The recent growing interest in sorghum and sorghum-related products has been manifested in presentations given at a number of conferences held during the last few years. Both paper and poster presentations by students as part of product development competitions and by independent researchers from industry and academia have highlighted the interest in developing new sorghum-based products. Examples of new products promoted by recent student product development competitions include

- **Simply Sweet Sorghum Treats**: Both ice cream and cones are made with sorghum grain varieties. Cooking liquid is used as the medium for the ice cream, and cooking solids are added to whole sorghum flour to make ice cream cones. Phenolic-rich sorghum extracts provide an array of colors, enabling ice cream with red velvet, tart pink, and berry blue flavors to be produced.

- **Granotè—Pineapple & Orange Sorghum Herbal Tisane**: This all-natural, caffeine-free, high-antioxidant health-promoting beverage incorporates sorghum. Cracked and roasted red sorghum varieties are combined with a dried pineapple and orange fruit mix to appeal to a wide range of consumers.

- **Gluten-free Cereal Bar with Sorghum and Tropical Fruits**: The development of sorghum-based products specifically for incorporation into cereal bars is being spurred by the growing popularity of cereal bar products due to their convenience and association with health benefits.

- **Home-style Waffle Melts**: These waffles are formulated with whole grain white sorghum flour and based on frozen waffle products.

In developing parts of the world, sorghum has remained a dietary mainstay since the earliest human settlements began cultivating crops. Promotion of sorghum grains and their products is becoming more commonplace in the developed world with the growing awareness of the potential applications of this largely untapped food resource among the scientific community, food industry, and health-conscious consumers. This article focuses on the historical importance of this essential nutrient-rich grain and its potential role in modern food development. Specific product development examples and a discussion of future trends are provided.

### Background on Sorghum

Sorghum is a good source of dietary fiber and phenolic compounds and is an important food staple for people in many parts of the world. It is a true ancient grain and is known to have been collected 8,000 years ago in Nabta Playa in southern Egypt. Sorghum was domesticated in Ethiopia and Sudan and from there cultivation spread throughout Africa, where it remains an important cereal grain. Sorghum likely traveled to India during the 1st millennium B.C. as food on ships and then continued to be disbursed along the silk trade routes. It most likely arrived in the Americas with slave traders from Africa in the 19th century A.D. (52).

If you ask a hundred people if they have ever eaten sorghum, chances are they’ll have no idea what you’re talking about. However, sorghum (*Sorghum bicolor* (L.) Moench) is the fifth most widely grown cereal crop in the world, following wheat, corn, rice, and barley. Due to its natural drought tolerance and versatility, sorghum is an important food staple for people in semiarid parts of the world with an uncertain food supply (55). Nigeria, Sudan, Ethiopia, and Burkina Faso account for nearly 70% of the sorghum grown in Africa. Throughout Africa, sorghum porridge or gruel is commonly consumed in almost every country, as well as flatbreads such as Ethiopian injera, which is made from sorghum, teff, or a combination of both. Sorghum also is used to make both alcoholic and nonalcoholic beverages. Most of these products incorporate fermented or sprouted sorghum, because these two processes make sorghum’s nutrients more available and increase their shelf life and food safety.

Although sorghum has fed people in developing parts of the world for centuries, there has been little interest in sorghum as a food source in the United States, where it has mainly been used for livestock feed and in a growing number of ethanol plants (1,46). However, there is a
growing interest in sorghum grain and its products by U.S. consumers and the food industry due, in part, to growth in the “gluten-free” trend.

**Sorghum Production**

Sorghum (or milo as it is sometimes referred to in the United States) represents the third-largest cereal grain crop grown in the United States, following wheat and corn. Its comparative advantage is its drought tolerance, resistance to mycotoxins and fungi, and ability to grow under relatively harsh climate conditions (50).

Currently, sorghum production is 396.11 million bu (1 bu is 56 lb) worldwide. In 2012, leading producers around the world included Mexico, the United States, Nigeria, India, and Argentina (59). In the United States, sorghum is grown primarily on dryland acres; the “sorghum belt” stretches from South Dakota to southern Texas (Fig. 1).

Sorghum is grown in 14 U.S. states. Historically, Kansas and Texas have been the top two sorghum-producing states, harvesting 79% of the U.S. sorghum crop. In 2012, Texas produced 112.1 million bu valued at $703.1 million, and Kansas produced 81.9 million bu valued at $582.5 million. Other states producing large quantities of sorghum include Louisiana, Arkansas, South Dakota, and Oklahoma (59). The United States is the leading exporter of sorghum. In recent years, it has accounted for more than 65% of world trade. The top importers during the 2010–2011 crop year were Mexico (60%), the European Union (22%), and Japan (9%) (60).

**Characteristics of Sorghum Grain**

Sorghum (*S. bicolor*) is a cereal of remarkable genetic variability, which makes it difficult to classify. A few names for sorghum include milo, jowar, kafir corn, Guinea corn, and cholam. The seed or caryopsis of sorghum is a major source of calories and protein in the diets of millions of people in Africa and Asia. Sorghum is grown from traditional hybrid seeds and does not contain traits gained through biotechnology, making it non-transgenic (non-GMO) (61).

In the United States, four distinct varieties of sorghum are grown for different uses: 1) grass sorghum is used as cattle feed; 2) broom sorghum, which is not a food source, makes good brooms; 3) sweet sorghum, like sugar cane, yields syrup; and 4) grain sorghum is ground for flour and is used in beer.

Sorghum grain characteristics have been documented in detail by Rooney and Miller (47). The kernel or grain is considered a naked caryopsis, although some African varieties retain their glumes after threshing. Sorghum caryopales differ widely in weight (3–80 mg), test weight (708–785 g/L), and density (1.15–1.38 g/cm³). Commercial U.S. sorghum varieties have kernels that are generally 4 mm long, 2 mm wide, and 2.5 mm thick, with a kernel weight of 25–35 mg, test weight of 747–772 g/L, and density of 1.28–1.36 g/cm³ (47).

The appearance and quality of sorghum are affected significantly by genetically controlled characters (61). The caryopsis consists of three distinct anatomical components: pericarp (outer layer), endosperm (storage tissue), and germ (embryo) (Fig. 2). The outer layer (pericarp) originates from the ovary wall (19) and is divided into three histological tissues: epidermis, mesocarp, and endocarp (16).

The outermost layer of the pericarp (epicarp) is generally covered with a thin layer of wax, is two or three cell layers thick, and consists of rectangular cells that often contain pigmented material. Unlike most cereals, the sorghum mesocarp contains starch granules. A thick pericarp usually contains three or four mesocarp cell layers filled with small starch granules (Fig. 3).
Sorghum endosperm proteins have equal or lower in vitro pepsin digestibility in raw flour and substantially lower digestibility in cooked products than those of other cereals (25). The reasons sorghum proteins are less digestible than those of other cereals have not yet been completely elucidated. However, several factors have been identified that may play a role in determining the digestibility of sorghum endosperm proteins, including physical grain structure, protein body structure, protein cross-linking, starch properties, and phenolic content or composition of the grain. The majority of proteins contained in the sorghum endosperm are found in digestion-resistant spherical protein bodies that have highly cross-linked outer layers. Disulfide bond-mediated cross-linking increases during cooking of sorghum, resulting in the formation of highly cross-linked web-like protein structures. Protein digestibility has a substantial impact on the nutritional properties of sorghum utilized in the production of human foods, animal feeds, and bioindustrial applications such as ethanol (4).

Mycotoxins are less of a problem in sorghum than in maize (Zea mays L.). In contrast to maize, fumonisin has not been found at significant levels in sorghum. In similar drought-prone environments, aflatoxin levels can be excessive in maize, while sorghum has nonsignificant aflatoxin levels. Although aflatoxin is not found at significant levels on sorghum in the field, it can be found on improperly stored, high-moisture sorghum (45).

U.S. Sorghum Grain Standards
Sorghum grain is marketed in the United States according to established U.S. grain standards (58):

- **Sorghum grade**: Sorghum does not contain more than 3% sorghum with a pigmented testa or undercoat.
- **White sorghum grade**: White sorghum contains sorghum with a white pericarp without a pigmented testa. It cannot contain more than 2% sorghum with a pigmented pericarp or testa.
- **Mixed sorghum grade**: Mixed sorghum contains mixtures of sorghum with and without pigmented testa.
- **Tannin sorghum grade**: Tannin sorghums contain proanthocyanidins as part of their phenolic compounds but do not contain tannic acid or hydrolyzable tannins. Tannin sorghums have pigmented testa on the innermost layer of the pericarp. The pigmented testa is seen as a dark layer between the light endosperm and pericarp when the caryopsis is scraped to remove the pericarp.

When damaged immature pericarp tissues respond with antimicrobial phenolic compounds that form pigments that stain the pericarp and endosperm. Insect and mold damage to the pericarp commonly occurs together when caryopses mature in hot, humid environments (61) (Fig. 4).

Some specialty sorghum varieties contain substantial quantities of phenolic compounds, which are generally located in the outer layers of the kernel in the epicarp and testa (2,40). Common specialty sorghum varieties include red, tan, and black (sumac and high-tannin), and black (Fig. 5).

Nonfood Sorghum Applications
In addition to feed and food applications, sorghum can be manufactured into a wide variety of products. For example, because of its poor conductivity sorghum is well-suited to biodegradable packaging material applications (53). In addition, it is being utilized in housing wallboard (35).

**Ethanol.** Sorghum is increasingly being used in ethanol production because it produces approximately the same amount of ethanol per bushel as corn while requiring one-third less water. Sorghum is a good fit for different types of ethanol production, including traditional starch from grain; sugar from pressed juice; and biomass production. In fact, the entire sorghum plant can be used as biomass. Currently, ≈12% of the U.S. sorghum crop is utilized in ethanol production. Sweet sorghum in particular is being pursued as feedstock for half of the planned ethanol plants in Florida (18).

**Animal Feed.** Globally, ≈50% of the sorghum consumed is consumed by humans, but in the United States more than 90% of the sorghum consumed is consumed as a component in livestock feed. Corn (maize) is the main alternative ingredient for sorghum in livestock feed (9). Although corn and sorghum have similar chemical makeups, corn is easier for livestock to digest and utilize than sorghum. Certain processing techniques have been developed, however, to break down the sorghum kernel so it is as easy for livestock to digest and utilize as corn. Many studies have compared the effects of different processing techniques on the

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**Fig. 3.** Sorghum grain thin and thick pericarp. P: Pericarp; Al: aleurone layer. (Courtesy of Cassandra McDonough, Cereal Quality Lab, Texas A&M University)

**Fig. 4.** When damaged, immature pericarp tissues respond with antimicrobial phenolic compounds that form pigments that stain the pericarp and endosperm. (Courtesy of Cassandra McDonough, Cereal Quality Lab, Texas A&M University)
ability of different types of livestock to digest and utilize sorghum in feed. Studies on cattle show that steam-flaked sorghum was preferable to dry-rolled sorghum because it improved daily gain and feed efficiency (37).

Sorghum Food Applications and Benefits

Flavor. Sorghum grains offer nutritional and functional benefits as well as unique flavors in food applications. Sorghum varieties vary in composition, kernel structure, and unique phytochemical contents. Sorghum grains are consumed as porridges, flatbreads, cooked whole grain (similar to rice), and a wide variety of fermented products. Sorghum syrup is pressed from the stalks of sweet sorghum plants, similar to sugar cane, and then boiled down into concentrated syrup. As it cooks, the syrup develops a rich, earthy, honey-like flavor. It can be used on its own as a topping for pancakes and oatmeal or, like honey or molasses, in desserts and baked goods. This syrup can also be used like malt extract to brew gluten-free beer (50).

Gluten-free. Sorghum is naturally gluten-free and may be used as an alternative ingredient in food products that traditionally contain gluten. Over the last decade, there has been increasing interest in utilization of sorghum products for development of products that are safe for people with celiac disease or wheat allergies (1). Although it has long been thought that sorghum is safe for those with celiac disease, no clinical testing was done until 2007. Italian researchers (8) first conducted laboratory tests. After the tests established the likely safety of sorghum, they fed celiac patients sorghum-derived food products for 5 days. The patients experienced no symptoms, and the level of disease markers (antitransglutaminase antibodies) was unchanged at the end of the 5 day trial (8).

Celiac disease is a disorder caused by an abnormal immune response to gluten proteins found in wheat, rye, barley, and possibly oats (64). Gluten triggers inflammatory reactions in people with celiac disease or gluten sensitivity that can cause abdominal pain and digestive issues and can eventually lead to joint pain and intestinal damage. The only treatment for individuals with celiac disease is to avoid all foods containing gluten. The FDA allows a product to be labeled as gluten-free if it contains <20 ppm gluten. According to the latest research, ingesting 50 mg of gluten/day causes intestinal damage in people with celiac disease (42). This means that at least 5 lb of gluten-free foods containing <20 ppm gluten must be consumed per day for damage to occur.

Initial consumer perceptions of gluten-free foods were that they were bland, boring substitutes for more appealing gluten-containing products. With improvements in product formulations and alternative ingredients, perceptions of gluten-free products have begun to improve as well. Three-quarters (75%) of consumers surveyed who do not have celiac disease or a sensitivity to gluten eat these foods because they believe they are healthier, despite the lack of scientific research confirming the validity of this theory. Almost one-third of U.S. adults (29%) surveyed say they want to cut down on the gluten they consume or follow a gluten-free diet. In 2010 sales of gluten-free products reached more than $2.6 billion and are expected to exceed $5 billion by 2015 (43). These numbers suggest the gluten-free market is here to stay. With so many people needing to avoid foods that contain gluten, a need for special products has arisen, and more and more gluten-free products are finding their way onto supermarket and health-food store shelves or are being offered via the Internet.

Nutrients in Whole Grain. Sorghum is a grain with many attractive features and, as a whole grain, provides many nutritional benefits. Unlike refined grains, whole grain foods contain dietary fiber (soluble and insoluble), resistant starches, vitamins, minerals, phytoestrogens, and antioxidants that may protect against non-communicable diseases (NCDs). The epidemiologic evidence for the association between whole grain intake and NCDs is largely consistent, with most studies suggesting diets high in whole grains are inversely associated with risk of type 2 diabetes, cardiovascular diseases, and certain cancers (29).

According to the 2010 USDA Dietary Guidelines for Americans report, at least half of daily grain food intake should be in the form of whole grains. The FDA allows health claim labels for foods containing 51% whole grains by weight when the whole grains contain ≥11% dietary fiber. Despite these recommendations,
affected. The researchers concluded that “Good” (HDL) cholesterol was not reduced.

Reductions ranged from 18% in hamsters (31). Exact mechanisms and potential for managing cholesterol. They reported that different levels of lipids contained more valuable phytochemicals, such as phytosterols, policosanols, unsaturated fatty acids, aldehydes, and steryl/wax esters, with potential health benefits (7). Lee et al. (31) observed that sorghum is a rich source of phytochemicals and decided to study sorghum’s potential for managing cholesterol. They reported that different levels of lipids from sorghum significantly reduced “bad” (non-HDL) cholesterol in hamsters when they were fed these lipids for 4 weeks. Reductions ranged from 18% in hamsters fed a diet including 0.5% lipids from sorghum to 69% in hamsters fed a diet including 5% lipids from sorghum. “Good” (HDL) cholesterol was not affected. The researchers concluded that

**Lipids.** The wax surrounding the sorghum grain contains compounds called policosanols that may have an impact on human cardiac health (2,7). Sorghum grain lipids have been consistently reported to contain valuable phytochemicals, such as phytosterols, policosanols, unsaturated fatty acids, aldehydes, and steryl/wax esters, with potential health benefits (7). Lee et al. (31) observed that sorghum is a rich source of phytochemicals and decided to study sorghum’s potential for managing cholesterol. They reported that different levels of lipids from sorghum significantly reduced “bad” (non-HDL) cholesterol in hamsters when they were fed these lipids for 4 weeks. Reductions ranged from 18% in hamsters fed a diet including 0.5% lipids from sorghum to 69% in hamsters fed a diet including 5% lipids from sorghum. “Good” (HDL) cholesterol was not affected. The researchers concluded that

- **Phenolic Compounds.** Some specialty sorghums, which contain a variety of phenolic compounds, are high in antioxidants that are believed to help lower the risk of certain cancers, diabetes, heart disease, and some neurological diseases. Evidence suggests that the phenolic compounds in sorghum produce specific health benefits that are not observed for other grains such as corn, rice, and wheat (2). Phenolic compounds are concentrated in the bran, along with high levels of antioxidants, dietary fiber, and luteolinidins and apigenidins that are relatively rare in nature (14,26). Awika and Rooney (2) stated that tannin sorghums can and should be considered a source of natural antioxidants, dietary fiber, and color compounds.

- Breeders have developed specific sorghums with unique combinations of these components. Specialty and white sorghums have been incorporated into a wide array of food product formulations, including dark purple tortillas; chips; naturally colored, high-fiber baked products; and cooked whole grain (similar to rice). The high levels of compounds such as the stable 3-deoxyanthocyanin (3-DXA) pigments, condensed tannins, flavones, and flavanones found in some sorghum varieties is of special interest from both commercial and health-benefit perspectives. Stable 3-DXA compounds are present in darker colored sorghums and to a lesser extent in white sorghum (15).

- Although whole grain consumption has long been correlated with reduced risk of certain forms of digestive tract cancers, especially colon cancer, how much of these effects are contributed by dietary fiber and/or phytochemicals concentrated in the grain bran is still unknown. Additional in vitro data, as well as controlled animal studies, are necessary to understand how the levels and composition of polyphenols in sorghum affect certain cancers and which specific components are responsible.

- Sorghum has been widely consumed as a staple food and in beverages throughout Africa for centuries. More recently, corn has replaced sorghum in some areas. Researchers from the University of Witwatersrand Medical School in South Africa (28) have suggested that the change

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**Fig. 6.** Sorghum varieties and colors. (Courtesy of Cassandra McDonough, Cereal Quality Lab, Texas A&M University)
in the staple diet of South Africans from sorghum to maize (corn) is the cause of an epidemic of squamous carcinoma of the esophagus seen in South Africans. They linked the cancer to *Fusarium* fungi that grow freely on maize but are far less common on sorghum, stating that countries in Africa in which the staple food is sorghum have a low incidence of squamous carcinoma of the esophagus (28).

Although, data on cancer relating to sorghum are too limited to draw firm conclusions, in vitro studies have revealed that sorghum has some anticarcinogenic properties. Grimmer et al. (23) found that high molecular weight (MW) procyanidins (tannins) had higher antimutagenic activity compared with lower MW tannins. Gómez-Cordovés et al. (20) showed that sorghum tannins had anticarcinogenic activity against human melanoma cells. They concluded that all four components (phenolic fractions) “have potential as therapeutic agents in the treatments of human melanoma,” although the mechanism by which each slows cancer growth may differ.

Many fruits also contain these compounds; however, sorghum bran may prove to be the richest and cheapest source of phenolic compounds. Use of sorghum may provide a way to reintroduce a quality source of nutrients into many products that now use bleached and refined flours. Because most chronic disease states in humans are associated with chronic inflammation and high oxidative stress, a food ingredient such as phenolic-rich sorghum bran could potentially improve the nutritional benefits of certain processed foods and the overall diet.

**Starch Digestibility.** Phenolic compounds complex with proteins and carbohydrates, generating insoluble compounds that are resistant to digestive enzymes. Specialty sorghum varieties contain various types of phenolic compounds, including condensed tannins (polymers of flavan-3-ols) and anthocyanins (luteolinidin and apigeninidin). There has been increasing interest in applications for starches that are more slowly digested in minimally cooked or processed foods and their potential role in reducing calories, increasing dietary fiber, and providing energy over extended periods. Readily digestible carbohydrates lead to rapidly elevated blood glucose levels and insulin secretion, both of which contribute to the health complications caused by diabetes. Starch digestibility depends on the plant source, extent of starch–protein interaction, physical form of the granule, inhibitors such as tannins, and starch type (27, 48,51,62).

Postprandial blood glucose changes can be used to categorize the glycemic index (GI). GI can be estimated based on in vitro rate and extent of starch digestibility, known as the estimated glycemic index.
lated from sorghum grain inhibited the varieties (5,10–12,48). Davis and Hoseney less digestible than other depauperate cereals (48). In raising sorghum digestibility to that of flaking and reconstitution, are effective in processing methods that break open kernels limits access to the interior (25,48). Pro- stock feeding (44) and brewing (22) sug- gestion of proteins surrounding starch in the endosperm (50). Experience with live- stock feeding (44) and brewing (22) su- ggests that starch in whole sorghum grain may be slightly less digestible due to its hard peripheral endosperm layer, which limits access to the interior (25,48). Pro- cessing methods that break open kernels and expose the interiors, such as steam- flaking and reconstitution, are effective in raising sorghum digestibility to that of corn (2). Some specialty sorghum varieties are less digestible than other cereals (48). In particular, varieties that contain con- densed tannin have been reported to be less digestible than other depauperate varieties (5,10–12,48). Davis and Hoseney (11) reported that condensed tannins iso- lated from sorghum grain inhibited the enzyme α-amylase and that condensed tannins also bind to starch granules to varying degrees. Barros et al. (3) also reported that condensed tannins in sor- ghum strongly interacted with amylase and linear fragments of amylopectin in starch, resulting in decreased starch digestibility. Daiber (10) and Beta et al. (5) found that condensed tannins inacti- vated malt amylases, reducing starch breakdown and sugar production during brewing. Thompson and Yoon (56) investigated the relationship between polyphenol intake and blood glucose response in healthy and diabetic volunteers. They found a negative correlation between GI and concentration or total intake of poly- phenols. Polyphenols, especially large polymeric compounds or condensed tan- nins, appeared to be responsible, in part, for a reduced glycemic response to carbo- hydrate foods and relatively low blood glucose response to legumes compared with cereal products (56).

Farrar et al. (17) found that phenolic-rich sorghum brans inhibited protein gly- cation (restriction of advanced glycation improves insulin resistance), whereas wheat, rice, oat, and low-phenolic sor- ghum brans did not. Hargrove et al. (26) reported that certain varieties of sorghum bran may affect critical biological processes that are important in diabetes and insulin resistance. They also compared the ability of simple flavonoids and con- densed tannins in tannin sorghum bran extracts to inhibit enzymes in vitro and found that sumac sorghum bran extract, which is high in condensed tannin, inhib- ited α-amylase at a much lower concen- tration than did black sorghum bran extract, which does not contain con- densed tannin. However, Mkandawire et al. (39) reported that condensed-tannin content was not correlated with the in vitro starch digestibility of cooked grain sorghum.

Phenolic compounds, especially those that offer potential health benefits. Sor- ghum grain composition and qual- ity varies from white grain varieties, which have a bland flavor, to black, red, and brown grain varieties, which have an array of stronger flavors. It can be easily processed into food products using extru- sion, steam-flaking, micronization, and other processes. Sorghum can also be substituted for wheat flour in a variety of gluten-free baked goods, and its neutral, sometimes sweet, flavor and light color make it easily adaptable to a variety of dishes. Because it does not contain gluten, bakers often incorporate a binder such as xanthan gum or corn starch to improve elasticity in doughs containing sorghum flour. Sorghum can be substituted for other ingredients in existing formulations as well.

Sorghum also offers several potential functional and health benefits. Sorghum starch is digested more slowly and has a lower GI, so it lingers in the digestive tract longer than starches from other grain flours or flour substitutes. In addition, specialty sorghum varieties are rela- tively inexpensive sources of phenolic compounds and have favorable storage stability, drought tolerance, high grain yield, and anti-inflammatory properties. Both tannin and black sorghum varieties can be used to formulate functional foods that offer potential health benefits. Sor- ghum bran is not only a good source of dietary fiber but provides a number of unique nutritional components as well. If interest in sorghum continues, sorghum bran extracts could easily be incorporated into a variety of foods and beverages as a liquid concentrate or dried powder.

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