COMPREHENSIVE REVIEWS IN FOOD SCIENCE AND FOOD SAFETY

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

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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

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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).

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.

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

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	—

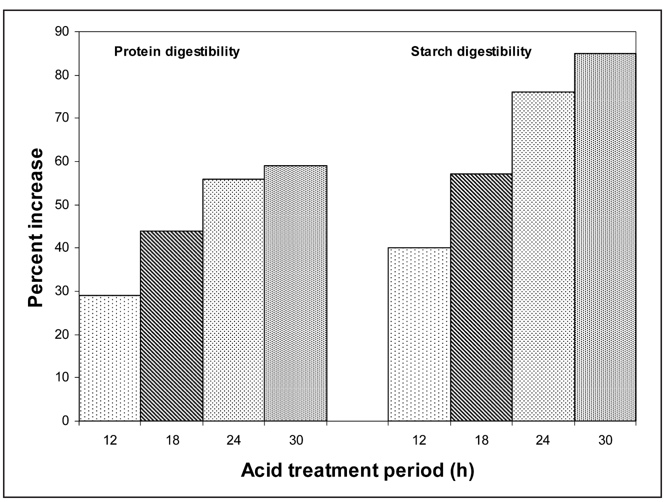

Figure 1—Percent increase in *in vitro* protein and starch digestibility of acid-treated pearl millet flour over untreated (control).

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 nontraditional 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

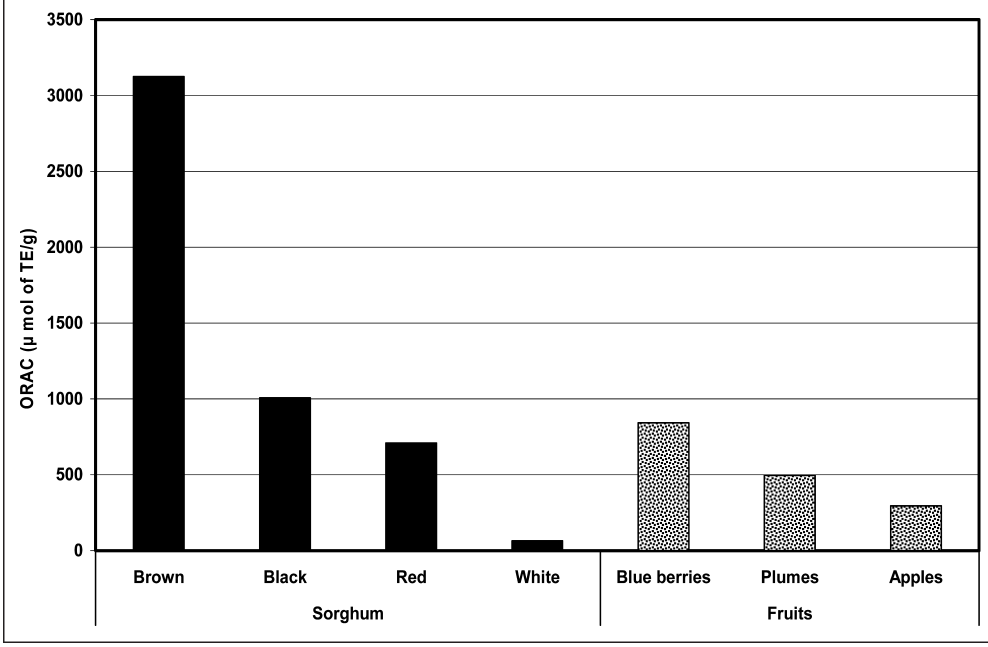

Figure 2—Oxygen radical absorbance capacity (ORAC) in sorghum bran and fruits (dry basis). TE = trolox equivalent (Source: Awika and others 2003; Wu and others 2004).

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.

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