Comprehensive REVIEWS in Food Science and Food Safety

Millet Grains: Nutritional Quality, Processing, and Potential Health Benefits

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Abstract: In the 21st century, climate changes, water scarcity, increasing world population, rising food prices, and other socioeconomic impacts are expected to generate a great threat to agriculture and food security worldwide, especially for the poorest people who live in arid and subarid regions. These impacts present a challenge to scientists and nutritionists to investigate the possibilities of producing, processing, and utilizing other potential food sources to end hunger and poverty. Cereal grains are the most important source of the world's food and have a significant role in the human diet throughout the world. As one of the most important drought-resistant crops, millet is widely grown in the semiarid tropics of Africa and Asia and constitutes a major source of carbohydrates and proteins for people living in these areas. In addition, because of their important contribution to national food security and potential health benefits, millet grain is now receiving increasing interest from food scientists, technologists, and nutritionists. The aim of this work was to review the recent advances in research carried out to date for purposes of evaluation of nutritional quality and potential health benefits of millet grains. Processing technologies used for improving the edible and nutritional characteristics of millet as well as challenges, limitations, and future perspectives to promote millet utilization as food for a large and growing population are also discussed.

Introduction

Interest in the development of policy statements about drought-tolerant grains is increasing in several developing countries such as India, China, and some countries of Africa because of water scarcity and increasing populations. In addition, the earmarked funds to scientific research for purposes of improving and increasing their production and utilization as food have also been increased. Millet is one of the most important drought-resistant crops and the 6th cereal crop in terms of world agriculture production. Also, millet has resistance to pests and diseases, short growing season, and productivity under drought conditions, compared to major cereals (Devi and others 2011). Therefore, millet grains are now receiving specific attention from these developing countries in terms of utilization as food as well as from some developed countries in terms of its good potential in the manufacturing of bioethanol and biofilms (Li and others 2008).

Millets are small-seeded with different varieties such as pearl millet (*Pennisetum glaucum*), finger millet (*Eleusine coracana*), kodo millet (*Paspalum setaceum*), proso millet (*Penicum miliaceum*), foxtail millet (*Setaria italic*), little millet (*Panicum sumatrense*), and barnyard millet (*Echinochloa utilis*). They are known as coarse cereals beside maize (*Zea mays*), sorghum (*Sorghum bicolor*), oats (*Avena sativa*), and barley (*Hordeum vulgare*) (Bouis 2000; Kaur and others 2012). The world total production of millet grains at last count was 762712 metric tons and the top producer was India with an annual production of 334500 tons (43.85%) (FAO 2012; Table 1). Millet is known as *ragi* and *mandia* in the Bastar region of Chhattisgarh and offers both nutritional and livelihood security for human beings and also feed security for diverse livestock populations in dryland regions of rural India (Pradhan and others 2010).

Millets are not placed as a single important commodity in the North American and European food basket at the present time, but their importance as an ingredient in multigrain and gluten-free cereal products has been highlighted. However, in many African and Asian areas, millets serve as a major food component and various traditional foods and beverages, such as bread (fermented or unfermented), porridges, and snack foods are made of millet, specifically among the nonaffluent segments in their respective societies (Chandrasekara and Shahidi 2011a; Chandrasekara and others 2012). In addition to their nutritive value, several potential health benefits such as preventing cancer and cardiovascular diseases, reducing tumor incidence, lowering blood pressure, risk of heart disease, cholesterol and rate of fat absorption, delaying gastric emptying, and supplying gastrointestinal bulk have been reported for millet (Truswell 2002; Gupta and others 2012). Millet grains, before consumption and for preparing of food, are usually processed by commonly used traditional processing techniques include decorticating, malting, fermentation, roasting, flaking, and grinding to improve their edible, nutritional, and sensory properties.

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Table 1–Top world millet grains producers (2010).

Country	Seed (tons)
India	334500
Niger	108798
Nigeria	59994
Mali	43878
Senegal	30995
China	26429
Burkina Faso	20428
Russian Federation	20000
Chad	14775
Uganda	11750
Sudan (former)	11000
World total	762712[A]

A = May include official, semiofficial or estimated data
Source: FAO (2012).

However, negative changes in these properties during processing are not avoidable because industrial methods for processing of millets are not as well developed as the methods used for processing of wheat and rice (FAO 2012). Therefore, with value-added strategies and appropriate processing technologies, the millet grains can find a place in the preparation of several value-added and health food-products, which may then result in high demand from large urban populations and nontraditional millet users (Mal and others 2010).

In China, because of their potential contribution to national food security, millet grains as a food resource have been relatively neglected but are now receiving increasing attention from agriculture and food security policymakers. This work is supported by ongoing research projects for studying the processing, food manufacturing, nutritive value improvement, and potential health benefits of millet grains to promote their utilization as food for in China. The aim of this article is to review the latest scientific research on millet, with the hope that it will continue.

Nutritive Value of Millet Grains

Nutritional quality of food is a key element in maintaining human overall physical well-being because nutritional well-being is a sustainable force for health and development and maximization of human genetic potential. Therefore, for solving the problem of deep-rooted food insecurity and malnutrition, dietary quality should be taken into consideration (Singh and Raghuvanshi 2012). In addition to their cultivating advantages, millets were found to have high nutritive value and comparable to that of major cereals such as wheat and rice (Parameswaran and Sadasivam 1994). It has also been reported that millet proteins are good sources of essential amino acids except lysine and threonine but are relatively high in methionine. Millets are also rich sources of phytochemicals and micronutrients (Mal and others 2010; Singh and others 2012).

For example, pearl millet was found significantly rich in resistant starch, soluble and insoluble dietary fibers, minerals, and antioxidants (Ragaee and others 2006). It contains about 92.5% dry matter, 2.1% ash, 2.8% crude fiber, 7.8% crude fat, 13.6% crude protein, and 63.2% starch (Ali and others 2003). Also, foxtail millet protein characterization showed that its protein concentrate is a potential functional food ingredient and the essential amino acid pattern suggests possible use as a supplementary protein source to most cereals because it is rich in lysine (Mohamed and others 2009).

Finger millet also is known to have several potential health benefits and some of the health benefits are attributed to its polyphenol contents (Chethan and Malleshi 2007). It has a carbohydrate content of 81.5%, protein 9.8%, crude fiber 4.3%, and mineral 2.7% that is comparable to other cereals and millets. Its crude fiber and mineral contents are markedly higher than those of wheat (1.2% fiber, 1.5% minerals) and rice (0.2% fiber, 0.6% minerals); its protein is relatively better balanced; it contains more lysine, threonine, and valine than other millets (Ravindran 1991; Sripriya and others 1997). In addition, black finger millet contains 8.71 mg/g dry weight fatty acid and 8.47 g/g dry weight protein (Glew and others 2008). Kodo millet and little millet were also reported to have 37% to 38% of dietary fiber, which is the highest among the cereals; and the fat has higher polyunsaturated fatty acids (Malleshi and Hadimani 1993; Hegde and Chandra 2005). The protein content of proso millet (11.6% of dry matter) was found to be comparable with that of wheat and the grain of proso millet was significantly richer in essential amino acids (leucine, isoleucine, and methionine) than wheat protein (Kalinova and Moudry 2006). Thus, the presence of all the required nutrients in millets makes them suitable for large-scale utilization in the manufacture of food products such as baby foods, snack foods, and dietary food and, increasingly, more millet products have entered into the daily lives of people, including millet porridge, millet wine, and millet nutrition powder from both grain and flour form (Subramanian and Viswanathan 2007; Liu and others 2012). The average of nutrient composition of some millet grains and other grains is summarized in Table 2.

Table 2–Nutrient composition of millets and other cereals (per 100 g edible portion; 12% moisture).

Food	Protein[a] (g)	Fat (g)	Ash (g)	Crude fiber (g)	Carhohydrate (g)	Energy (kcal)	Ca (mg)	Fe (mg)	Thiamin (mg)	Riboflavin (mg)	Niacin (mg)
Rice (brown)	7.9	2.7	1.3	1.0	76.0	362	33	1.8	0.41	0.04	4.3
Wheat	11.6	2.0	1.6	2.0	71.0	348	30	3.5	0.41	0.10	5.1
Maize	9.2	4.6	1.2	2.8	73.0	358	26	2.7	0.38	0.20	3.6
Sorghum	10.4	3.1	1.6	2.0	70.7	329	25	5.4	0.38	0.15	4.3
Pearl millet	11.8	4.8	2.2	2.3	67.0	363	42	11.0	0.38	0.21	2.8
Finger millet	7.7	1.5	2.6	3.6	72.6	336	350	3.9	0.42	0.19	1.1
Foxtail millet	11.2	4.0	3.3	6.7	63.2	351	31	2.8	0.59	0.11	3.2
Common millet	12.5	3.5	3.1	5.2	63.8	364	8	2.9	0.41	0.28	4.5
Little millet	9.7	5.2	5.4	7.6	60.9	329	17	9.3	0.30	0.09	3.2
Barnyard millet	11.0	3.9	4.5	13.6	55.0	300	22	18.6	0.33	0.10	4.2
Kodo millet	9.8	3.6	3.3	5.2	66.6	353	35	1.7	0.15	0.09	2.0

[a] All values except protein are expressed on a dry weight basis.
Sources: Hulse and others (1980); United States National Research Council/National Academy of Sciences (1982); USDA/HNIS (1995); FAO (1995).

Effects of Processing Technologies on the Nutritional Quality of Millet Grains

Related to improvement of nutritional characteristics, sensory properties, and convenience, there are some processing technologies that are used in manufacturing of food products. Several traditional household food processing and preparation methods can also be used to enhance the bioavailability of micronutrients in plant-based diets. These include thermal processing, mechanical processing, soaking, fermentation, and germination/malting. These procedures aim to increase the physicochemical accessibility of micronutrients, decrease the content of antinutrients, such as phytates, or increase the content of compounds that improve bioavailability (Hotz and Gibson 2007).

Mechanical Processing Technologies

Decortication

Millet and some other coarse grains are usually dehulled and subjected to different treatments before consumption to improve their sensory and edible quality (Liu and others 2012). It has been reported that the food uses of finger millet are confined to flour-based products because it has not been possible to decorticate millet similar to other cereals. This is mainly due to millet grains that are small compared to other cereals. But it was observed that the hydrothermal treatment of millet hardened the endosperm texture and enabled its decortication. The decorticated millet could be cooked as discrete grains similar to rice to obtain soft edible texture within 5 min, which was not possible before. The pasting and the dough properties and also some of the functional characteristics of the product indicated its versatility for diversified food uses (Shobana and Malleshi 2007). However, decortication of hydrothermally processed finger millet caused significant changes in the nutrient contents (Dharmaraj and Malleshi 2011).

The influence of traditional decortication of pearl millet and white sorghum by hand-pounding or using a mechanical device were performed and compared to abrasive decortication in the laboratory using the same kernel lots. The decortication characteristics and nutritional composition (iron, zinc, phytates, lipids, fibers, and starch) of decorticated grains were measured. The results showed that decortication had numerous effects on grain composition, but no significant differences were observed between the 2 traditional methods of decortication (Hama and others 2011). Furthermore, decortication was found to have no effect on the protein and fat content of millets; however, it significantly decreased the content of crude fiber, dietary fiber, minerals, total phenols content, and antioxidant capacity. Therefore, the applicability of millets as functional food was decreased (Lestienne and others 2005; Bagdia and others 2011). It has also been reported that dehulling of pearl millet grains reduced total phytic acid, polyphenols, and tannin and significantly ($P \leq 0.05$) increased the protein digestibility but decreased the quality attributes of millet (ElShazali and others 2011; Chandrasekara and others 2012; Krishnan and others 2012). The reduction in some nutrients (minerals, fibers, and antioxidants) and antinutrients (phytates, tannin) could be attributed to the fact that they are mainly located in the peripheral parts of the grains (pericarp and aleurone layer); therefore, removing of the pericarp during decortication leads to reduce their contents (Hama and others 2011).

Now we have come to the fact that although decortication of millet grains was found to reduce some nutrient contents such as fiber and minerals, but usually they are decorticated before consumption to improve their edible and sensory properties and to increase the appearance of their food products. Therefore, there is a need for innovative decortication technology that can be used to decorticate large amounts of grains in a short time at commercial scale compared with the traditional decortication methods.

Milling and sieving

Millet grains are usually milled by a nonmotorized grain mill that cranks by hand or another nonelectric method, especially in rural areas for household uses. However, a manual grain mill that has been attached to a gas or electric motor by a pulley system can also be used. Effects of milling on nutritional contents of millet grains and their milling fractions have been studied by a number of researchers. In one study, milling of pearl millet grains was found to reflect a change in gross chemical composition. However, baking did not cause a significant change in nutrient content of raw pearl millet flour. In addition, milling and heat treatment during *chapati* (an unleavened bread) making lowered polyphenols and phytic acid and improved the protein digestibility and starch digestibility to a significant extent (Chowdhury and Punia 1997). In another study, 2 pearl millet varieties were milled into whole flour, semirefined flour, and a bran-rich fraction and were evaluated for nutrients, antinutrients, and mineral bioaccessibility. The results showed that nutrient content of semirefined flour was comparable to whole flour, except for the fat content (1.3%). Due to partial separation of the bran fraction, semirefined flour was low in antinutrients that improved its mineral bioaccessibility making it nutritionally superior. The bran-rich fraction, a by-product of flour-milling contained a significantly ($P \leq 0.05$) higher ash content (Suma and Urooj 2011a). In addition, steaming the millet at elevated pressure and temperature increased the milling yield, and steaming beyond the threshold level showed a detrimental effect on the yield of head grains (Dharmaraj and others 2011).

Finger millet whole flour (WFM), sieved flour (SFM), wafers, and vermicelli with altered matrices (added Fe or Zn or reduced fiber) were analyzed for chemical composition, bioaccessible Fe, Zn, and Ca, *in vitro* digestible starch (IVSD), and protein (IVPD) and bioactive components (polyphenols and flavonoids). It was found that WFM and SFM flours differed significantly in their composition. Sieving decreased the content of both nutrients and antinutrients in WFM but increased their digestibility/bioaccessibility. WFM had the highest levels of total polyphenols and flavonoids, 4.18 and 15.85 g/kg, respectively; however, bioaccessibility was highest in SFM vermicelli (Oghbaei and Prakash 2012). It has also been reported that protein, fat, ash, and fiber contents were decreased according to the increase of moisture and milling time and 8% to 10% (db) of moisture content, and 3 min of milling time could be recommended for polishing barnyard millet in a rice polisher without much loss of nutritional values (Lohani and others 2012). Therefore, removing of the bran fraction by sieving, which is known rich in nutrients, such as fiber, minerals, and antioxidants, leads to decrease the nutritive value and potential health benefits of grains, thus using whole grains flour in human nutrition is suggested more beneficial in health promotion.

In conclusion, and as mentioned for decortication, milling and sieving of millet grains is mostly carried out manually; therefore, there is a need for convenient and motorized milling technology for millet grains to provide a large amount of flour to ensure a consistent source for industrial food uses at commercial scale to help in promoting their utilization. In return, a consistent source of high-quality millet grains for millers must be available. In addition, optimization of milling conditions for providing high yield of millet flours with high nutrient composition and quality should be performed by future research.

Traditional and Bioprocess Technologies

Germination or malting

Germination or malting of cereal grains may result in some biochemical modifications and produce malt with improved nutritional quality that can be used in various traditional recipes. It has been found that germination of proso millet grains increased the free amino acids and total sugars and decreased the dry weight and starch content. Increases in lysine, tryptophan, and nonprotein nitrogen were also noticed (Parameswaran and Sadasivam 1994). Germination also appreciably improved the *in vitro* protein (14% to 26%) and starch (86% to 112%) digestibility in pearl millet, and the improvement by germination was significantly higher than by blanching (Archana and Kawatra 2001). The improvement in protein digestibility after germination, soaking, debranning, and dry heating can be attributed to the reduction of antinutrients such as phytic acid, tannins, and polyphenols, which are known to interact with proteins to form complexes (Hassan and others 2006). However, crude protein and fat contents were decreased in foxtail millet after germination. This decrease in the protein and fat contents can be attributed to loss of low molecular weight nitrogenous compounds during soaking and rinsing of the millet grains and hydrolysis of lipid and oxidation of fatty acids during germination (Choudhury and others 2011). Also, the changes in nutrient contents of grains after germination can be attributed to the utilization by growing sprouts (Hooda and Jood 2003). It has also been found that the *in vitro* extractability and bioaccessibility of minerals such as calcium, iron, and zinc were increased in finger millet and pearl millet by germination; however, the antinutritional factors such as phytic acid were decreased (Mamiro and others 2001; Suma and Urooj 2011b; Krishnan and others 2012). Furthermore, the relative *in vitro* solubility of iron was doubled by the germination of pearl millet grains (Eyzaguirre and others 2006). In terms of its potential for lager beer brewing, pearl millet malt was reported to have some advantages compared to sorghum as it has higher beta-amylase activity and higher free α-amino nitrogen (Pelembe and others 2004). In addition, finger millet can be incorporated as a source of dietary fiber both in the native and malted forms, in the preparation of various health foods without altering the dough characteristics or the quality of the end product (Rao and others 2004). Therefore, malting generally improves the nutrient content and digestibility of foods and it could be an appropriate food-based strategy to derive iron and other minerals maximally from food grains (Platel and others 2010).

Effect of germination and fermentation of pearl millet on proximate, chemical, and sensory properties of instant *fura* (a Nigerian cereal food) was examined. It was found that germination appeared to be a promising food processing method for improving the nutrient and energy densities of *fura* and, when combined with fermentation, reduced phytic acid significantly ($P < 0.05$) (Inyang and Zakari 2008). It has also been indicated that a pearl millet-based, germinated, autoclaved, and fermented food blend maintained adequate cell viability as compared to a nongerminated food blend. Germination and probiotic fermentation caused significant improvement in the contents of thiamine, niacin, total lysine, protein fractions, sugars, soluble dietary fiber, and *in vitro* availability of Ca, Fe, and Zn of food blends (Arora and others 2011). Increased mineral availability during germination may be due to increased phytase activity, which resulted in decreased content of phytate in sprouts. Antinutrients like polyphenols and saponins are also known to hinder the availability of minerals, which are catabolized during germination leading to improvement in mineral availability (Grewal and Jood 2006). Furthermore, germination of foxtail millet for 3 d resulted in flour with a high concentration of minerals (Coulibaly and Chen 2011). Therefore, germination of millet grains can be used as a technique or in combination with other processing treatments to prepare malt rich in nutrients that can be used for the preparation of several healthy and nutritional food products such as infant formula, complementary food products, and composite flours or food blends. However, there is a need for the application of malting at an industrial scale using novel germinators enhanced by a control system of germination conditions to provide high-quality malt products that can be easy to handle and consumed by larger populations to help in promoting millet utilization.

Fermentation and enzymatic hydrolyzation

Due to the importance in food preservation, fermentation is widely used throughout Africa where modern food preservation methods are still not common. It helps to preserve many food products, provides a wide variety of flavors, and significantly improves the nutritional properties of the raw material. Fermented foods are also produced and consumed worldwide in terms of their importance for human food (Mugocha and others 2000; Gotcheva and others 2001). The chemical compositions of millet grains and their food products were found to be modified by fermentation. Therefore, millet grains are used to produce different kinds of traditional fermented foods in developing countries in Africa and Asia. Fermentation is one of the processes that decrease the levels of antinutrients in food grains and increase the protein availability, *in vitro* protein digestibility (IVPD), and nutritive value. It has been indicated that fermentation of processed pearl millet grains caused significant reduction in antinutritional factors, which was accompanied by significant improvement in the IVPD (Hassan and others 2006). This improvement in the IVPD caused by fermentation could be attributed to the partial degradation of complex storage proteins to more simple and soluble products (Chavan and others 1988). It has also been found that the chemical components, with the exception of starch, were reduced when the millet grain was fermented into *ogi*, a naturally fermented cereal product in Nigeria. However, availability of starch and protein for digestion was higher in *ogi* than in the grain. In addition, lysine, tryptophan, and vitamin B2 contents were increased, while vitamin A and flavaonoid contents and paste viscosity were reduced by the conversion of grain into ogi (Akingbala and others 2002).

Fermentation of pearl millet caused appreciable changes in the chemical composition (moisture, ash, fiber, protein, and fat contents), but markedly reduced the mineral contents (Na, K, Mg, Cu, Fe, Mn, and Zn) (Ahmed and others 2009). Fermentation also enhanced the crude protein and reduced fat and crude fiber after 16 h in fermented-cooked-fermented *rabadi* prepared in steel and earthen pots and cooked-fermented *rabadi* (a traditional fermented food) in earthen pots. Enhanced flavonoids were also observed in all samples after 16 h of fermentation (Gupta and Nagar 2010). However, fermentation of finger millet resulted in a smaller or insignificant effect on the *in vitro* extractability of minerals (Mamiro and others 2001). Furthermore, it was found that during a 24 h fermentation of pearl millet, protein and lipid contents were not significantly ($P > 0.05$) changed. Carbohydrate content significantly ($P > 0.05$) decreased with a parallel increase in soluble sugars. In addition, amino acid analysis revealed that fermentation significantly ($P > 0.05$) decreased glycine, lysine, and arginine contents. Fermentation was also found to cause significant reduction in trypsin and amylase inhibitor activities and the phytic acid content. However, tannin content showed a significant ($P < 0.05$) increase after fermentation (Osman 2011).

Various microbial types were used for fermentation of millet grains and their food products. In one study, mixed-culture fermentation of pearl millet flour with *Saccharomyces diastaticus, Saccharomyces cerevisiae, Lactobacillus brevis,* and *Lactobacillus fermentum* caused an improvement in its biological utilization in rats. In addition, protein efficiency ratio, feed efficiency ratio, apparent protein digestibility, true protein digestibility, net protein utilization, net protein retention, protein retention efficiency, and utilizable protein values in the case of pure-culture-fermented pearl millet flour were higher than in the control (Khetarpaul and Chauhan 1991). In another study, pearl millet grains were fermented with Lactobacilli and yeast alone, in combination and with the natural flora at 30 °C for 48 h after giving various processing treatments. It was found that combination of Lactobacilli and yeast was more effective in increasing the protein as well as starch digestibility as compared to pure culture fermentation (Sharma and Kapoor 1996). This increase in the protein digestibility could be attributed to the degradation of tannins, polyphenols, and phytic acid by microbial enzymes (Hassan and others 2006). However, the changes in starch content and digestibility in the fermented product may be attributed to amylolytic action of microorganisms in the fermenting mixture (Arora and others 2011). Commercial cultures can also be successfully used to produce a composite fermented beverage from finger millet and skim milk (Mugocha and others 2000). However, natural fermentation was also found to cause a significant reduction in total polyphenols and phytic acid content of pearl millet (Elyas and others 2002). In addition, natural lactic acid fermentation of pearl millet slurries resulted in a decrease of phytates and α-galacto-oligosaccharides (Songré-Ouattara and others 2008).

The enhanced proteolytic activity during fermentation is generally associated with improved protein digestibility, which increases amino nitrogen by partial breakdown of proteins to peptides and amino acids (ElHag and others 2002). Dehulled and cooked grains of 5 millet varieties (kodo, finger, proso, foxtail, and pearl) were subjected to *in vitro* enzymatic digestion and microbial fermentation under physiological conditions in order to determine the bioaccessibility of their phenolic compounds. It was demonstrated that phenolic compounds of processed millets were bioaccessible and colonic fermentation released the phenolics bound to the insoluble fiber in the grain (Chandrasekara and Shahidi 2012). In another study, the effect of enzymatic hydrolysis, desalting, and debittering on the functional properties of defatted foxtail millet protein hydrolysates was examined. The functional properties studied exhibited good qualities that make them acceptable for use in such applications as hypoallergenic infant formulas, sports nutrition, and functional foods (Kamara and others 2011; Kamara and others 2010). However, enzymatic treatment was also reported as an option to modify the attributes of finger millet flour (FMF) dough related to processing and product development (Raghu and Bhattacharya 2010).

Based on the literature, it can be concluded that fermentation and enzymatic hydrolysis are promising techniques that can be used as single or in combination with other techniques to prepare fermented food products with high nutritive value from millet grains. However, the application of these techniques for the preparation of millet food products on a commercial scale is limited and most of the applications are carried out at the household level for the preparation of some traditional foods or at laboratory scale. Therefore, industrial application of these methods, using modern equipment and optimized conditions, is needed for the preparation of high-quality and safe millet food products at commercial scale, such as fermented drinks, and millet fractions rich in functional components that can be used for therapeutic purposes and food of large populations.

Popping or puffing

Popping or puffing is one of the traditional food processing methods used for the preparation of expanded cereals and grain legumes to prepare ready-to-eat products. It has been reported that the traditional (popping and flaking) as well as contemporary methods (roller-drying and extrusion-cooking) of cereal processing could be successfully applied to foxtail millet to prepare ready-to-eat products, thereby increasing its utilization as a food (Ushakumari and others 2004). Decorticated finger millet was subjected to a high-temperature short-time treatment to prepare expanded millet, a ready-to-eat new-generation product. It was observed that flattening the grains to the desired shape and moisture content were critical factors for obtaining millet with maximum expansion ratio. The optimum conditions for preparing a product with the highest expansion ratio were found to be about 40% moisture content prior to flattening, with the shape factor ranging from 0.52 to 0.58 and drying time varying from 136 to 150 min (Ushakumari and others 2007). However, it has been found that crude fat and crude fiber contents of popped foxtail millet were significantly lower than raw millet, while the carbohydrate and energy values were significantly higher. This is mainly because fat and fiber contents are higher in outer coat of grains, thus more affected by processing compared with nutrients located in inner layer (Choudhury and others 2011). Therefore, the use of novel technology with optimization of puffing conditions, popping technique can be used as a strategy or in combination with other pretreatments to produce ready-to-eat expands from millet grains at the commercial scale, thus promoting utilization of millet grains.

Soaking and cooking

Soaking of grains is a popular food preparation technique used for reducing antinutritional compounds such as phytic acid to improve bioavailability of minerals. The degradation and leaching of phytates, phytase activity, and iron and zinc concentrations have been studied after soaking of whole seeds, dehulled seeds, and flours of millet. The results indicated that dehulling and milling before soaking facilitated the leaching of phytates and phytases in aqueous medium, and hence, phytate degradation. However, cooking of flours with water used for soaking did not increase phytate degradation (Lestienne and others 2007). Furthermore, the effects of single operations of pearl millet and of porridge preparation scenarios on levels and *in vitro* solubility of iron, zinc, and mineral-complexing factors (phytates) were tested. Soaking of pearl millet grains resulted in a 25% loss of iron, but also facilitates endogenous phytates degradation, particularly when combined with milling and cooking. Zinc *in vitro* solubility tended to increase on cooking with kanwa (alkaline rock salt), but decreased in cooked fermented flour (Eyzaguirre and others 2006).

Mineral contents, especially those of phosphorus, calcium, and iron, were reduced with an increase in period of soaking of pearl millet in acid, but HCl-extractability improved to varying extents. The reduction in minerals content of pearl millet may be attributed to leaching out of these minerals into the soaking medium. However, improvement in HCl-extractability, which is an index of the bioavailability of minerals, may be explained by the acid treatment possibly released these minerals from mineral–antinutrient complexes to free form, thereby increasing their HCl-extractability (Arora and others 2003). Furthermore, it was found that the irradiation process alone had no effect on tannin and phytate contents of 2 cultivars of pearl millet, but when followed by cooking significantly ($P \leq 0.05$) reduced the level of antinutrients for whole and dehulled flour of both cultivars. Also, irradiation alone for the whole or dehulled seeds had no effect on the protein digestibility but slightly improved the quality attributes of both cultivars. However, irradiation followed by cooking significantly ($P \leq 0.05$) reduced the protein digestibility but improved the quality attributes of both cultivars (ElShazali and others 2011). In addition, the simple processing of foxtail millet-like dehulling, soaking, and cooking resulted in a significant decrease in antinutrients such as polyphenols and phytate, and improved the bioavailability of minerals such as iron and zinc and also protein digestibility *in vitro* (Pawar and Machewad 2006). Therefore, soaking and cooking of millet grains can be used as pretreatments under optimized conditions to reduce the antinutrition contents in millet grains to enhance nutrient bioavailability and nutritional quality of millet food products.

Food Manufacturing and Formulation Technologies

Conversion into pure-millet food products

Processing and converting millet for use in traditional meals is common in many developing countries in Africa and Asia. In many African countries, millet is often the main component of many meals and is essentially consumed as steam-cooked products ("couscous"), thick porridges ("To"), and thin porridges ("ogi") that can be used as a complementary food for infants and young children, it is also used in brewing beer (Obilana 2003; Lestienne and others 2005). In Nigeria, kunu is a very nutritious beverage that can supply most of the nutrient requirements by the body. Also, from the analysis, it was seen that kunu from millet gives the highest nourishment to the body; it has more nutritive value and is a good source of energy because of the high amount of protein, normal total solids, moderate pH, and acidity. Millet does have a high amount of calcium that helps in healthy bone strength and strong teeth (Adebayo and others 2010). In Saudi Arabia, pearl millet is grown in the south–west region of Jazan and used by locals to prepare fermented bread known as lohoh (Osman 2011). In the northern area of China, foxtail millet has been widely used as a nourishing gruel or soup for pregnant and nursing women, and has been applied as food therapy (Li 1986). The grains of Japanese barnyard millet are a traditional food in the cold districts of Japan, especially in the Tohoku district where it is considered an important crop because of its ability to be stored for a long time as a food, as well as a seed with extended germination ability (Watanabe 1999).

A number of research studies have been carried to investigate the possibility of producing ready-to-eat food products from pure-millet grains. For example, white proso and foxtail millets have been used in the formulation of a flaked whole grain ready-to-eat breakfast cereal where the effects of dried honey or molasses as secondary sweeteners were also evaluated. The results showed that use of 100% millet in ready-to-eat breakfast cereals seems feasible. The type of sweetener affects the cereal color, flavor, and crispness when in milk. Honey appears to have an effect of maintaining cereal crispness after addition of milk, and using a combination of sweeteners may be beneficial (Ferriola and Stone 1998). Based on starch and analysis, lajia noodles (noodles were found remaining from late Neolithic China) were propositioned to be made of foxtail millet and proso millet flours by repeatedly stretching the dough (Lu and others 2005). However, in order to test the proposition that the lajia noodles can be made from millet, noodle-manufacturing experiments using different flours and starch grains analysis were performed. The results demonstrated that it was not possible to stretch pure-millet dough into noodles (Ge and others 2011).

Conversion of millet grains to *fura*, a common millet food in the West African region and one of the major sources of nutrients in the region, has been studied with respect to its nutrient and flavanol contents and its storage properties. The results showed that flavanol content of the grain decreased during conversion to *fura* by about 46.3%. Vitamin B2 content was also decreased during transformation of grain to meal, flour, and *fura* by 31.4%, 34.3%, and 45.7%, respectively (Durojaiye and others 2010). Furthermore, *upma*, a popular breakfast of southern India, traditionally made from wheat, was prepared using pearl millet semolina. The sensory quality during storage was found to be stable for 6 mo at ambient conditions (20 to 35 °C) in polyethylene pouches (75 μm). It has also suggested that being a high energy (29.5% fat) and good protein (6.7%) source, it can be used in mid-day meals and other feeding programs (Balasubramanian and others 2012).

Now we come to the conclusion that deficiency of millet grains in gluten as we mentioned above, which is very important to give a dough with elastic and extensible properties, makes them unsuitable for the preparation of easy-to-handle pure-millet solid food products, particularly bakery or noodle products. However, they can be converted into liquid or semiliquid food products, such as peer and porridge and other traditional household foods.

Therefore, there is a need for innovative processing technologies to convert millet grains into liquid foods such as drinks of high nutritional quality and safety that can be consumed by large populations in rural and urban areas.

Blending in composite flours and food products

For improvement of the nutritive value of food and diet to avoid malnutrition and certain diseases, different approaches are needed to offer adults and children improved food with low-cost and locally available food formulations. It has been established that porridges prepared from extruded millet and press-dried cowpea had high nutritional quality with acceptable properties of weaning foods (an intermediate consistency, smooth texture, and pleasant color and flavor) (Almeida-Dominguez and others 1993). In one study, biscuits were produced from millet flour and pigeon pea flour blends with blending ratios millet/pea of 100 : 0, 75 : 25, 65 : 35, and 50 : 50. It was found that all biscuits contained high proportions of protein and digestible carbohydrate. Sensory evaluation results also indicated that all the biscuits had high sensory ratings and the recipe with the 65% millet/35% pea blend resulted in the highest scores for flavor, texture, and general acceptability (Eneche 1999). In another study, biscuits prepared from flour composites containing 60 : 40 and 70 : 30 (w/w) finger millet : wheat flour were evaluated for dough characteristics and biscuit quality. It was indicated that a composite of finger millet and wheat flour (60 : 40) was best, particularly regarding biscuit quality (Saha and others 2011). For the preparation of breads, millet-based composite flours were optimized. Barnyard millet plus wheat composite flour was formulated and prepared by mixing 61.8 g/100 g barnyard millet, 31.4 g/100 g wheat, and 6.8 g/100 g gluten. The results of sensory analysis showed that the acceptability of bread samples prepared from composite flours was almost equal to that of the wheat bread (Singh and others 2012). Furthermore, the suitability of oat, millet, and sorghum in bread making was assessed in simple binary wheat flour matrices in which wheat flour was replaced from 0% to 60%. The results indicated that oat, millet, and sorghum represent a viable alternative to make aerated breads with mitigated technological and sensory constraints based on nonviscoelastic cereals (Angioloni and Collar 2012a).

The incorporation of millet flour blend was also found to improve the quality of composite flour containing kodo and barnyard millet flour, whole wheat flour and defatted soy flour in terms of increasing nutrient density, thinner gruel by lowered viscosity, and an increase in the level of syneresis that may improve the resistant starch content on storage (Vijayakumar and Mohankumar 2009). The effect of replacement of wheat flour with 0%, 20%, 40%, 60%, 80%, and 100% FMF, 60% FMF, emulsifiers and hydrocolloids on the batter microscopy, rheology, and quality characteristics of muffins were also studied. Use of a combination of additives in muffins with 60% FMF significantly improved the volume and quality characteristics of muffins (Rajiv and others 2011). Furthermore, whole pearl millet, finger millet, and decorticated soybean-blended (millet plus soy) extrudate formulations were designed using a linear programming (LP) model to minimize the total cost of the finished product. LP-formulated composite flour was extruded through a twin-screw food extruder at different extrusion conditions. It was found that the pearl-millet-based blend expanded snacks showed promising features for the production of low-cost extrudates (Balasubramanian and others 2012). Millet was also used with amaranth and buckwheat in the manufacture of extruded breakfast cereal products as a replacement for wheat and maize flour. The results showed that the use of these flours altered the physical and nutritional quality of extruded breakfast cereals. Further, all of the extruded products made with the inclusion of pseudocereals showed a significant reduction in readily digestible carbohydrates and slowly digestible carbohydrates compared to the control product during predictive *in vitro* glycemic profiling (Brennan and others 2012).

In order to develop finger-millet-incorporated noodles for diabetic patients, FMF was blended in various proportions (30% to 50%) into refined wheat flour and used for the preparation of noodles. Based on the basis of sensory evaluation, the 30% finger-millet-incorporated noodles were selected and evaluated for glycemic response compared to a control. The results indicated that glycemic index of 30% finger-millet-incorporated noodles was significantly lower than control noodles (Shukla and Srivastava 2011). Furthermore, finger millet and kidney beans (*Phaseolus vulgaris*) were processed by soaking, germination, autoclaving, and fermentation for incorporation into a complementary food for children. The results showed that various processing methods, especially germination, increased mineral extractability. Addition of vitamin C and mango could be used to enhance mineral extractabilities, thereby helping to alleviate micronutrient deficiencies in populations subsisting on these foods (Mamiro and others 2001). In addition, the finger millet seed coat is an edible material and contains a good proportion of dietary fiber, minerals, and phytochemicals. The seed coat matter (SCM) forms a by-product of the millet milling, malting, and decortication industries and can be utilized as a composite flour in biscuit making. The sensory evaluation of the biscuits indicated that 10% of SCM from native and hydrothermally processed millet and 20% from malted millet could be used in a composite biscuit flour (Krishnan and others 2011).

From the literature above, it can be seen that blending of millet grains, or their milling fractions combined with other treatment, is one of the most convenient techniques to produce food products with high nutritional and functional quality and to promote their utilization in a large range of food products. This is because conversion of millet grains in pure-millet bakery goods and some solid food products is not easy because of the deficiency of millet in gluten and some functional properties that are needed to make easy-to-handle, good texture, and ready-to-eat products compared with wheat and some other cereal grains.

Fortification and supplementation

Fortification of grain foods was found to be an effective strategy that can be used to overcome nutrient deficiencies. Micronutrient deficiencies, especially of vitamin A, iron, iodine, and zinc, are widely prevalent in both developing as well as some developed countries. However, iron deficiency is a major public health problem in developing countries, it affects up to 50% of infants, children, and women of child- bearing age in poorer populations of Africa, Asia, and Latin America. It has been established that fortified pearl millet flour seems to be a satisfactory candidate for fortification with zinc, and so can be exploited to address zinc deficiency (Tripathi and others 2011). On the other hand, heat processing of FMF improved the bioaccessibility of iron from both unfortified and fortified flour. Fortification with iron also did not affect the bioaccessibility of the native zinc from the flour (Tripathi and Platel 2012). Furthermore, double fortification of FMF with ferrous fumarate, zinc stearate, and EDTA did not negatively alter the sensory quality of the products prepared from them. In addition, the shelf-life of the fortified flours was also satisfactory up to a period of 60 d, as indicated by the moisture and free fatty acid contents in the fortified flours (Tripathi and others 2010).

Therefore, it can be said that fortification of millet flours is a technique to enrich them with micronutrients, such as microelements and vitamins, to improve their nutritional quality, but cost-effectiveness of this processing should be considered.

IVPD and the amino acid profile of pearl millet supplemented with soybean protein (5% to 15%) were investigated. Supplementation of millet flour with soybean protein steadily decreased IVPD with an increase in the portion of soybean in the blend. Further, essential amino acids of millet flour were enriched on supplementation with soybean protein. Supplementation significantly increased lysine 1.5- to 2.4-fold. In addition, essential amino acid content remained higher in the cooked composite flours when compared with the cooked native millet flour (Ali and others 2010). It has also been found that supplementation of pearl millet with whey protein resulted in a significant increase in protein content compared to the control. In addition, sensory evaluation revealed higher acceptability for whey-protein-supplemented formulas compared to the control (Mallasy and others 2010). Therefore, it can be concluded that supplementation of millet grains with natural food products to enhance their nutritive value can be promising and with high cost-effectiveness compared with fortification by chemical synthetic nutrients.

Preservation Treatments

Generally, whole matured dry cereal grains have the ability to be stored for a long time at ambient conditions. However, their milling fractions, such as flour, and the final prepared food products need some treatments or convenient conditions to improve shelf-life stability because of the impact of moisture and enzymes. Thermal processing is the most extensively used method in food preservation to destroy microorganisms thereby extending shelf-life. However, thermal processing has long been perceived while generally increasing the digestibility of foods, also to lead to a loss of certain heat-labile nutrients thus lowering the nutritional value (Randhir and others 2008). It has been found that hot-water blanching at 98 °C for 10 min or dry-heating of grains at 100 °C for 120 min is very effective in minimizing the undesirable changes in lipids of pearl millet meal during storage (Kadlag and others 1995). Furthermore, hydrothermal treatment of pearl millet grains was found an effective method to inactivate lipase and to enhance the shelf-life of the resultant flour. Hydrothermally treated grains yielded flour with acceptable physical, functional, and pasting properties and increased the storage stability significantly ($P < 0.05$) up to 50 d at ambient conditions (15 to 35 °C) as compared to 10 d for the control flour (Yadav and others 2012). However, hydrothermal treatment did not change the gross nutrients composition of finger millet, it only affected the nutrient profile (Dharmaraj and Malleshi 2011).

The refrigeration effects during storage on total protein and amino acids composition of raw and processed flour of 2 pearl millet cultivars were evaluated. The effect of refrigeration in combination with the storage period, cooking, or dehulling was found to be vary between amino acid composition and even between cultivars. Regardless of the storage period and processing method, the amino acid content remained unchanged after refrigeration for both cultivars (Mohamed and others 2011). It has also been reported that thermal treatments can be applied to extend whole pearl millet flour shelf-life, and the treatment such as toasting, boiling, and toasting and then boiling can be used to produce pearl millet flour that cooks more quickly (Nantanga and others 2008). Furthermore, irradiation-induced effects during storage on total protein and amino acid compositions of raw and processed flour of 2 pearl millet cultivars were also evaluated. Storage of the irradiated whole and dehulled flour for 60 d slightly reduced the protein content, even after cooking. The effect of irradiation in combination with the treatments applied to the grains and/or flour on amino acid was found to be varying between the cultivars. Most of the amino acids were stable against all treatments except leucine, glutamic acid, and phenylalanine (Mohamed and others 2010). Therefore, it can be said that refrigeration, irradiation, and hydrothermal treatment or a combination of more than 1 technique extend shelf-life of millet grains and their milling fractions as well as their food products. This can be attributed to inactivation effect of these treatments on endogenous enzymes and microorganisms. However, using of these techniques should be under optimized conditions to avoid unlikable changes in quality attributes of millet grains and their food products.

Other Processing Technologies

Application of high hydrostatic pressure (HHP) in food processing has been increased within the food industry as an alternative to thermal processing to protect sensory and nutritional attributes of food products (San Martín and others 2002). The impact of HHP treatment on dough viscoelastic reinforcement of highly replaced wheat cereal matrices has been investigated. It was found that HHP is an efficient strategy to modify the gelatinization and gelling behavior of oat, millet, sorghum, and wheat hydrated flours. Strong HHP treatment, over 350 MPa, does not always promote the degree of starch gelatinization in batters. By selecting the proper dough yield (DY = 200) and pressure conditions (350 MPa), HHP treatment can be used to improve the viscoelastic properties of highly replaced (up to 60%) composite wheat dough matrices. It was also suggested that further studies are required to know more about the qualitative and quantitative effects of pressure-treated oat, millet, and sorghum flours on the technofunctional and nutritional characteristics of composite wheat breads (Angioloni and Collar 2012b). The effect of depigmentation on sensory characteristics and nutritional parameters of pearl millet pasta was also studied. Pearl millet grains were depigmented by soaking in 0.2 N hydrochloric acid for 18 h, fol1owed by washing, blanching (98 °C for 30 s), and sun-drying. It was found that depigmentation is an effective processing technique for developing acceptable pearl millet products with better *in vitro* protein and starch digestibility (Rathi and others 2004).

Potential Health Benefits of Millet Grains and Their Fractions

Epidemiological evidence from research studies has shown that diets rich in plant foods are protective against several degenerative diseases such as cancer, cardiovascular ailments, diabetes, metabolic syndrome, and Parkinson's disease (Manach and others 2005; Scalbert and others 2005; Chandrasekara and Shahidi 2012). In addition, there is strong epidemiological evidence that whole-grain cereals protect the body against age-related diseases such as diabetes, cardiovascular diseases, and some cancers (Fardet and others 2008). However, for years, the vitamins, minerals, essential fatty acids, and fiber in whole grains were believed to be responsible for their health benefits, but recent research suggests that the combination of other bioactive substances also works to exert positive effects. They include resistant starch; oligosaccharides; lipids; antioxidants such as phenolic acids, avenanthramides, and flavonoids; hormonally active compounds including lignans and phytosterols; and antinutrients such as phytic acid and tannins (Miller 2001; Edge and others 2005). Millets must also be accepted as functional food and nutraceuticals because they provide dietary fibers, proteins, energy, minerals, vitamins, and antioxidants required for human health. Several potential health benefits such as preventing cancer and cardiovascular diseases, reducing tumor incidence, lowering blood pressure, risk of heart disease, cholesterol, and rate of fat absorption, delaying gastric emptying, and supplying gastrointestinal bulk were reported for millets (Truswell 2002; Gupta and others 2012). Recently, the U.S. Dept. of Agriculture's nutritional guidelines put grains and grain products at the base of the food guide pyramid to emphasize grains or grain product consumption as part of a normal diet for optimal health (USDA 2000, 2005).

Aantioxidant contents and activities

The growing public awareness of nutrition and health care research substantiates the potential of phytochemicals such as polyphenols and dietary fiber on their health beneficial properties (Devi and others 2011). The increased consumption of whole grains and whole grain products has been associated with reduced risk of developing chronic diseases such as cardiovascular disease, type 2 diabetes, some cancers, and all-cause mortality. In addition, whole grains contain unique phytochemicals that complement those in fruits and vegetables when consumed together (Liu 2007). Polyphenols are the biggest group of phytochemicals that have been found in plant-based foods and have been linked to several health benefits. Therefore, dietary polyphenols have received tremendous attention among nutritionists, food scientists, and consumers due to their roles in human health (Tsao 2010). It has been reported that soluble- and insoluble-bound phenolic extracts of several varieties of millet (kodo, finger, foxtail, proso, pearl, and little millets) whole grains are rich sources of phenolic compounds and show antioxidant, metal chelating, and reducing powers. However, the potential of whole millets as natural sources of antioxidants depends on the variety used (Chandrasekara and Shahidi 2010).

Much attention has been devoted to investigations of the nutraceutical and antioxidant properties of some major millet varieties, including finger millet, pearl millet, and foxtail millet. It has been reported that foxtail millet contains 47 mg polyphenolics/100 g and 3.34 mg tocopherol/100 g (wet basis); however, proso millet contains 29 mg polyphenolics/100 g and 2.22 mg tocopherol/100 g (wet basis). In addition, a positive and significant correlation ($R^2 = 0.9973$, $P < 0.01$) between polyphenolic content and radical cation scavenging activity was observed (Choi and others 2007). For finger millet, the high-performance liquid chromatography (HPLC) analysis of polyphenols indicated nearly 30 prominent constituent phenolics, but only about 30% of them could be identified (Chethan and Malleshi 2007). Furthermore, phenolic acids from the milling fractions of finger millet (whole flour, seed coat, 3%, 5%, and 7%) were also isolated. Acidic methanol extracts from seed coat to whole flour were rich in polyphenol content and were found to be stable up to 48 h at pH 4, 7, and 9 (Viswanath and others 2009). Currently, over 50 phenolic compounds belonging to several classes, namely, phenolic acids and their derivatives, dehydrodiferulates and dehydrotriferulates, flavan-3-ol monomers and dimers, flavonols, flavones, and flavanonols in 4 phenolics fractions of several whole millet grains (kodo, finger, foxtail, proso, little, and pearl millets) were positively or tentatively identified using HPLC and HPLC-tandem mass spectrometry (MS). However, insoluble bound fraction of kodo millet showed the highest phenolic content as well as antioxidant activity in the *in vitro* test systems employed (Chandrasekara and Shahidi 2011a). Therefore, and based on literature data, millet grains can be used as functional food ingredients and as sources of natural antioxidants.

The antioxidant activity of phenolics and other bioactive components extracted from millet grains and their fractions was evaluated in a number of research studies. It was reported that 3 antioxidative phenolic compounds, 1 serotonin derivative, and 2 flavonoids were isolated from an ethanol extract of Japanese barnyard millet grains. Their structures were established to be *N*-(*p*-coumaroyl) serotonin, luteolin, and tricin. Although the antioxidant activity of luteolin was lower than that of *N*-(*p*-coumaroyl) serotonin, it was nearly equal to that of quercetin, whereas the activity of tricin was lower than that of luteolin (Watanabe 1999). Kodo millet, finger millet, little millet, foxtail millet, barnyard millet, and sorghum *bicolor* grown in India and their white varieties were screened for free radical quenching of 1,1, diphenyl-2-picrylhydrazyl (DPPH) by electron spin resonance. Methanol extracts of the kodo millet flour showed 70% DPPH quenching in comparison to other millet extracts that showed 15% to 53%. Further, the white varieties of sorghum, finger millet, and foxtail millet showed lower quenching than their colored counterparts, indicating that phenolics in the seed coat could be responsible for the antioxidant activities. However, the content of the phenols and tannin in these grains did not correlate with the antioxidant activities (Hegde and Chandra 2005). Furthermore, finger millet extracts were found to have a potent radical-scavenging activity that is higher than those of wheat, rice, and other species of millet (Dykes and Rooney 2006). In addition, the reducing power of finger millet seed coat extract was significantly ($P < 0.05$) higher than that of whole flour extract (Viswanath and others 2009). Moreover, xylo-oligosaccharides (XOs) mixture of finger millet exhibited relatively higher antioxidant activity than the XOs of rice, wheat, and maize by DPPH and ferric reducing antioxidant power assays (Veenashri and Muralikrishna 2011). For foxtail millet, methanolic extracts of whole flour and bran-rich fraction exhibited a significantly higher ($P < 0.05$) radical-scavenging activity (44.62% and 51.80%, respectively) using a DPPH model system, and reducing power (0.381 and 0.455, respectively) at 2 mg, than the ethanol and water used for extraction (Suma and Urooj 2011c). On the other hand, 50% ethanol extract from defatted foxtail millet bran was found to be the best-promoting phenolic compound with substantial antioxidant activity (Amadou and others 2011). In addition, defatted foxtail millet protein hydrolysates also exhibited antioxidant potency (Mohamed and others 2012). Thus, millet may serve as a natural source of antioxidants in food applications and as a nutraceutical and functional food ingredient in health promotion and disease risk reduction. However, more studies in animal models and with human subjects should be performed to verify their activity and health benefits.

Effect of processing on antioxidant activity of millet grains

The processing methods mentioned above such as malting, decortication, soaking, and cooking were also found to affect the content and activity of the antioxidants in millet grains. In one study, the antioxidant capacity of the fraction containing free phenolic acids was increased (2-fold) after 96 h of malting of finger millet, whereas the antioxidant capacity of the fraction containing bound phenolic acids was decreased (Rao and Muralikrishna 2002). In another study, a growth-promoting medium was developed to enhance the production of a hydroxyl radical inhibitory water-soluble protein from germinated millet. The single factor test indicated that H_2O_2 plays a key role in the inhibition activity (Li and others 2007). In addition, to further increase the yield of the hydroxyl radical inhibitory water-soluble protein from stress-germinated millet, the effects of the sprouting conditions (temperature, time, and pH of stress medium) on the hydroxyl radical inhibition were investigated. The optimal conditions were identified as temperature 28 °C, culture time 54 h, and stress medium pH 7.5. Under optimum conditions, the highest inhibition (60.38%) was achieved (Li and others 2008). Also, germination of foxtail millet for 3 d allowed obtaining flour with high DPPH-scavenging activity (Coulibaly and Chen 2011).

Cooking of kodo or finger millet by roasting or boiling resulted in a reduction in antioxidant activity. Fractionation of kodo millet into husk and endosperm also decreased the DPPH quenching activity and the phytochemicals appeared to act synergistically (Hegde and Chandra 2005). Furthermore, effects of germination, steaming, and roasting on the nutraceutical and antioxidant properties of little millet were also investigated. The results showed that the total phenolic, flavonoid, and tannin contents of processed little millet increased by 21.2, 25.5, and 18.9 mg/100 g, respectively, compared to the native sample (Pradeep and Guha 2011). However, dehulling and hydrothermal treatments were found to affect the antioxidant potential and phenolic content of pearl millet grains (Chandrasekara and others 2012). The reduction in antioxidant contents and their activities can be attributed to oxidation and degradation reactions taken place during thermal treatments, such as cooking, boiling, and roasting. However, the reduction happened by dehulling can be attributed to removing of pericarp layer from the grains, which is known rich in polyphenol and antioxidant compounds. Therefore, processing of millet grains, their fractions, and food products must be under optimized conditions to protect their quality and potential health benefits. In addition, the increase in antioxidant contents and their activities by germination can be attributed to conversion of complex components to simpler compounds with higher antioxidant activity by endogenous enzyme during germination.

Millet for diabetics

Diabetes mellitus is a chronic metabolic disorder characterized by hyperglycemia with alterations in carbohydrate, protein, and lipid metabolism. It is considered as the most common endocrine disorder and results in deficient insulin production (type 1) or combined resistance to insulin action and the insulin-secretory response (type 2). However, although chemical synthetic inhibitors of alpha-glucosidase and pancreatic amylase play a vital role in the clinical management of postprandial hyperglycemia, natural inhibitors are potentially safer. The intake of whole grain foods is suggested to be beneficial for the prevention and management of diabetes mellitus, and epidemiologically lower incidence of diabetes has been reported in millet-consuming populations (American Diabetes Association 2005; Shobana and others 2009; Kim and others 2011). For example, consumption of finger-millet-based diets resulted in significantly lower plasma glucose levels, mean peak rise, and area under curve that might have been due to the higher fiber content of finger millet than rice and wheat. The lower glycemic response of whole finger-millet-based diets may also have been due to the presence of antinutritional factors in whole FMF, which are known to reduce starch digestibility and absorption (Kumari and Sumathi 2002). In addition, the role of finger millet feeding on skin antioxidant status, nerve growth factor (NGF) production, and wound healing parameters in healing-impaired early diabetic rats has been reported. Increased levels of oxidative stress markers accompanied by decreased levels of antioxidants play a vital role in delaying wound healing in diabetic rats. However, finger millet feeding to the diabetic animals, for 4 weeks, controlled the glucose levels and improved the antioxidant status, which hastened the dermal wound healing process (Rajasekaran and others 2004).

Dehulled and heat-treated barnyard millet has been reported beneficial for type 2 diabetics in which low glycemic index for dehulled millet (50.0) and heat-treated (41.7) was recorded (Ugare and others 2011). It has also been documented that all the extruded products made with the inclusion of pseudocereals (amaranth, buckwheat, and millet) showed a significant reduction in readily digestible carbohydrates and slowly digestible carbohydrates compared to the control product during predictive *in vitro* glycemic profiling (Brennan and others 2012). In addition, FMF-incorporated noodles were found nutritious and showed a hypoglycemic effect (Shukla and Srivastava 2011). Phenolic compounds from millet grains also showed potential antidiabetic effects. In one study, finger millet polyphenols (FMPs) were reported as major antidiabetic and antioxidant components, when evaluated for aldose reductase (AR)-inhibiting activity. Phenolic constituents in FMP such as gallic, protocatechuic, p-hydroxy benzoic, p-coumaric, vanillic, syringic, ferulic, trans-cinnamic acids, and quercetin inhibited cataract eye lens effectively. Structure-function analysis also revealed that phenolics with an OH group at the 4th position were important for aldose reductase inhibition. Further, the presence of a neighboring o-methyl group in phenolics denatured the AR activity. Therefore, these results provide strong evidence for the potentials of FMP in inhibiting cataractogenesis in humans (Chethan and others 2008). In another study, phenolic compounds from the millet seed coat showed strong inhibition toward α-glucosidase and pancreatic amylase (Shobana and others 2009). However, 70% ethanol extracts from foxtail millet and proso millet exhibited no visible or detectible inhibitory effect on α-amylase or on α-glucosidase activity (Kim and others 2011). Furthermore, the aqueous extracts of foxtail millet grains were found to have excellent antihyperglycemic activity (Sireesha and others 2011). Therefore, millet grains and their milling fractions can be used in preparing various food products for diabetics.

Some *in vivo* studies were carried out in order to investigate the effect of millet grains and their fractions on diabetes. In one study, the influence of 6 Sudanese traditional carbohydrate-rich meals on glucose and insulin responses in diabetic subjects was measured. The results showed that millet acida (porridge) followed by wheat gorasa (pancakes) displayed significantly lower postprandial glucose and insulin responses, whereas maize acida induced a higher postprandial glucose and insulin response (Abdelgadir and others 2004). In another study, the levels of enzymatic (glutathione and vitamins E and C) and nonenzymatic antioxidants (superoxide dismutase, catalase, glutathione peroxidase, and glutathione reductase) and lipid peroxides were significantly reduced in diabetic animals and restored to normal levels in the millet-fed groups (Hegde and others 2005). The feeding of proso millet protein improved glycemic responses and insulin in genetically obese type-2 diabetic mice under high-fat feeding conditions (Park and others 2008). It has also been documented that finger millet helps to control blood glucose levels in diabetic patients very efficiently (Desai and others 2010). Furthermore, studies were conducted on human diabetics (male and female) living in different rural and urban locations in India, and 13 diabetics were selected and asked to replace their regular wheat chapati with multigrain chapati (millet and wheat in a 30 : 70 ratio). The sugar level in high-glucose persons was lowered by continuous consumption of multigrain flour. All persons who consumed the multigrain chapati were found to have considerably decreased blood glucose levels (Pradhan and others 2010). Therefore, millet grains have the potentials to be useful in preventing diabetes and for treatment of diabetics. In addition, there is an essential need for studies in animal models and human subjects to verify the antidiabetic activity of millet grains and their fraction and extracts.

Millet and cardiovascular disease

Obesity, smoking, unhealthy diet, and physical inactivity increase the risk of heart attacks and strokes. Most of the world countries face high and increasing rates of cardiovascular disease. It has been demonstrated that rats fed with a diet of native and treated starch from barnyard millet had the lowest blood glucose, serum cholesterol, and triglycerides compared with rice and other minor millets (Kumari and Thayumanavan 1997). Also, the feeding of proso millet protein improved plasma levels of adiponectin, high-density lipoprotein (HDL) cholesterol in genetically obese type-2 diabetic mice under high-fat feeding conditions (Park and others 2008). Furthermore, concentrations of serum triglycerides were significantly lower in the finger millet and proso millet groups of hyperlipidemic rats than those of the white rice and sorghum groups. In addition, concentrations of serum total, HDL, and low-density lipoprotein (LDL) cholesterols were significantly higher in the sorghum group than in the white rice, finger millet, and proso millet groups. Therefore, finger millet and proso millet may prevent cardiovascular disease by reducing plasma triglycerides in hyperlipidemic rats (Lee and others 2010). In addition, phenolic extracts from kodo, finger, proso, foxtail, little, and pearl millets were evaluated for their inhibitory effects on lipid peroxidation in *in vitro* copper-mediated human LDL cholesterol oxidation and several food model systems, namely, cooked comminuted pork, stripped corn oil, and a linoleic acid emulsion. At a final concentration of 0.05 mg/mL, millet extracts inhibited LDL cholesterol oxidation by 1% to 41%. All varieties exhibited effective inhibition of lipid oxidation in food systems used in this study and kodo millet exhibited superior inhibition of lipid peroxidation, similar to butylated hydroxyanisole at 200 ppm (Chandrasekara and Shahidi 2011b).

Millet against cancers and celiac disease

Millet grains based on literature values are known to be rich in phenolic acids, tannins, and phytate that act as "antinutrients" (Thompson 1993). However, it has been established that these antinutrients reduce the risk for colon and breast cancer in animals (Graf and Eaton 1990). It has also been reported that populations consuming sorghum and millet have lower incidences of esophageal cancer than those consuming wheat or maize (Van Rensburg 1981). Furthermore, a recent study has demonstrated that millet phenolics may be effective in the prevention of cancer initiation and progression *in vitro* (Chandrasekara and Shahidi 2011c).

The overall growing demand for novel, tasty, and "healthy" foods, together with the increasing number of people suffering from celiac disease, has given birth to a new market consisting of cereal products made from grains other than wheat and rye. In this challenging market, oat, sorghum, and millet have gained a special position (Angioloni and Collar 2012a). Celiac disease is an immune-mediated enteropathy triggered by the ingestion of gluten in genetically susceptible individuals. It is one of the most common lifelong disorders worldwide. In the past, celiac disease was considered a rare disorder, mostly affecting children of European origin. Recently, a huge number of studies have shown that celiac disease is one of the commonest lifelong disorders affecting humans in many areas of the world (Catassi and Fasano 2008). A gluten-free diet primarily affects food consumption from the grain food group. In place of wheat, barley, and rye-based foods, persons adhering to a gluten-free diet must consume foods made from gluten-free grains, including rice, corn, sorghum, millet, amaranth, buckwheat, quinoa, wild rice, and oats (Thompson 2009). In the developed countries, there is a growing demand for gluten-free foods and beverages from people with celiac disease and other intolerances to wheat, barley, or rye. However, since millets are gluten-free, they have considerable potential in foods and beverages that can be suitable for individuals suffering from celiac disease (Taylor and others 2006; Taylor and Emmambux 2008; Chandrasekara and Shahidi 2011b, 2011c). Therefore, millet grains and their fractions have the potential to be useful in cancer prevention and for producing food products for celiac people.

Millet and aging

The chemical reaction between the aldehyde group of reducing sugars and the amino group of proteins, termed as nonenzymatic glycosylation, is a major factor responsible for the complications of diabetes and aging (Monnier 1990). Millet grains are rich in antioxidants and phenolics; however, it has been established that phytates, phenols, and tannins can contribute to antioxidant activity important in health, aging, and metabolic syndrome (Bravo 1998). It has also been found that methanolic extracts from finger millet and kodo millet inhibited glycation and cross-linking of collagen (Hegde and others 2002). Therefore, there is potential usefulness of millets in the protection against aging.

Antimicrobial activity

Millet grain fractions and extracts were found to have antimicrobial activity. In one study, seed protein extracts of pearl millet, sorghum, Japanese barnyard millet, foxtail millet, samai millet, and proso millet were evaluated *in vitro* for their ability to inhibit the growth of *Rhizoctonia solani, Macrophomina phaseolina,* and *Fusarium oxysporum.* Protein extracts of pearl millet were highly effective in inhibiting the growth of all 3 examined phytopathogenic fungi. The results indicated that the 23-kDa thaumatin-like proteins (TLPs) were predominantly expressed in the seeds and inflorescence of pearl millet (Radhajeyalakshmi and others 2003). In another study, phenolic acids from finger millet milled fractions (whole flour, seed coat, 3%, 5%, and 7%) were isolated. The seed coat extract showed higher antimicrobial activity against Bacillus cereus and Aspergillus flavus than whole flour extract. Therefore, the results indicated that potential exists to utilize finger millet seed coat as an alternative natural antioxidant and food preservative (Viswanath and others 2009). Furthermore, phenolics in finger millet grain were found to influence its malt quality positively by contributing to attenuation of the fungal load on the germinating grain and malt quality, and high-phenol finger millet types were better than low-phenol types (Siwela and others 2010). In addition, a novel antifungal peptide with high potency was isolated from foxtail millet seeds (Xu and others 2011). Therefore, extracts of phenolic acids and other bioactive components have the potential to be used as natural alternatives in food preservation and for therapeutic purposes. However, more studies are needed to verify their potential antimicrobial effects.

Challenges and Future Perspectives

From the literature reviewed above, it can be observed that although nutritive value and potential health benefits of millet grains were found comparable to major cereals such as wheat, rice, and maize and although processing technologies such as fermentation, soaking/malting, and fortification/supplementation were found to improve their edible and nutritional characteristics, utilization of millet grains as food is still mainly limited to populations in rural areas at the household level. This is due to lack of innovative millet processing technologies to provide easy-to-handle, ready-to-cook or ready-to-eat, and safe products and meals at a commercial scale that can be used to feed large populations in urban areas (Ushakumari and others 2004). However, with an increasing population and thus increasing demands for food, feed, and fuel, society will be pressed to increase agricultural production—whether by increasing yields on already cultivated lands or by cultivating currently natural areas—or to change current crop consumption patterns (Licker1 and others 2010). Moreover, diversification of food production must be encouraged both at national and household levels in tandem with increasing yields. Providing more healthful and traditional whole-grain and multigrain substitutes for refined carbohydrates can be one important aspect of therapeutic dietary modification and promoting utilization of minor-grain foods (Singh and Raghuvanshi 2012).

Gluten protein is well known in terms of the importance for producing easy-to-handle and high-quality bakery products and some other grain foods that require elastic and extensible dough. However, since millet grains are gluten-free and based on results of some laboratory trials, they seem unsuitable to be converted into pure-millet bakery and some other easy-to-handle solid food products. Thus, use of millet grains as replacement in wheat composite flours, complementary food, and food blends seems the best method that can be used for the preparation of nutritional, "healthy" and safe, high-quality, and shelf-stable food products at household and commercial scales to promote utilization of millet grains. In addition, to produce high-quality products at a commercial scale for urban consumers, there is a need for innovative processing technologies for decortication, milling, and other preparation treatments of millet grain food. In return, a consistent supply of high-quality millet grains for industrial uses and development of millet cultivars with high essential amino acid content are needed. Evaluation of nutritive value and potential health benefits of millet grains and their fractions in animal and human models should be performed in future research studies to support efforts for promoting their utilization as food.

Conclusion

This article presents the recent research carried out to date for purposes of processing and nutritional quality improvement of millet grains and their food products. Based on the results of studies carried out, we can observe that millet grains contain many health-promoting components such as dietry fiber, minerals, vitamins, and phytochemicals that include phenolic compounds, and they are comparable to those of major grains and they also have several potential health benefits. However, novel processing and preparation methods are needed to enhance the bioavailability of the micronutrients and to improve the quality of millet diets. Research is also needed to determine the bioavailability, metabolism, and health contribution of millet grains and their different fractions in humans. Making millet food products that deliver convenience, taste, texture, color, and shelf-stability at economical cost for poor people is needed. In addition, for promoting utilization of millet grains in urban areas to open new markets for farmers to improve their income, developing highly improved products from millet is needed.

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