others 2007). In some cases, additional equipment may be needed. For example, a dosing machine is required in flour fortification. But in such cases, the additional equipment must be easily merged in the normal production process without the need for additional time (Nestel and Ritu 2000). Fortification of fish sauce with NaFeEDTA requires an additional mixing tank and time (Asian Development Bank 2004), while there is no need in the case of $FeSO_4$ + citric acid (Chavasit and others 2003). Triple fortification of the seasoning powder for instant noodles can be performed by mixing the premix with other ingredients during the blending step (Chavasit and Tontisirin 1998). A more complicated technique, such as extrusion, is used for producing fortified restructured rice (Zilberboim 1994; Moretti and others 2005). As mentioned previously, the fortification process directly depends on the food vehicle and the type of fortificant selected. An inappropriate decision can cost more and burden the country in the future.

Food Fortification Program Implementation

Generally, the target population in developing countries is the low-income people who do not pay much attention to the nutritive values of foods. Consequently, fortification is not a selling point for them. Most international agencies prefer a country to have food fortification on a mandatory basis rather than a voluntary one (FAO 1996). Iodization of salt is mandated in most countries of the world, while other food commodities, such as wheat flour, cooking oil, and sweetened condensed milk, are mandatorily fortified depending upon the eating patterns of a country's population. Mandating a fortified food requires a well-established monitoring system, consisting of in-house pre- and postmarketing. The system should include a sampling plan, method of analysis, and mechanism for result interpretation. An inefficient system can contribute to program failure. For example, the use of a test kit for checking the iodize quality of salt at the factory can be misleading, since the tiny amount used in the test cannot represent the tons of salt that the factory is fortifying. Instead, the test kit is only suitable for qualitative pretesting or creating social awareness. Furthermore, a test kit for any nutrient may be more beneficial for a product that is homogeneous in nature, especially foods in liquid form.

Where the food fortification program is performed on a voluntary basis, food and nutrition labels are important tools for quality monitoring. In addition to a routine food control system, the government may need to assist food producers by educating consumers to differentiate between fortified and unfortified products. For example, a special "Nutrition Seal" can be issued to certain products that are fortified with essential nutrients and which reach target populations. A seal that is a symbol that producers are allowed to show on the food label can be a good marketing tool when efficiently promoted by the government.

Regardless of whether the program is mandatory or voluntary, a sustainable program should distribute the fortification cost among consumers instead of burdening any party such as government or producer. However, the government can support the program through a taxation system. For example, the Thai government reduces the tax for premix from 33% to 1% to reduce the cost of triple fortification in instant noodles (Chavasit and Tontisirin 1998).

While a government should play an important role in controlling and enforcing the quality of the fortified foods, distributing the benefits of food fortification among all partners such as consumers, the food industry, government, and academia is another important key for a successful fortification program. An example of a successful industrial fortification program is double-fortified fish sauce in Thailand. The technology required for this program was undertaken by the Institute of Nutrition, Mahidol Univ, Thailand. Local industries produce the product, while large international retail outlets distribute the product to consumers throughout the country.

Impact Evaluation

Since food fortification is one type of health investment, its benefit needs to be evaluated. In 2002, the Asian Development Bank introduced a model for evaluating the economic cost-benefit of a food fortification program, which can be proposed to policy makers for their decision on program establishment (National Food Fortification Committee Ministry of Public Health Thailand 2003). Such a model can predict impact by using health economic knowledge, which must be based on accurate data from various sources.

For the implemented food fortification programs, either successes or failures, very few have formally evaluated their impact on nutrition status (Allen and Ahluwalia 1997; Allen and others 2006). Therefore, it is difficult to know whether subsequent improvements in the nutritional status of a population are due to the introduction or to other changes that occurred over the same period of time. Direct impact of the fortified nutrient on nutritional status can be evaluated by methods of different complexity and cost. At a lower cost, an *in vitro* method, such as dialyzability, can be a useful preliminary screening tool for predicting the bioavailability of minerals and other compounds for humans (Forbes and others 1989). Efficacy trials, which are performed at a higher cost, are used for evaluating the impact of a test intervention under ideal circumstances, which involve all test subjects consuming a known amount of the fortified food. Efficacy trials, such as those using stable isotope techniques, can be performed with a small number of subjects within a short period of time, while a trial in a population needs a much larger number of subjects and a longer experimental period (normally > 100 and > 6 mo) (Allen and others 2006).

Impact of an intervention or program in actual practice (not under controlled conditions) is determined by effectiveness evaluation. Normally, the impact of an intervention from effectiveness evaluation is likely to be less than in an efficacy trial due to factors such as the lack of consumption of the fortified foods.

Coverage of the fortified food in the vulnerable population is also used as an indicator of program success. However, correlation between percent product coverage and related nutrition status must be evaluated to verify the impact. For example, an area that has high coverage of iodized table salt may not have a satisfactory impact on nutrition status if the vulnerable group does not use salt in seasoning their foods. Instead, the impact may be better if universal salt iodization is implemented and all condiments used for salty seasoning are produced by using iodized salt with minimum losses during production, storage, distribution, and food preparation.

Conclusions

A food fortification program in developing countries should be initiated from micronutrient deficiency problems of the population by using an appropriate food vehicle and fortificant. A solid partnership between industry, government, and academia focusing on the benefits for consumers is one of the key factors for the success of a food fortification program. In addition, the impact of the fortified nutrient on the nutrition status of a target population must be evaluated to verify its bioavailability and effectiveness.

References

Allen L, de Benoist B, Dary O, Hurrell R. 2006. Guidelines on food fortification with micronutrients. Geneva, Switzerland: World Health Organization.

Allen LH, Ahluwalia N. 1997. Improving iron status through diet, the application of knowledge concerning dietary iron bioavailability in human populations. Dept. of Nutrition, Univ. of California at Davis and The Pennsylvania State Univ.

Asian Development Bank. 2004. Country investment plan: Vietnam. Chapter II. Proposing food vehicles and 10-year investment plan for food fortification. Available from: http://www.adb.org/Projects/Food-Fortification/cip-vietnam.pdf. Accessed Nov 1, 2007.

Blum M. 1997. Status paper: food fortification, a key strategy to end micronutrient malnutrition. NUTRIVIEW 97/Special Issue. Basel, Switzerland: Vitamin Division, F. Hoffmann-La Roche Ltd.

Chavasit V, Tontisirin K. 1998. Triple fortification of instant noodles. Food Nutr Bull 19:164–8.

Chavasit V, Nopburabutr P, Kongkachuichai R. 2003. Combating iodine and iron deficiencies through the double fortification of fish sauce, mixed fish sauce, and salt brine. Food Nutr Bull 24(2):200–7.

Chitpan M, Chavasit V, Kongkachuichai R. 2005. Development of fortified dried broken rice as a complementary food. Food Nutr Bull 26(4):376–84.

[FAO] Food and Agriculture Organization. 1996. Food fortification: technology and quality control. Report of an FAO Technical Meeting held in Rome, 1995 Nov 20–23. FAO Food and Nutrition Paper. Rome, Italy: FAO.

Forbes AL, Adams CE, Arnaud MJ, Chichester CO, Cook JD, Harrison BN, Hurrell RF, Kahn SG, Morris ER, Tanner JT, Whittaker P. 1989. Comparison of *in vitro*, animal, and clinical determinations of iron bioavailability: International nutritional anemia consultative group task force report of iron bioavailability. Am J Clin Nutr 49:225–38.

Hurrell R, Egli I. 2007. Optimizing the bioavailability of iron compounds for food fortification. Chapter 7. In: Kraemer K, Zimmermann MB, editors. Nutritional anemia. Switzerland: Sight and Life Press. p 77–97.

Lotfi M, Mannar MGV, Merx RHJM, Naber-van den Heuvel P. 1996. Micronutrient fortification of foods: current practices, research and opportunities. Ottawa, Canada: The Micronutrient Initiative, and Wageningen, The Netherlands, International Agriculture Centre.

Moretti D, Lee TC, Zimmermann MB, Nuessli J, Hurrell RF. 2005. Development and evaluation of iron-fortified extruded rice grains. J Food Sci 70:S330–6.

Motzok I, Pennell MD, Davies MI, Ross HU. 1975. Effect of particle size on the bioavailability of reduced iron. J Assoc Off Anal Chem 58:99–103.

National Food Fortification Committee Ministry of Public Health Thailand. 2003. Thailand's country investment plan on food fortification. Reported to Asian Development Bank.

Nestel P, Ritu N. 2000. Manual for flour fortification with iron. Guidelines for the development, implementation, monitoring and evaluation of a program for wheat flour fortification with iron. (Part 1 of 3). Mictronutrient Initiative/OMNI/USAID. October (2000) IDPAS# 189.

Nilson A. 1994. Fortification of staple food. NUTRIVIEW 3/94. Basel, Switzerland: Vitamin Division, F. Hoffmann-La Roche Ltd.

Nilson A, Piza J. 1998. Food fortification: a tool for fighting hidden hunger. Food Nutr Bull 19:49–60.

OMNI/Roche/USAID. 1997. Fortification basics: choosing a vehicle. Basel, Switzerland: Roche Vitamins & Chemicals. IDPAS# 054.

Phillips M, Sanghvi T, Suárez R, McKigney J, Vargas V, Wickham C. 1994. The costs and effectiveness of three vitamin A interventions in Guatemala. Washington, D.C.: US Agency for Intl. Development.

Puysuwan L, Chavasit V, Sungpuag P, Hediger D, Punvichai T. 2007. Feasibility and use of vitamin A-fortified vegetable oils among consumers of different socioeconomic status in Thailand. Food Nutr Bull 28(2):181–7.

Sandström B. 2001. Micronutrient interactions: effects on absorption and bioavailability. Br J Nutr 85(Suppl 2):S181–5.

Verma RS, Motzok I, Chen SS, Rasper J, Ross HU. 1977. Effect of storage in flour and of particle size on the bioavailability of elemental iron powders for rats and humans. J Assoc Off Anal Chem 60:759–65.

Watanapaisantrakul R, Chavasit V, Kongkachuichai R. 2006. Fortification of soy sauce using various iron sources: sensory acceptability and shelf stability. Food Nutr Bull 27(1): 19–25.

[WHO] World Health Organization. 1999. International program on chemical safety. Additives and contaminants. Joint FAO/WHO Expert Committee on Food Additives (JECFA). 53rd meeting, 1999 June 1–10; Rome, Italy. Rome, Italy: Food and Agriculture Organization of the United Nations. Additives and contaminants.

WHO/UNICEF/ICCIDD. 2001. Assessment of iodine deficiency disorders and monitoring their elimination. WHO/NHD/01.1. Geneva, Switzerland: World Health Organization.

World Bank. 1993. Investing in health. World Development Report 1993. New York: Oxford Univ. Press.

Zilberboim R. 1994. Fortification of rice with iron and iron absorption-enhancing factors: production and evaluation of extruded simulated rice. New Brunswick, N.J.: Rutgers Univ.

COMPREHENSIVE REVIEWS IN FOOD SCIENCE AND FOOD SAFETY

Ethics and Public Health Policy: Lessons from Salt Iodization Program in India

R. Sankar, C.S. Pandav, and G. Sripathy

ABSTRACT: India had launched a Natl. Goitre Control Programme (NGCP) in 1962. Initially, the NGCP was limited to geographical areas with high goiter prevalence. By the early 1980s, data showed that iodine deficiency is a public health problem in all the states and union territories and it was decided to iodize all salt for humans in a phased manner, and the program was renamed as Natl. IDD Control Programme (NIDDCP) in 1992. The infrastructure to produce the required quantity of iodized salt was established, and India enacted legal measures that mandated iodization of all edible salt. The ban on the sale of noniodized salt was lifted in September 2000. In April 2001, concessional tariff for transport of iodized salt was removed and freight for transporting salt by rail was hiked. These measures resulted in a significant drop in the household coverage of iodized salt from 49.3% (NFHS 2 1998–1999) to 37% (DLHS 2002–2004). Why is there a need for legislation and compulsory salt iodization? Can people have a choice? There are situations in which, in the absence of proper education, "the freedom to choose" may not offer the right choice—and salt iodization is one of them. Law is essential and needs to be combined with advocacy, consumer education, and quality assurance.

Introduction

Iodine deficiency results in a wide spectrum of disorders collectively known as iodine deficiency disorder (IDD) (Hetzel 1987). Worldwide nearly 2.2 billion people live in iodine-deficient areas and are at risk. Adequate evidence is now available both from controlled trials and successful iodization programs that IDD can be prevented by correction of the iodine deficiency (Hetzel 1987). Prevention will result in improved quality of life and productivity and also in improved educability of children.

India was a pioneer in both recognizing iodine deficiency as a national public health problem and providing iodized salt to its population. Iodized salt was first made available in 1956 during a seminal study on goiter prevention and control in the Kangra district of Himachal Pradesh (Sooch and others 1973). While only a few countries in 1980s had recognized iodine deficiency as a public health problem or established a national IDD control program, India by 1962 had launched a national goiter control program (NGCP; Pandav and others 1989).

By the early 1980s, data collected from different regions of India revealed that iodine deficiency was a public health problem in all the states and union territories (ICMR 1989; Pandav and others 1989). Around this time, convincing evidence was accumulating on the need for optimal iodine intake for normal physical and mental development. In the light of increasing evidence of the existence of iodine deficiency in most parts of India, the scope of the NGCP was expanded to cover the entire country and it was decided to iodize all salt for human consumption by 1990 (universal salt iodization, USI), in a phased manner. In September 2000, the ban on the sale of noniodized salt was lifted (GOI Gazette 2000). The Indian government cited freedom of choice as the reason for this retrograde step. This measure resulted in significant drop in household coverage of iodized salt. The Natl Family Health Survey-2 (NFHS-2) in 1998–1999 showed that 49.3% of households in India were consuming adequately iodized salt (NFHS 2000). The Reproductive and Child Health (RCH) survey in 2001–2002 showed that this had dropped to 37%, and that in several north Indian states, the household coverage was abysmally low. There are ideological debates on individual freedom and choice, which are used to argue against compulsory iodization. This article uses the example of salt iodization program in India to discuss the issues that help implement sustainable universal salt iodization programs.

Iodine

The physiological role in the body

Iodine is a trace element. It is an essential micronutrient and is present in the body in minute amounts (15 to 20 g). Its only confirmed role is in the synthesis of the thyroid hormones, thyroxine (T4), and triiodothyronine (T3). Thyroid hormones regulate many important functions of the body such as calorigenesis,

---

MS 20080112 Submitted 2/13/2008, Accepted 6/6/2008. Author Sankar is with Global Alliance for Improved Nutrition (GAIN), New Delhi, India. Author Pandav is with Centre for Community Medicine, All India Inst. of Medical Sciences (AIIMS), New Delhi, India. Author Sripathy is with Inst. of Nuclear Medicine and Allied Sciences, Defence Research and Development Organisation, Delhi, India. Direct inquiries to author Sankar (E-mail: rsankar@gaingeneva.org).

thermoregulation, and intermediary metabolism. The most important function of the thyroid hormones is in human brain maturation. The "critical period" for dependency is known to extend from conception to 3 y of age, with a progressively decreasing dependence over that interval. The dietary allowances of iodine recommended by WHO/UNICEF/ICCIDD are shown in Table 1 (WHO 1996).

Food sources

Oceans are the primary sources of iodine in the world. There is a cycle of iodine in which, iodine from the sea is carried with the rain and precipitated on the soil, from where it is washed out and carried back to the sea. How much iodine is present in any particular soil depends on the amount of precipitation, its organic content, and especially how permanent the superficial soil layers are. The iodine content of plants and water depends critically on the content in the soil. The iodine content in animals depends on the concentration of this element in the plants on which they feed. Most of the iodine one needs comes from food. No plant is known to concentrate iodine preferentially.

Iodine deficiency

Iodine deficiency is due to low content of iodine in the local environment. When the soil of any area lacks iodine, the crops too are deficient in this essential nutrient. Those people who live in an iodine-deficient environment and eat its crops regularly do not get their requirement of iodine.

Iodine deficiency is a major public health problem worldwide. Iodine is a water-soluble element. It is present in the upper crest of the Earth. Iodine-deficient soil is encountered in high mountainous areas. It is also encountered in areas with high rainfall and where floods are frequent. All areas where soil erosion is seen are also becoming iodine deficient. Staple foods cultivated in such soil are deficient in iodine and result in iodine deficiency in the indigenous population.

Consequences of iodine deficiency

When the physiologic requirement of iodine are not met in a given population it results in a wide spectrum of effects of iodine deficiency on growth and development, collectively termed iodine deficiency disorders (IDD). A diet deficient in iodine affects people of all ages, but particularly pregnant women, the developing fetus, and the neonate.

Iodine deficiency disorders (IDD)

IDD include goiter at all ages; endemic cretinism, characterized most commonly by mental deficiency, deaf-mutism, and spastic diplegia, and lesser degree of a neurological defect related to fetal iodine deficiency; impaired mental function; increased stillbirths, and perinatal and infant mortality.

Goiter refers to an enlargement of the thyroid gland. When goiter is present in 10% or more of the population in any geographical region, it is referred to as endemic goiter. Iodine deficiency is the most important cause for endemic goiter.

Table 1—Recommended daily iodine intake in human beings (WHO/UNICEF/ICCIDD).

Nr	Age group	Iodine requirement (μg)
1.	Infants (0 to 11 months)	50
2.	Children (12 to 59 mo)	90
3.	School age children (6 to 12 y)	120
4.	Adults (above 12 y)	150
5.	Pregnant and lactating women	200

What Is the Social Cost of Iodine Deficiency?

Iodine deficiency at critical stages during fetal and early postnatal life impairs development of the brain and, consequently results in impaired mental function. Mental and motor development in children from iodine-deficient areas is lower compared to children from iodine-sufficient environment (Mehta and others 1987; Sankar and others 1994). Hypothyroxinemia is common in iodine-deficient areas. Maternal thyroxine is crucial for brain development in early fetal life, including the 1st trimester, before the onset of fetal thyroid function (Morreale de Escobar and others 1985; Escobar del Rey and others 1986). Several publications have drawn attention to the relation between the thyroid hormone status of the mother and the future neuropsychological development of the child (Haddow and others 1999; Pop and others 1999). Recent studies also support the possibility of improving the intelligence quotient of children from areas with mild iodine deficiency by ensuring an iodine intake sufficient to achieve a urinary iodine concentration of more than 100 μg/L (Santiago-Fernandez and others 2004). Iodine deficiency shifts the population mean of intelligence quotient to the left. On an average, children living in iodine-deficient areas have intelligence quotient which is 13 points lower than children living in iodine-sufficient areas (Bleichrodt and Born 1994).

Global Prevalence of IDD

Iodine deficiency constitutes one of the most important nutritional groups of diseases all over the world. The developing countries are more severely affected. In the year 1960, WHO monograph, Kelly and Snedden estimated a population of 200 million in the world to be suffering from goiter. Subsequent estimates greatly exceeded this figure. A recent WHO review reveals that of 191 countries, IDD was a public health problem in 130, and the data were insufficient to categorize another 41. Only 20 countries could be classified as no longer having IDD. Globally, about 740 million people have goiter, that is nearly 13% of the world's population, and over 2 billion people are exposed to the risk of IDD. Global prevalence is shown in Table 2.

Magnitude of the Problem in India

Iodine deficiency disorders (IDD) have been an ancient scourge of mankind. They have been depicted in sculptures and paintings worldwide, including those of ancient India.

India is the 2nd most populous country in the world with a population of 1027 million (2001 Census). There is a high prevalence of goiter and cretinism in the Himalayan and sub-Himalayan goiter belt from Jammu and Kashmir in the West to Arunachal

Table 2—Prevalence of IDD in school-age children based on urinary iodine.

WHO region[a]	Proportion of population with UI $<$ 100 μg/L (%)	Population with UI $<$ 100 μg/L (in millions)[b]
Africa	42.3	49.465
The Americas	10.1	9.955
Eastern Mediterranean	55.4	40.224
Europe	59.9	42.215
South East Asia	39.9	95.628
Western Pacific	26.2	47.956
Total	36.5	285.443

[a] 192 WHO Member States
[b] Based on population estimates for the year 2002.
Source: WHO Global Database on IDD, 1993 to 2003.

Pradesh in the East and along this entire length extending at least 500 km south of the Himalayas into the flat sub-Himalayan *terai* (plains). The Himalayan goiter belt includes Jammu and Kashmir, Himachal Pradesh, Punjab, Haryana, Uttar Pradesh, Bihar, West Bengal, Sikkim, Assam, Mizoram, Meghalaya, Tripura, Manipur, Nagaland, and Arunachal Pradesh.

In addition to the well-known Himalayan endemic belt, iodine deficiency and endemic goiter have been reported from many other States in India (Pandav and others 1989).[3] In 1989, the Indian Council of Medical Research (ICMR) published the findings of a multicentric IDD prevalence study. Nine states outside the "traditional goiter belt" were studied for the prevalence of goiter and cretinism. Goiter and cretinism were reported in 21.1% and 0.7% of the total 409923 individuals examined (ICMR 1989).

Results of sample surveys conducted by different agencies in 283 districts of 29 states and 4 Union territories of India have shown a high prevalence of IDD in 247 districts. No State and Union territory in the country is free from IDD making it a major public health problem.

IDD—Solution

Everyone needs and consumes salt, usually in fairly constant daily amounts. The average daily salt intake per person in India is 10 g. The sources of salt are usually limited and thus it is feasible to add iodine to salt. The techniques for iodization are simple and well established and iodization does not affect the appearance or taste of salt; iodized salt is well accepted by the consumer. Therefore, salt iodization is the preferred strategy for elimination of iodine deficiency and is currently practiced in more than 130 countries.

In India, over the past few years, considerable progress has been made in improving the availability and accessibility of good quality iodized salt to the population. The Salt Commissioner's office under the Ministry of Industry is responsible for monitoring, production and distribution of iodized salt to the States and Union territories. The Salt Commissioner's office is also responsible for monitoring the quality of iodized salt at the production level. The Salt Commissioner, in consultation with the Ministry of Railways and State Governments, arranges for the movement of iodized salt from the production centers to the Sates and Union territories. The Ministry of Health, Government of India, is also providing financial grants to the Salt Commissioner's office for the running and maintenance of 9 quality control laboratories at the iodized salt production centers.

Iodized salt production increased from 0.2 million metric tons in 1983 to more than 4 million metric tons in 2000. The infrastructure to produce the required quantity of iodized salt has been established and the proportion of the population consuming iodized salt has the potential to reach or exceed 90%. However, the policies relating to salt iodization has not been consistent. In September 2000, the Government of India lifted the ban on the sale of noniodized salt. The reason given by the Government of India: "matters of public health should be left the informed choice, and not enforced through compulsion." Lifting of the ban resulted in a significant drop in the household coverage of iodized salt in all the states.

Ethics and Public Health Policy

There are 4 basic principles that govern medical ethics: (1) autonomy—this is about human dignity and freedom, the fundamental rights of the individual; (2) nonmaleficence—this is the principle of doing no harm; (3) beneficence—this is the principle of doing good which the public health professionals believe is the main function of health care; (4) justice—this in the ethical sense means natural justice, distributive justice, fairness, equity, and impartiality. These principles are upheld as far as possible in all aspects of health care, but sometimes they are in conflict.

Health is a "Merit Good." Governments have a responsibility to protect public health. Individuals often cannot make good choices when the benefits are preventive in nature or in the future. For a population at the base of the economic pyramid, nutrition is a low-purchase priority. These people are cost-sensitive. Additionally, there is no perceived need as most of the consequences of iodine deficiency are hidden. Therefore, the most at risk choose the least expensive product. It is therefore absolutely necessary to have a system by which the access to high quality iodized salt is made available at an affordable price. The decision of India on 27 May 2005 to re-impose the ban on the sale of noniodized salt is a step in the right direction.

Legislation as Opposed to Choice

Is there a need for legislation and compulsory salt iodization? Can people have a choice? There are situations in which, in the absence of proper education, "the freedom to choose" may not offer the right choice—and salt iodization is one of them. Individuals often need to be convinced to make good choices when the benefits are preventive in nature. There are ideological debates on individual's freedom and choice, which are used to argue against compulsory iodization. Public health experts who see iodine deficiency as a critical problem should lead the fight against the ideological arguments tilted in the direction of doing nothing. It is helpful to remember that the history of government interventions on behalf of public health, including the campaign against smoking, is one of consistent life-enhancing success. We need to strive to make iodized salt available, accessible, and affordable to every Indian citizen for all time to come.

Legislation is 1 essential step; but in itself, it is not sufficient to achieve USI. Despite well meaning legislation, practice often lags behind policy. Legislation presupposes effective monitoring and enforcement based on the partnership of the salt industry and governmental agencies. In such a partnership, the government seeks improved public health, and the industry seeks protection against competition with noniodized salt. In the Indian salt iodization program, the supportive legislation was found essential as evident from the fact that when the law was repealed the household coverage dropped significantly. However, the legislation in itself is not sufficient in that the household coverage with adequately iodized salt was less than 50%. Therefore, success and sustainability of salt iodization programs would depend on supportive legislation, regulatory monitoring and enforcement of law, quality assurance, and consumer demand through behavior change communication.

References

Bleichrodt N, Born M. 1994. A meta-analysis of research on iodine and its relationship to cognitive development. In: Stanbury JB, editors. The damaged brain of iodine deficiency—cognitive behavioural, neuromotor, educative aspects. New York: Cognizant Corp. p 195–200.

District level household survey-Reproductive and Child Health (DLHS-RCH)2002-203. Ministry of Health and Family Welfare, Government of India.

Escobar del Rey F, Pastor R, Mallol J, Morreale de Escobar G. 1986. Effects of maternal iodine deficiency on the L-thyroxine and 3,5,3′ triiodo-L-thyronine contents of rat embryonic tissues before and after onset of foetal thyroid function. Endocrinology 118:1259–65.

Gazette. 2000. Government of India. September 13.

Haddow JE, Palomaki GE, Allan WC, Williams JR, Knight GJ, Gagnon J. 1999. Maternal thyroid deficiency during pregnancy and subsequent neuropsychological development of the child. N Engl J Med 341:549–55.

Hetzel BS. 1987. An overview of the prevention and control of iodine deficiency disorders. In: Hetzel BS, Dunn JT, Stanbury JB, editors. The prevention and control of iodine deficiency disorders. Elsevier Science Publishers B V. p 25–27.

ICMR. 1989. Epidemiological survey of endemic goitre and endemic cretinism: reports of ICMR Task Force Study. New Delhi: Indian Council of Medical Research.

Mehta M, Pandav CS, Kochupillai N. 1987. Intellectual assessment of school children from severely iodine deficient villages. Ind Pediatr 24:467–70.

Morreale de Escobar G, Pastor R, Obregon MJ, Escobar del Rey F. 1985. Effects of maternal hypothyroidism on the weight and thyroid hormone content of rat embryonic tissue, before and after onset of foetal thyroid function. Endocrinology 117:1890–900.

NFHS. 2000. National Family Health Survey (NFHS-2) 1998-99. Mumbai: Intl. Inst. for Population Sciences.

Pandav CS, Mohan R, Karmarkar MG, Subramanian A, Nath LM. 1989. Iodine deficiency in India. Natl. Med J Ind 2(1):18–21.

Pop VJ, Kuijpens JL, van Baar AL, Verkerk G, van Son MM, de Vijlder JJ. 1999. Low maternal thyroid deficiency during early pregnancy are associated with impaired psychomotor development in infancy. Clin Endocrinol (Oxf) 50:149–55.

Sankar R, Rai B, Pulger T, Tara S, Tara L. 1994. Intellectual and motor development in school children from severely iodine deficient region—Sikkim. Ind J Pediatr 61:407–14.

Santiago-Fernandez P, Torres-Barahona R, Muela-Martinez JA, Rojo-Martinez G, Garcia-Fuentes E, Garriga MJ. 2004. Intelligence quotient and iodine intake: a cross-sectional study in children. J Clin Endocrinol Metab 89:6054–60.

Sooch SS, Deo MG, Karmarkar MG, Kochupillai N, Ramachandran K, Ramalingaswami V. 1973. Prevention of endemic goitre with iodised salt. Bull WHO 49:307–12.

WHO/UNICEF/ICCIDD. 1996. Recommended iodine levels in salt and guidelines for monitoring their adequacy and effectiveness. Geneva: WHO/NUT/96,13.

COMPREHENSIVE
REVIEWS
IN FOOD SCIENCE AND FOOD SAFETY

Development of the Double-Fortified Salt from the National Institute of Nutrition

S. Ranganathan and B. Sesikeran

ABSTRACT: The Natl. Inst. of Nutrition (NIN), Hyderabad, developed iodine and iron double-fortified salt (DFS) as "one intervention controlling two problems," namely, iodine deficiency disorders (IDDs) and iron deficiency anemia (IDA). NIN-DFS contains foodgrade common salt with low magnesium and high NaCl, potassium iodate, ferrous sulfate heptahydrate, and sodium hexametaphosphate (SHMP) as a stabilizer, and 30 ppm iodine and 1000 ppm iron. Large-scale production in factories is by dry-mixing powdered salt with iodine and iron compounds. The stability of iodine and iron in this salt has been shown to be more than 1 y. Organoleptic trials with commonly consumed Indian foods indicated good acceptability. Human metabolic studies showed excellent bioavailability of iron and iodine. Biosafety studies confirmed the safety of NIN-DFS. Epidemiological studies showed significant reduction in the prevalence of total goiter and anemia. The cost of 1 kg NIN-DFS works out to be 1 rupee (0.025 US$) more than that of iodized salt. A high-power committee, constituted by the Ministry of Health and Family Welfare, Government of India, recommended the introduction of NIN-DFS in nutrition programs. Establishment of the specifications under the Prevention of Food Adulteration Act (PFA; 2008), Government of India and the standards of the Bureau of Indian Standards (BIS) are in progress. A memorandum of understanding (MoU) is being signed for free technology transfer between NIN and salt manufacturers who would supply at least 20% of the produce to the Government for distribution through the public distribution system for the benefit of people living below the poverty line at a price fixed by the Government.

Introduction

Iodine deficiency disorders (IDDs) and iron deficiency anemia (IDA) form the major micronutrient deficiencies of public health significance in India. Several surveys have indicated that no state in the country is free from IDDs and nearly two-thirds of children, women of reproductive age, and adolescent girls across the country are estimated to be suffering from IDA (NNMB 2003; Report 2003; The State of the World's Children 2007). The control of micronutrient deficiencies by food fortification is one of the most significant developments in recent years. Probably no other technology available today offers such a wide scope to improve the health and nutritional status of people in the most cost-effective way (World Bank 1994; Adamson 2004). Next to water, salt is consumed by all sections of a community irrespective of economic level; it is consumed at approximately the same level throughout the year in a given region by all normal populations; it has very little likelihood of overdosing; production of salt is limited to few centers; salt is an ideal vehicle for micronutrient fortification and micronutrients like iodine and iron introduced through salt will be ingested by each individual at a uniform dosage throughout the year. Because of these reasons, a major proportion of the world's salt is currently iodized. India has made rapid progress in this regard and has been successfully using low-cost technologies for the production of iodized salt (Ranganathan and others 1997, 2000) and iron-fortified salt (Ranganathan 1992; Ranganathan and others 1993).

Genesis of NIN-DFS

As a sequel to the introduction of universal iodization of edible salt as a National Policy in the country, NIN evolved the concept of double-fortification of salt (DFS) with iodine and iron for controlling the deficiencies of both these micronutrients in a single

MS 20070921 Submitted 12/12/2007, Accepted 2/27/2008. Authors are with Natl. Inst. of Nutrition, (Indian Council of Medical Research), Ministry of Health and Family Welfare, Govt. of India, Jamai-Osmania, Hyderabad 500007, India. Direct inquiries to author Ranganathan (E-mail: dirnin_hyd@yahoo.co.in)

measure as "one intervention controlling two problems." NIN-DFS was developed with good-quality foodgrade salt (100%); potassium iodate, KIO_3 (0.0067%); ferrous sulfate heptahydrate, $FeSO_4.7H_2O$ (0.508%); and sodium hexametaphosphate (SHMP) at the 1% level to provide simultaneously about 30 to 40 μg iodine and 1000 μg iron/g of DFS (Rao 1994). SHMP is a permitted food additive (JECFA 1992) and is extensively used in the food industry. SHMP in NIN-DFS is intended to protect and prevent the interaction of iodine from undesirable reactions with iron and other constituents of the salt in DFS. Good-quality foodgrade common salt (magnesium < 0.10%, moisture < 1.5%, NaCl > 98%) and foodgrade chemicals are used in the production of NIN-DFS. Higher levels of magnesium or moisture in salt are detrimental to the stability of iodine in DFS (Ranganathan and others 1996).

Double-Fortification Strategy

NIN-DFS is intended to provide the daily requirements of 150 μg iodine and 10 mg iron with an average consumption of about 10 g salt per adult per day in India. Iron content exceeding 1 mg/g in DFS is not compatible with desirable stability of iodine in DFS and, therefore, at the suggested level of 1000 ppm the amount of iron available from DFS will be 10 mg per person per day, which is nearly 30% of recommended daily intake (RDI) for iron. This was shown to be practical to prevent anemia or reduce the prevalence of IDA through regular and continued consumption of DFS over a period. At the level of one-third of RDI for iron, the consumption of DFS is only prophylactic and not, therefore, expected to result in any dramatic increase in hemoglobin instantaneously. In view of this, it is necessary to consume NIN-DFS over a long period of above 2 y to result in any significant impact on hemoglobin levels. However, the absorption is likely to be relatively higher in pregnant women (due to their higher physiological requirement) and anemic subjects; and thus consumption of NIN-DFS could lead to a swift increase in the hemoglobin levels of these groups.

Process and Methods of Fortifying Salt

The DFS is produced according to a dry mixing method reported by Ranganathan and others (1996). The production of DFS with effective quality control measures consists of (1) addition of premix and (2) blending of salt. Premix can be added to salt in 2 ways: manually or using an automatic dosifying machine; the premix is prepared on a batch basis for batch mixing process and on a shift basis for continuous process (Ranganathan 2005).

Stability of Nutrients

Laboratory studies, factory studies, and community studies have shown good stability of iodine and iron beyond 6 mo (Brahmam and others 1994; Rao 1994; Ranganathan and others 1996). In the double-blind placebo study carried out with NIN-DFS in school children (1996–1998), 1 batch of DFS showed less than 15 ppm of iodine (Brahmam and others 2000). Due to the double-blind nature of this study, no corrective measures could be taken during the study and, therefore, more detailed investigations were carried out later. A series of studies including a large-scale multicentric study (Interim Report 2003; Ranganathan and others 2005) were carried out on the stability of iodine under programmatic conditions. It was found that the method of iodine estimation using sulfuric acid, usually applied to iodized salt, did not yield consistent results of iodine content with DFS. Therefore, a modified method was developed for iodine estimation of DFS (Ranganathan and Karmarkar 2006). When the modified method was employed NIN-DFS showed excellent stability of iodine and iron longer than 1 y (Figure 1). Such data were confirmed independently in different laboratories under good quality control; also, the variations observed in iodine values of duplicate samples narrowed down appreciably (Ranganathan and others 2007). In no instance in the series of studies carried out there was any problem in the stability of iron in DFS (Table 1).

Acceptability

NIN-DFS and unfortified common salts were used in the preparation of various commonly consumed foods (n = 30) and the acceptability of DFS was studied. Foods prepared with unfortified common salt served as control (double-blind). Volunteers between age 25 and 50 y (n = 40) evaluated all the food items. They were not aware of the presence or absence of DFS in the food items and they were asked to rate the quality of different attributes by assigning scores from 1 to 5 (1 = poor, 5 = very good). When the difference between mean scores allotted was tested, the results showed that there was no difference in the organoleptic properties of a variety of foods between DFS (4.1 to 5.0) and unfortified salt (4.0 to 4.9); there were no changes in color, appearance, taste, and odor of the foods (Ranganathan and others 1996). DFS was well accepted in day-to-day cooking, and there were no complaints regarding the quality of the foods prepared with it (Brahmam and others 1994, 2000; Sivakumar and others 2001).

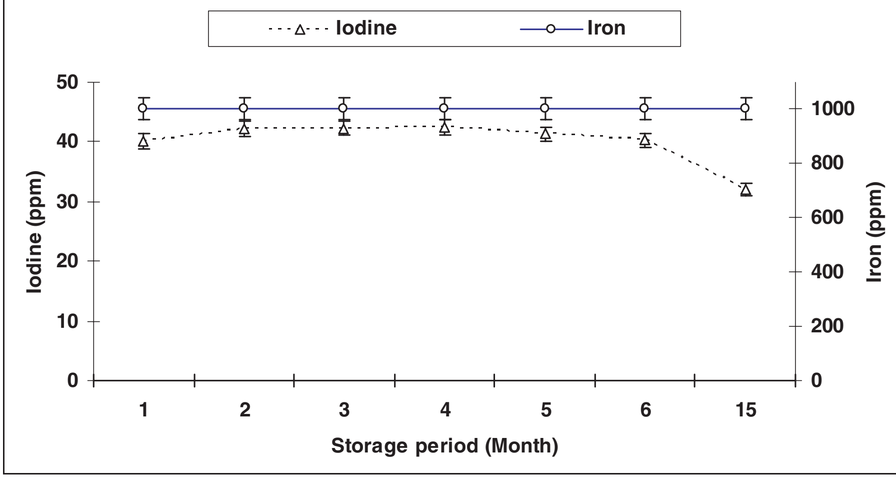

Figure 1 – Stability of iodine and iron in NIN double-fortified salt over time.

Bioavailability of Nutrients

Before NIN-DFS could be recommended for use in the community to control IDDs and IDA, it was necessary to demonstrate the bioavailability of iron and iodine in the predominantly cereal-based diets consumed in the country. Iron absorption was studied in human volunteers by a double-isotope technique using radiolabeled iron salts. The mean absorption of iron from DFS when consumed with a rice-based meal was 6.1% for DFS as compared to 3.9% for control salt; the absorption of iodine from DFS and iodized salt (IS) determined by urinary iodine excretion (UIE) remained the same and was not affected by the presence of either SHMP or iron in DFS (Rao 1994).

Operational Feasibility

The operational feasibilities of NIN-DFS were successful, which can be understood from the following.

Production

The technology of NIN-DFS is based on a simple method of dry-mixing salt with iodine and iron compounds and does not involve elaborate or expensive measures (Ranganathan and others 1996). Large-scale production of DFS (9 to 60 metric tons) was successful in salt factories located at Hyderabad, Chennai, Valinokkam, Alathur, Thirupporur, Bhubaneswar, Mithapur, Gandhidham, and Tiruchengode throughout the country.

Transportation

Packing of NIN-DFS in 0.5-kg or 1-kg low-density polyethylene pouches and long-distance transportation by road (1) from Valinokkam to Hyderabad, (2) from Hyderabad to remote tribal areas of the East Godavari district of AP, (3) from Chennai to Hyderabad, (4) from Alathur to Bhubaneswar, Dibrugarh, Delhi, Surat, and Mumbai, and (5) from Bhubaneswar to Delhi and Hyderabad was found to be feasible and smooth (Brahmam and others 1994, 2000; Rao 1994; Ranganathan and others 1996, 2005, 2007; Interim Report 2003).

Distribution

NIN-DFS was distributed to households periodically in 1-kg pouches in the community study in tribal areas of the East Godavari district of AP, while it was supplied in 50-kg sacs to the residential schools in Hyderabad for over 2 y in each study (Brahmam and others 1994, 2000; Sivakumar and others 2001).

Biosafety

SHMP is an internationally permitted food additive (JECFA 1992). Furthermore, the daily ingestion of phosphorus is 30 mg through the intake of 10 g NIN-DFS. Nevertheless, the biosafety of NIN-DFS was reevaluated as an item for daily consumption through foods. The SHMP being a polyphosphate, perhaps could alter calcium/phosphorus turnover and thus bone metabolism. Therefore, the safety of long-term (9 mo) feeding of DFS in relation to Ca and P metabolism was tested in rats. In addition, the hemoglobin regenerating ability of diet with DFS was compared with both iron-fortified salt (IFS) and unfortified salt using a depletion-repletion rat model. The results at the end of 4 wk revealed that the amounts of hemoglobin regenerated in both the fortified-salt-fed groups (DFS: 13.0 ± 1.4 and IFS: 11.7 ± 1.4 g/dL) were significantly higher than that in the unfortified salt group (7.6 ± 4.0 g/dL); at the end of 9 mo, the hemoglobin levels increased to 15g/dL in both DFS and IFS groups; no untoward effect was observed on the integrity of bone and the histopathology of various tissues in experimental rats (Nair and others 1998a). It was concluded from the results that long-term feeding of NIN-DFS containing SHMP does not apparently impair Ca and P balances in rats and is relatively safe in day-to-day use in the diets. Similar results were obtained for Ca and P balances in children (Nair and others 2000). Thus, the daily consumption of DFS was proved to be safe.

Efficacy Study 1: Tribal Areas

The purpose of this study was to choose a population suffering from IDDs as well as IDA and to demonstrate the effect of DFS on the control of both the disorders. The tribal Agency area, Rampachodavarm, East Godavari district, reported to be suffering from the twin problems was chosen for this study. This study was carried out in 4 selected blocks of Andhra Pradesh in the district of East Godavari. In each block, about 5000 individuals living in 15 to 20 contiguous villages were covered in the study. After conducting a baseline survey, DFS, IFS, and IS were provided, respectively, in the experimental areas for 2 y, while in the control area unfortified salt was consumed. The study was initiated in 1989 and completed in 1992. The DFS was produced in a salt factory in Hyderabad. Production, transportation, and distribution of fortified salts were carried out without any problem. The salts were packed in 1-kg low-density polyethylene pouches, with suitable color codes (for easy monitoring) and distributed to the households every month, at the rate of 0.5 kg per person per month. As it was a single-blind study, the investigators were

Table 1 — Distribution (percent) of samples with iodine of $\geq$ 15 ppm and iron of 850 to 1100 ppm at 6 mo in different studies carried out with NIN-DFS.

							%[a]	
Nr	**Study**	**Year**	**Salt produced (metric ton)**	**Salt supply (kg)**	**Study period**	**Samples tested (n)**	**Iodine (≥15 ppm)**	**Iron (850 to 1100 ppm)**
1	Laboratory	1981–1984, 1997	0.1	1	1 y	300	100	100
2	Factory	1984, 1996	20	50	6 mo	500	100	100
3	Community	1989–1992	60	1	2 y	1500	91–98	100
4	Residential school	1997–1998	9	50	2 y	12[b]	100 in 2 batches[c] and 50 in 1 batch[c]	100
5	Multicentric stability	2001–2003	6	1	2 y	1440	76[c]	100
6	Multicentric stability	2004	0.5	0.5	6 mo	720	100	100

[a] Mean values of duplicates of respective number of samples.
[b] Main emphasis on iron impact.
[c] Sulfuric acid method for iodine estimation.

unaware of the type of salt used in each area; the color codes were broken only at the end of the study. All the families in the study accepted NIN-DFS as cooking salt and the compliance was 100%. None of the beneficiaries complained of any side effects due to the consumption of NIN-DFS. No undesirable effect, allergy, or toxicity was encountered throughout the study period of 2 y (Brahmam and others 1994; Nair and others 1998b). The average intake of salt was around 8.0 g/d per person and did not differ from salt to salt.

Efficacy Study 2: Residential Schools

A double-blind placebo study was carried out for 2 y from 1996 in 4 social welfare residential schools around Hyderabad. One each of boys' and girls' schools was randomly allocated to experimental DFS and the remaining to control IS. The main aim of the study was to study the impact on iron status and not that of iodine status. The study population was a captive group consisting of children belonging to school classes 5 to 10 of age 10 to 15 y, stratified into 4 groups, namely, DFS boys, DFS girls, IS boys, and IS girls in 2 treatment units and thus has comparable age, gender, and education levels in between schools for treatment effect. Nine metric tons each of DFS and IS, manufactured in a salt factory at Chennai, were supplied in 50-kg high-density polyethylene bags in 3 and 2 batches, respectively. Hemoglobin status, urinary iodine excretion (UIE) and calcium-phosphorus homeostasis of the beneficiaries were evaluated. NIN-DFS was readily accepted as cooking salt and the compliance was 100%. No undesirable effect, allergy, or toxicity was observed during the entire study period (Nair and others 1998b; Brahmam and others 2000). The average intake of DFS or IS was about 7.0 g/d per person.

Impact on Iodine Status

NIN-DFS was as effective as IS in controlling IDDs in the tribal population as shown by a significant reduction in the prevalence of goiter from 28% to 14% in the DFS group (Figure 2) and 26% to 16% in the IS group (not shown in Figure 2). The median urinary iodine excretion levels increased significantly in the DFS group from 116 to 155 μg/L in the tribal study and from 68 to 108 μg/L in the residential school study (Figure 2). Thus, the results clearly proved that NIN-DFS was very effective in controlling IDDs of the population (Brahmam and others 1994, 2000).

Impact on Iron Status

The overall prevalence of anemia in the DFS supplement group in the tribal study decreased from 74% to 36% in 1- to 5-y-old children (boys and girls), 80% to 55% in boys 6 to 13 y of age, 79% to 66% in girls 6 to 13 y old, 67% to 28% in boys of 14 to 17 y, 80% to 68% in girls 14 to 17 y old, 80% to 72% in pregnant women, and 87% to 60% in lactating women. The hemoglobin levels increased significantly in anemic children, while there was a marginal improvement or no improvement in nonanemic subjects. The proportion of anemic children decreased from 83% to 57% ($P < 0.01$) after supplementation with DFS (Figure 3) (Brahmam and others 1994). Though the study was carried out over 2 y and only initial and final hemoglobin values were considered for interpretation here, there was 1 more round of hemoglobin estimation carried out in between at the end of 1 y. The data showed that in every group, including the control, there was a decrease in the mean values of hemoglobin after 1 y but was followed by a definite increase in hemoglobin at 2 y. Such changes, including those in controls, could only be attributed to the environmental factors. The incidence of malaria in tribal areas accounts for 40% of the total malaria cases in the country, and it was at a maximum during the course of the study. It was found that this tribal belt was affected by outbreaks of malaria during the 1st year of the study (Central Bureau of Health Intelligence 1993; ICMR 1994). The improvement in hemoglobin status with iron supplementation is adversely affected in malarial endemic areas (INACG 1999). Thus, at the end of 2 y with improvement in the malarial situation, hemoglobin also perhaps showed marked recovery (Table 2).

Therefore, a study in 4 social welfare residential schools around Hyderabad (2 boys' and 2 girls') each having about 400 children where these potential confounding factors did not operate, was taken up mainly to assess the impact of NIN-DFS on hemoglobin status. The results of the residential school study showed a significant decrease in hemoglobin at the end of the study, in the group treated with DFS the fall in hemoglobin was less (Brahmam and others 2000). NIN-DFS improved the hemoglobin level of anemic children and was able to reduce the prevalence of anemia significantly (Figure 3) indicating the effect of NIN-DFS in reducing the prevalence of anemia. However, in the IS group, the decrease in the prevalence is not significant (before: 53.7% and after: 47.4%). Covariate, a statistical method of analysis to understand the variations in the initial hemoglobin with respect to gender, age, and

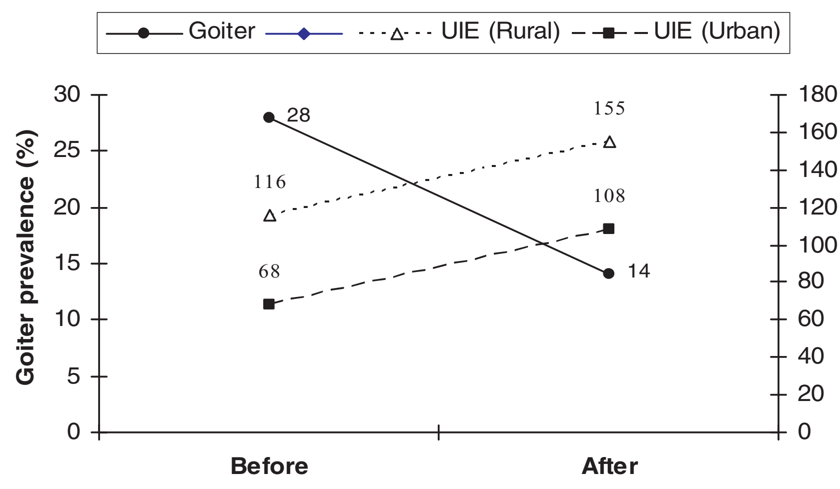

Figure 2—Impact of NIN-DFS on iodine status (UIE: urinary iodine excretion).

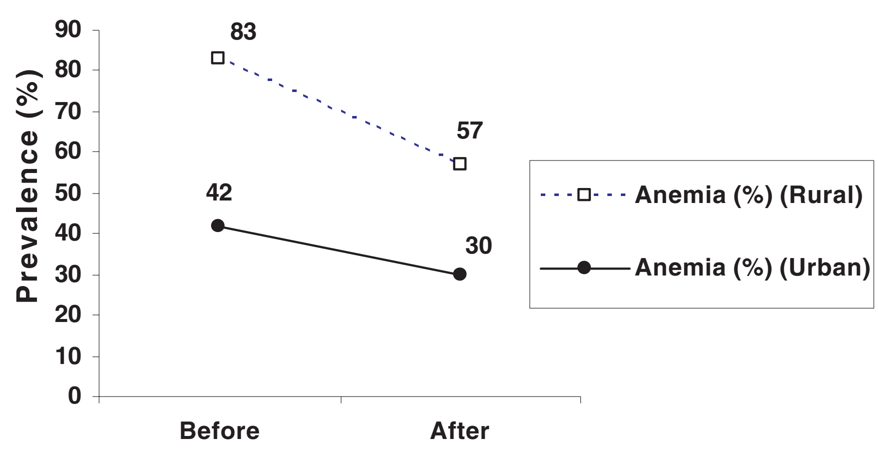

Figure 3—Impact of NIN-DFS on iron status.

Table 2—Change in mean hemoglobin (Hb) in double-fortified salt (DFS)[a] over control salt (CS).[a]

Age (years)	*N* DFS	*N* CS	Change in Hb (g/dL) in DFS over CS: 1st y–Initial	2nd y–1st y	Overall
1 to 5	233	243	−0.20	+0.20	0
6 to 13	278	341	−0.41	−0.05	−0.46
14 to 17	33	46	−0.91	+1.38	+0.47
≥18[b]	62	46	+0.89	−0.45	+0.44
Total	606	676	−0.63	+1.08	+0.45

[a] No difference in the initial Hb values.
[b] Women only.

Table 3—Approximate cost (in rupees) per kilogram of double-fortified salt (NIN-DFS) and iodized salt (IS).

Constituent	Cost per kilogram (Rs)[a] NIN-DFS	IS
1. Salt	2.00	2.00
2. Chemicals	1.00	0.10
3. Processing	0.40	0.30
4. Packing material	1.00	1.00
5. Amortization	0.20	0.20
6. Overheads	0.25	0.25
Production cost (1 to 7 = A)	4.85	3.85
7. Profit: (a) Factory	0.40	0.40
(b) Dealer	0.25	0.25
(c) Wholesale	0.20	0.20
(d) Retail	0.15	0.15
Total profit: 7 (a) to 7 (d) = B	1.00	1.00
8. Transport: C	1.00	1.00
9. Total cost: A + B + C	6.85	5.85

[a] 1 Rupee (Indian) = 0.025 US$ at current exchange rates.

school, showed that the mean increments of hemoglobin at the end of the school study, after adjusting for the differences in initial hemoglobin, were significantly higher in the DFS group ($P < 0.01$) as compared to the IS group. A comparison of the data has clearly shown that NIN-DFS is the only formulation that has been proved to be stable, acceptable, and had the desired impact (Sivakumar and Nair 2002). The efficacy of NIN-DFS in controlling anemia resulted in a mean (95% CI) rise in hemoglobin of 0.72 (0.43, 1.01) g/dL in comparison to iodized salt, which is well within the range of global experience (Bhan Committee 2006).

Cost

All the ingredients to manufacture NIN-DFS are readily available in the country at low cost. From the current cost of the materials, the approximate cost of production works out to be Rs. 4.85 (0.121 US$) per kg and when profits and transport costs are included it would be Rs. 6.85 (0.171 US$) per kg (Table 3). Thus, the expenditure would be about a paisa (0.00025 US $) per head per day (Technical Report 2005).

Current Status

The Ministry of Health & Family Welfare, Govt. of India, constituted a Technical Committee under the Chairmanship of Dr. M. K. Bhan, Secretary, Dept. of Biotechnology, Govt. of India, and Prof. N. K. Ganguly, Director-General, Indian Council of Medical Research, as Co-Chairperson on "Formulations of guidelines for use of double-fortified salt as a measure to reduce prevalence of anemia" via letter Nr Z 28020/16/2005-CH/PH dated 14th July 2005. The main Committee and the Sub-Committees met as per requirements and analyzed the data available on different formulations of DFS and finally approved only NIN-DFS because of convincing evidence from NIN-DFS based on (1) scientific publications, (2) formulation, (3) nutrient level, (4) process, (5) ultrastructure, (6) salt quality, (7) stability, (8) organoleptic studies, (9) acceptability, (10) factory production, (11) community acceptance, (12) safety evaluation, (13) bioavailability, (14) iron impact, (15) iodine impact, and (16) cost. Furthermore, the Dr. Bhan Committee recommended the introduction of NIN-DFS in nutrition programs (Bhan Committee 2006).

Based on the recommendations of the ICMR Expert Committee, NIN advertised in all leading newspapers, including vernacular papers, calling for applications from salt manufacturers for the transfer of NIN-DFS technology during 2007. The response was satisfactory. Recently, NIN has signed a memorandum of understanding (MoU) with salt manufacturers (small and major) for the transfer of NIN-DFS technology. While NIN is not charging for the technology transfer, the manufacturers would supply at least 20% of the produce to the public distribution system (PDS) at prices fixed by the Government for the benefit of people living below the poverty line. Furthermore, NIN has communicated to the Secretaries of the Women Development and Child Welfare Dept. as well as Health Dept. of all the States and Union Territories in the country, advocating the introduction of NIN-DFS in

Table 4 — Summary of NIN-DFS.

Characteristics	Outcome
1. Formulation	Made from permitted food additives by a simple low-cost technology. No elaborate or expensive measures.
2. Stability	Iodine and iron stable beyond 12 mo.
3. Organoleptic properties	No change in the organoleptic properties of different foods prepared with DFS.
4. Acceptability in community	Full-fledged acceptability demonstrated in rural and urban communities. No undesirable effect, allergy, or toxicity observed.
5. Bioavailability of iron and iodine	Metabolic studies: 6.1% iron absorption and urinary iodine levels increased as in the case of iodized salt.
6. Factory production	Large-scale production (0.5 to 60 tons) successfully done in different salt factories at Hyderabad, Chennai, Thirupporur, Alathur, Valinokkam, Mithapur, Bhubaneswar, Gandhidham, and Tiruchengode.
7. Stability of iodine and iron at the location	Stable beyond 1 y. Successfully tested under programmatic conditions.
8. Efficacy studies: (rural and urban settings)	Single-blind, placebo in 4 randomly selected blocks with 15 to 20 contiguous villages with a population of about 5000 each in the tribal areas of East Godavari district in AP (2 y). Double-blind, placebo in 4 residential schools, Hyderabad. (2 y).
9. Impact of iodine and iron (rural and urban settings)	Goiter prevalence decreased (from 28% to 14%) with DFS in the rural settings. Median urinary iodine excretion levels (μg/L) increased significantly (from 116 to 155 in the rural settings and from 68 to 108 in the urban settings). Significant reduction in the proportion of anemic children (from 83% to 57% in the rural settings and from 42% to 29.5% in the urban settings). Gain in hemoglobin of DFS over iodized salt was 0.72g/dL.
10. Safety issues	Only permitted food additives are used. The safety of SHMP in DFS reevaluated in rats and children and found to be safe. NIN-DFS is safe and free from toxic effects.
11. Cost	Not expensive and affordable: Re. 1 (0.025 US$) more than iodized salt per kg.

nutrition programs of the States and Union Territories. NIN has played an active role in the development of standards under PFA and BIS for DFS in 2008.

Conclusions

The NIN-DFS is the result of 2 decades of untiring, sustained pursuits and is aimed at controlling the twin problems of IDDs and IDA in the country by a simple indigenous technology at an affordable cost (Table 4). After Dr. Bhan Committee's recommendations, it is imperative that the benefits of NIN-DFS should reach the people with no further delay for which NIN reciprocated with free technology transfer. NIN believes in public–private partnership to face the nutritional challenges of the country. NIN is proud to present another promising prospective program (NIN-DFS) as a gift to the nation and rededicate itself in the service of the nation and its people.

Acknowledgment

This article is based on the contributions of several scientists of NIN at different stages of the development of NIN-DFS.

References

Adamson P. 2004. Vitamin and mineral deficiency: a global progress report. Oxfordshire, U.K.: UNICEF/Micronutrient Initiative.

Bhan Committee. 2006. Recommendations of the Technical Committee on "formulations of guidelines for use of double-fortified salt as a measure to reduce the prevalence of anemia". Ministry of Health and Family Welfare, Govt. of India: Under the Chairmanship of Dr. M. K. Bhan, Secretary, Dept. of Biotechnology, Govt. of India.

Brahmam GNV, Madhavan Nair K, Ranganathan S, Gal Reddy CH, Vishnuvardhana Rao M, Nadamuni Naidu A, Pralhad Rao N, Reddy V. 1994. Use of common salt fortified with iron and iodine (double- fortified salt)—a community study in Andhra Pradesh. National Inst. of Nutrition, ICMR, Hyderabad, India.

Brahmam GNV, Nair KM, Laxmaiah A, Gal Reddy C, Ranganathan S, Vishnuvardhana Rao M, Naidu AN, Vijayaraghavan K, Sivakumar B, Krishanaswamy K, Sastry JG, Ram MM, Rao NP, Reddy V. 2000. Community trials with iron- and iodine-fortified salt (double-fortified salt). In: Geertman RM, editor. Salt 2000. 8th World Salt Symposium, Vol. 2. The Hague: Elsevier. p 955–60.

Central Bureau of Health Intelligence. 1993. Health Information in India, Directorate General of Health Services, Ministry of Health and Family Welfare, Government of India, Nirman Bhavan, New Delhi. Health Information in India.

ICMR. 1994. Annual Report of Director-General 1993–94. New Delhi. Indian Council of Medical Research. 26 p.

INACG. 1999. Consensus statement. Safety of iron supplementation programmes in malaria-endemic regions. Washington, D.C. INACG Secretariat, ILSI.

Interim Report. 2003. Operational evaluation of the stability of iodine in double-fortified salt: a multicentric study. Natl. Inst. of Nutrition (Indian Council of Medical Research), Hyderabad, India.

JECFA (Joint FAO/WHO Expert Committee on Food Additives). 1992. Compendium of food additive specifications, Vol 2. Combined specifications from the first to the thirty-seventh meeting (1956-1990). FAO Food and Nutrition Paper 52/2. Rome: Food and Agriculture Organization.

Nair KM, Sesikeran B, Ranganathan S, Sivakumar B. 1998a. Bio-effect and safety of long-term feeding of common salt fortified with iron and iodine (double-fortified salt) in rat. Nutr Res 18:121–9.

Nair KM, Brahmam GNV, Ranganathan S, Vijayaraghavan K, Sivakumar B, Krishnaswamy K. 1998b. Impact evaluation of iron- and iodine- fortified salt. Indian J Med Res 108:203–11.

Nair KM, Brahmam GNV, Laxmaiah A, Gal Reddy Ch, Vishnuvardhana Rao M, Ranganathan S, Vijayaraghavan K, Sivakumar B, Kamala Krishnaswamy. 2000. Sodium hexametaphosphate (SHMP) as a stabilizer of double-fortified (iron and iodine) salt does not alter the calcium and phosphorus homeostasis. In: Geertman RM, editor. Salt 2000, 8th World Salt Symposium. Vol. 2. The Hague: Elsevier. P 1253–4.

Rao BSN. 1994. Fortification of salt with iron and iodine to control anaemia and goiter: Development of a new formula with good stability and bioavailability of iron and iodine. Food Nutr Bull 15:32–9.

NNMB (National Nutrition Monitoring Bureau). 2003. Prevalence of micronutrient deficiencies, NNMB Technical Report Nr 22, Natl. Inst. of Nutrition (Indian Council of Medical Research), Hyderabad, India.

Ranganathan S. 1992. Fortification of salt with iron: use of polyphosphate stabilizers. Food Chem 45:263–7.

Ranganathan S. 2005. Manual for salt fortification with iron and iodine (double-fortified salt): technical and operational procedures for double-fortified salt. Natl. Inst. of Nutrition (Indian Council of Medical Research), Hyderabad, India. P 8–11.

Ranganathan S, Karmarkar MG. 2006. Estimation of iodine in salt fortified with iodine and iron. Indian J Med Res 123:531–40.

Ranganathan S, Dilli Kumar PK, Ramamoorthy P, Reddy V. 1993. Large-scale production of iron-fortified salt. J Food Sci Technol 30:166–8.

Ranganathan S, Reddy V, Ramamoorthy P. 1996. Large-scale production of salt fortified with iodine and iron. Food Nutr Bull 17:73–8.

Ranganathan S, Sundaresan S, Raghavendra I, Kalyani S. 1997. Dry mixing technique for the large-scale production of iodine-fortified salt in India. Asia Pacific J Clin Nutr 6:92–4.

Ranganathan S, Rao BSN, Reddy V, Prakash R, Sundaresan S, Ansari MA. 2000. A new process for stabilizing iodine in iodized salt. In: Geertman RM, editor. Salt 2000. 8th World Salt Symposium. Vol. 2. The Hague: Elsevier. P 1051–6.

Ranganathan S, Brahmam GNV, Vishnuvardhana Rao M, Vijayaraghavan K, Sivakumar B. 2005. Stability of iodine in double fortified salt (DFS)—A short-term study. Natl. Inst. of Nutrition (Indian Council of Medical Research), Hyderabad, India.

Ranganathan S, Karmarkar MG, Krupadanam M, Brahmam GNV, Vishnuvardhana Rao M, Vijayaraghavan K, Sivakumar B. 2007. Stability of iodine in salt fortified with iodine and iron. Food Nutr Bull 28:109–15.

Report. 2003. Current status of iodine deficiency disorders in select districts of different regions of the country. Natl. Inst. of Nutrition (Indian Council of Medical Research), Hyderabad, India.
Sivakumar B, Nair KM. 2002. Double-fortified salt at crossroads. Indian J Pediatr 69: 617–23.
Sivakumar B, Brahmam GNV, Nair KM, Ranganathan S, Vishnuvardhana Rao M, Vijayaraghavan K, Krishnaswamy K. 2001. Prospects of fortification of salt with iron and iodine. Br J Nutr 85(Suppl 2):S167–73.
Technical Report. 2005. Double-fortified common salt (DFS) as a tool to control iodine deficiency disorders and iron deficiency anemia, Natl. Inst. of Nutrition (Indian Council of Medical Research), Hyderabad, India.
The State of the World's Children. 2007. The United Nations Children's Fund (UNICEF), 2006, UNICEF House, New York, U.S.A.
World Bank. 1994. Enriching lives: overcoming vitamin and mineral malnutrition in developing countries. Washington, D.C.: World Bank, Report nr 138000, Nov.