SPECIALTY SORGHUMS FOR HEALTHY FOODS

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I. INTRODUCTION

Sorghum is a major crop used for food, feed and industrial purposes worldwide. In the Western Hemisphere it is mainly used as a livestock feed and has not been considered a significant ingredient in foods. With over 40,000 accessions in the world collection, tremendous diversity exists in sorghum in both composition and processing properties. The kernel varies in size, shape, color, density, hardness, composition, processing properties, taste and texture and nutritional value.

This chapter reviews information on new food sorghums and other special sorghums with unique properties that could be used in producing a wide variety of food products for specialty markets and health foods. The paper will emphasize white food sorghum hybrids and special tannin and black sorghums with high levels of phytochemicals. These special sorghum varieties are an excellent source of nutraceuticals that can compete effectively with fruits and vegetable sources. In addition, we will indicate other opportunities for producing healthy foods from sorghum.

A. Sorghum production

Sorghum is the fifth most important cereal crop grown in the world. It is a major food grain in Africa and parts of India and China. In 2003, 42.1 million hectares of sorghum were harvested worldwide, with a total production of 54.7 million metric tons. United States, India, and Nigeria are the largest producers of sorghum representing approximately 19.2%, 14.5%, and 14.5% of the total world production, respectively, in 2003. Mexico and Sudan are also major producers, accounting for 10.2% and 8.0%, respectively, of world sorghum production in 2003. In terms of yield, the United States averages approximately 3,181 kg ha^{-1}, while Africa and India average 920 and 808 kg ha^{-1} respectively (Foreign Agricultural Service, USDA 2004). US sorghum production is concentrated in Kansas, Texas, Nebraska, Oklahoma and Missouri in order of decreasing importance. Sorghum is a drought tolerant crop that does well in harsh environments with limited water. It does not develop significant levels of aflatoxins and fumonisins in the field prior to harvest.

Recently in the United States significant research and development has lead to the production of food sorghums in significant quantities. Food sorghums are defined as white, tan plant sorghums with a clean bright grain. Actual food sorghum production occurs on 8100 hectares (20,250 acres) with a production of 10,000 tons. Some are grown under identity preserved production schemes while others are collected at harvest time and held for marketing. They are sold for use in feeds if sufficient food markets are unavailable.

Growing niche markets are major outlets for these white food type sorghums which have excellent properties for pet foods, poultry rations and for ethnic and dietary products i.e. gluten free foods for Celiacs. Companies are marketing dry mixes and other products containing sorghum, including high antioxidant bread, gluten free foods, flours, snacks and related products. The bottom line is that food sorghums are available for those who want them and are willing to contract production ahead of time.

Tannin sorghums are not grown in the United States because they cause reduced feed efficiency and have been discriminated against in commercial markets. However, commercial tannin hybrids with good grain yields exist so tannin sorghum can be grown for specialty markets easily under identity preserved systems. They would not be grown unless a contract was available to insure their use in special foods since the grain would be reduced in price for use in feeds.

The black sorghum is available only in an open pollinated variety which does not have outstanding grain yields. So it would cost more to produce and would only be grown under contract. The waxy and heterowaxy hybrids are available but would need to be grown under contract production schemes. The heterowaxy hybrids have excellent yields of grain while the waxy hybrids have slightly reduced grain yields and would require additional premiums for production.

B. Sorghum utilization

Many populations in Africa and India have consumed sorghum for thousands of years. Sorghum is used in many traditional foods including porridges, fermented and nonleavend breads, rice-like products including couscous, alcoholic and nonalcoholic beverages, snacks and many baked products. Industrial production of sorghum beer, non alcoholic beverages and porridges occurs in Africa, especially in Nigeria, South Africa and Botswana (Taylor and Dewar, 2000). Malt extracts are used extensively for nonalcoholic beverages and for commercial products like Bournevita and Milo in Africa. *Nini Nanini* is a stabilized opaque beer made in South Africa that has long shelf life.

African and Indian cultures, in general, have demonstrated preferences for white kernels preferably with a tan plant and glume color. The soft white sorghums grown under dry conditions during grain maturation and harvesting are often preferred. In India, Rabbi (dry season) sorghums of the Maldandi 35 type are often preferred over wheat for milling into whole grain flour for roti or chapattis. They are used in many foods including rice substitutes, thick and thin porridges, snacks and other products. Nearly all of the Rabbi sorghums are used for human foods and they command premium prices while the wet season (Kharife) sorghums are used only for livestock feed or for commercial alcohol production since the grain is often damaged by grain molds and turns black. There are other improved hybrids that produce grains of inferior quality and the Indian markets discount the price significantly.

The darker sorghums are usually avoided for these traditional products. However, in East and Southern Africa, soft endosperm tannin sorghums are grown to escape losses from birds and molds. Often these tannin sorghums are preferred for certain foods. For example, farmers doing field work prefer tannin sorghum porridges because they remain full longer. The slower digestibility of the tannin sorghums probably relates to the binding that occurs between the condensed tannins, proteins and other components of the grain. Often tannin sorghum foods are fed to new mothers and people with digestive problems. Dark colored sorghums are preferred for use in beer and alcoholic beverages in Africa. In East Africa, special procedures including cooking in alkali or malting are used to process tannin sorghums into foods.

The composition and structure of sorghum is similar to that of corn with minor differences (Waniska and Rooney 2000; Rooney and Waniska 2000). Sorghum grain has less oil with slightly more starch and protein than corn. The nutrients are distributed in the kernel similar to that of corn. The sorghum kernel contains up to 0.3% waxes as a thick layer on the pericarp surface. These waxes have some valuable components including phytosterols and policosanols. Sorghums differ dramatically in that some varieties contain high levels of condensed tannins and other phenolic compounds.

Sorghum is more slowly digested than other cereals. It has been considered more filling; its slower digestibility may be advantageous for diabetics. Being more filling and less digestible than other cereals, it may have some role in reducing obesity. The sorghum proteins contain more cross-linked prolamins than other cereals. These affect the processing properties and digestibility of the grain. There is a higher proportion of the kernel (corneous endosperm) that contains significantly larger amounts of protein surrounding the starch granules which makes the starch more difficult to solubilize.

Proper processing converts sorghum into highly digestible foods and feeds. However, the processes must disrupt the kernel structure especially that of the peripheral endosperm to increase digestibility. Steam flaking, micronizing, reconstitution and fine grinding are used to increase digestibility. Most food processing methods in Africa and Asia thoroughly alter the sorghum structure via attrition grinding and other methods.

II. SORGHUM TYPES

Two types of sorghum are grown worldwide, open pollinated varieties, found primarily in developing countries, and hybrids, which are grown predominately in developed countries. Most sorghum hybrids grown in the Western Hemisphere are red with a normal (nonwaxy) white or heteroyellow endosperm, and lack pigmented testas. The dark red color of the pericarp adversely affects the acceptability of the grain in many food ingredients where a light color is required. However, modern breeding programs have developed an array of special sorghums ranging from white food sorghums to sorghums with high levels of condensed tannins and anthocyanins.

III. SORGHUM ENDOSPERM TYPES

The composition of the endosperm can greatly affect the properties of sorghum in food production systems. Several types of endosperm exist and are summarized below.

A. Yellow endosperm

These cultivars contain high levels of carotenoid pigments in the endosperm. Caryopses appear yellow when the pericarp is thin, colorless, the testa is absent and the endosperm is yellow. A thick mesocarp and colorless pericarp cause a white or chalky appearance. Heteroyellow endosperm sorghum results when sorghums with yellow and nonyellow endosperm colors are hybridized (Rooney and Miller 1982). Bronze sorghums contain a thicker, red pericarp with yellow endosperm color, while cream sorghums contain a thicker, white pericarp with yellow endosperm. The levels of carotenoid pigments in yellow endosperm sorghums are not as high as yellow corn. In addition, the carotenoids are bleached during and after maturation because the kernel is exposed to sunlight. Sorghums can have a bright yellow pericarp color (rrYY) which is lost upon maturation because the pigments are bleached by the sun.

B. Waxy endosperm

These cultivars contain three genes (wx) in the recessive form. Heterowaxy genotypes contain one or two of these genes in the dominant form whereas normal or nonwaxy endosperm sorghums contain all three genes in the dominant form. Waxy cultivars contain nearly 100% amylopectin and the endosperm looks like candle wax (Rooney and Miller 1982).

The waxy sorghums have excellent expansion during extrusion and produce tender, crisp extrudates. They also produce steamed flakes and micronized flakes with significantly greater expansion and significantly more tender flakes compared to normal food sorghums (Cruz-Celis et al 1996; McDonough et al 1998; Rusnak et al 1980). In addition, the waxy sorghums have improved digestibility and feed efficiency when fed to feed lot cattle on high concentrate rations since they are more easily fermented (Rooney and Pflugfelder 1986). Current waxy hybrids do not have as high a yield as their nonwaxy counterparts. However, heterowaxy hybrids have excellent yields and modified processing properties. Special waxy or heterowaxy hybrids are available for contract production.

C. Other endosperm types

The high-lysine (hl) sorghums from Ethiopia have a soft, floury endosperm texture, a shriveled kernel structure, and are very susceptible to deterioration in humid environments during and post caryopsis development (Rooney and Miller 1982). The improved protein digestibility sorghum (Weaver et al 1998) and high-lysine sorghums have intermediate to soft endosperm textures which cause reduced grain yield and increased deterioration due to molds and weathering. Attempts to modify this highly digestible type into harder endosperm kernels continue. These highly digestible types of sorghum will most likely find applications in areas of the world where sorghums mature in dry, low humidity environments. In such cases they could be a significant improvement in lysine and digestibility. Areas where these types might be adapted are Ethiopia, Sudan and the Rabbi (dry season) in India.

Sugary endosperm sorghums exist and are used for roasting in the dough stage in Africa and India. These types have higher levels of free amino acids in addition to reducing sugars. During roasting they produce excellent aromatic flavors and are mixed with other sorghums to enhance their flavor.

IV. APPEARANCE AND GENETICS OF SORGHUM

Several interacting factors affect the color and overall appearance of sorghum caryopses. Appearance is mainly affected by pericarp color and thickness, presence of pigmented testa, and endosperm color (Rooney and Miller 1982). Secondary plant and glume colors, as well as, deterioration due to the environment, insects and molds, complicate the evaluation of pericarp color and other properties. Immature pericarp tissues, when damaged, respond by producing phenolic compounds which form pigments that stain the pericarp and endosperm. Insect and mold damage of the pericarp commonly occur when caryopses mature in hot, humid environments.

Pericarp color is genetically controlled by the R and Y genes. The combination of these genes produce white or colorless (R_yy or rryy), lemon yellow (rrY_), or red (R_Y_) color. The intensifier (I_) gene increases the intensity of the red pericarp color. The Z gene controls pericarp thickness. Sorghums with homozygous recessive (zz) genes possess a thick mesocarp. A thick pericarp contains small starch granules which causes a chalky appearance that masks the colors of the testa and endosperm (Earp et al 1983; Rooney and Miller 1982). A pigmented seed coat or testa is present when both B1_ and B2_ genes are dominant. The tptp genes control testa color which can be brown or purple. Caryopses with a pigmented testa (B1_B2_) and a recessive spreader gene (ss; type II) or dominant spreader gene (S; type III) contain condensed tannins and are called brown or tannin sorghums (Earp et al 2004; Hahn and Rooney 1986). Type III sorghum tannins are easier to extract than type II sorghum tannins, whereas, type I sorghums (without a pigmented testa) do not contain tannins (proanthocyanidins).

V. GRADING AND CLASSIFICATION IN THE UNITED STATES

Sorghum is marketed according to U.S. grain standards (Rooney and Waniska 2000) in four classes: sorghum, white sorghum, tannin sorghum, and mixed sorghum. The sorghum class cannot contain more than 3% sorghum with a pigmented testa or undercoat. The white grade contains sorghum with a white pericarp without a pigmented testa and cannot contain more than 2% of sorghum with colored pericarp or testa.

Tannin sorghums have a pigmented testa beneath the pericarp (Fig. 1). The pigmented testa is seen as a dark layer between the light endosperm and the pericarp when the caryopsis is scraped to remove the pericarp. Bleaching using the chlorox bleach test causes the constituents in the pericarp and testa to oxidize and gives a pronounced black color to the bleached kernels while non-tannin sorghums have a white appearance. The bleach test, however, can produce many false positives, especially with molded or weathered grain (McDonough et al, 2002) and should be used judiciously. Mixed sorghum contains sorghum with and without pigmented testa.

Sorghum in South Africa is graded into classes for feed, malting and tannin sorghums. The grain is tested quite similarly to the tests used in the US grading system. Taylor (personal communications) developed some simple methods to use in grading and classifying sorghum in Southern Africa.

VI. WHITE FOOD SORGHUMS IN THE UNITED STATES

U.S. “Food-Grade” white sorghum has a white kernel with tan plant and glume characteristics (white/tan/tan) with excellent quality for food use. The tan plant and light colored glumes reduce the amount of anthocyanin pigments that cause off-colors in the otherwise similar white grains that have purple or red glumes. The tan plant and straw color glumes provides grain with excellent properties for processing into whole grain foods or for milling into meal, flour, and grits for use in foods. The white food sorghums are non-GMO, gluten-free (as is all sorghum), bland in flavor, light colored and have excellent processing properties. Decorticated white sorghum compares favorably with rice for extrusion into bland extrudates that will carry mild flavors. It has a definite advantage over corn products because of the bland flavor.

Identity preserved production of food sorghums occurs in the sorghum belt where highly adapted hybrids are produced. Yearly production figures have increased to levels that are adequate for large scale production of food products as presented earlier. It is possible to obtain large quantities of food sorghums by contracting with farmer groups. Grain yields are comparable to red sorghum hybrids so the premium is for maintaining the identity and quality specifications of food grade sorghum.

Food sorghum is currently being used in production of high quality, gluten-free sorghum flour in the U. S. and is exported to Japan for use in a variety of foods, including snacks, baked products, porridges, rice-like products and other food ingredients. The cost of food sorghums is competitive, and in some cases lower than rice in some countries. Consequently, it can be substituted for rice in snack and breakfast foods to lower the cost.

A. Processing Properties of White Food Sorghums

The white food sorghum hybrids typically have harder kernels with a thin pericarp (Table I) compared to commercial red and white, purple plant colored hybrids. The data in Table I represent the means of selected hybrids grown at four locations in Texas, Nebraska and Kansas for each of three years. Both environment and hybrids significantly affect composition, physical and processing properties of the grains. However, the white tan sorghum (WT) hybrids were harder, more dense and lighter in color than grain of white purple (WP) or red hybrids.

The milling yields of white tan plant food sorghums are markedly better than those of red pericarp hybrids (Fig. 2, 3) especially when the yield of decorticated grain is adjusted to comparable color of decorticated grain or flour (Awika et al, 2002). The data for 11 white tan hybrids compared to three commercial red sorghum hybrids illustrates the tremendous advantage of white sorghums for milling into light colored milled products. It also shows that there is significant variation among different white tan hybrids.

The hardness, pericarp thickness and ease of removal, size and shape of the kernel affect the decortication procedure. In our studies of milling properties during the last 15 years, ATx635 (Miller et al, 1992) hybrids always have excellent decortication properties (Table I). It was selected for improved kernel hardness and density and is useful for whole grain extrusion (Acosta 2003). Variations of it are in commercial hybrid production although the hybrids are too tall and late for wide spread adoption. There are other hybrids commercially available that have good milling properties.

White pericarp, purple plant hybrids are more adversely affected by weathering and molds than white tan hybrids. A small amount of moisture during maturation moves the purple or red anthocyanins from the glumes into the pericarp and endosperm which reduces milling yields or causes off colored products. These types of sorghum are not recommended for food production in the U.S., although they have excellent properties when they mature and are harvested under dry conditions.

Efforts by breeders, agronomists and food technologists have produced tan white food-type sorghums with significantly improved food quality attributes. These sorghums can be processed into whole grain products easily because most have a thin pericarp and when grown under good environmental conditions produce excellent grain quality. For high quality, the white tan sorghums should be grown in environments with low humidity and low risk of grain mold or weathering. Experimental red tan plant hybrids also have significantly better milling properties than the red purple sorghum hybrids. The red tan plant sorghums are more useful in high rainfall or humidity areas such as the Coastal Bend area of Texas.

B. Grain Molds and Staining

The environmental conditions during caryopsis development and maturation greatly affect the appearance of sorghum because the panicle or head is exposed to biotic and abiotic stress. A hot, humid environment during maturation negatively affects sorghum quality. Deterioration results from insects, molds, moisture, and sunshine. Physical damage resulting from insect attack causes the plant to secrete phenolic compounds that produces discolored spots in the pericarp and endosperm. Mold colonization discolors the pericarp surface, breaks down the endosperm structure, and adversely affects processing quality (Waniska et al 1989). Sorghums that have an open panicle structure and caryopses with thin pericarp, condensed tannins, corneous endosperm and large, tight glumes are generally considered more resistant to molding and weathering. Grain molds are a major limitation preventing more widespread use of sorghum in foods around the world.

VII. FOOD TYPE SORGHUMS AROUND THE WORLD

White food sorghums are used extensively in India, i.e., Rabbi season, where they sell at prices higher than wheat. The Rabbi sorghums are preferred for food because of their light color, sweet taste and functional properties for roti, a flat bread. Sorghum of good quality is necessary for value-added products. The products are acceptable and purchased by consumers provided convenience, good taste, appearance and consistent quality is available at competitive prices. In South Africa, significant quantities of Mabella (sorghum) meal for thick porridges are consumed even though the price is significantly higher than mealy meal (maize). Botswana is an example where maize consumption is decreasing while sorghum consumption is increasing even though red or brown sorghum must be imported from South Africa. The white sorghums are preferred for injera in Ethiopia according to recent studies (Yetneberk 2004).

In Mali, white tan plant photoperiod sensitive guinea sorghums have been developed to replace white purple plant color guineas. The grain yields of the new tan plant guineas are equal to or better than those they are replacing, and both farmers and processors like the improved taste and color of the food products made from these grains. Contract production with identity preservation of the tan varieties is now beginning and processors are making improved quality food products.

A similar situation exists in Central America where sorghum is used alone or in mixtures with maize for tortillas, pan dulce, muffins, bread, rosquetes, rosquillos and other variations of these products (Almeida-Dominguez et al 1991). The new white tan plant sorghum varieties, Sureno, Dorado, Soberano, RCV, SV- 3 and others are preferred by farmers because the grain yields are equal to or better than the old varieties (Maicillo Criollos) and the forage and food quality is significantly improved. There are many examples of small farmers who produce the white tan varieties, store the grain and market it in baked products over the following year as a form of value added marketing. This illustrates the value of the tan plant color because the old varieties (Maicillo Criollos) with white kernels and purple plant color often produced dark purple tortillas and off-color bread because of the anthocyanin pigments.

There is significant interest in use of sorghum flour in blends and alone for baked products (Gordon 2001). Thus, whole grain white sorghum flours can be utilized in a wide variety of food systems in baking as a partial or complete substitute for wheat flour. The bland flavor of sorghum is particularly important, as it allows for a greater percentage of substitution without loss of flavor or taste. For example, maize meal (because of its strong taste) cannot be substituted for more than 5-10% wheat flour. Sorghum can go to very high levels if it is a white food type.

The white food type sorghums can be used as a whole ground grains for brewing of beer and production of extracts for nonalcoholic beverages because of their light color, thin pericarp and reduced oil compared to maize. New technologies for filtration of the commercial enzyme converted sorghum mash allow practical industrial application. Thus, it is likely that in most African areas sorghum malting will be replaced by conversion with commercial enzymes since dry matter losses during conventional malting are up to 20% of the original weight. The white sorghums provide excellent raw materials. The beer produced has acceptable properties although it differs from barley beer. In addition, other sources of color and flavor can be added to the beverages more economically. This practice is increasing especially in Nigeria.

VIII. EXTRUSION PROCESSING

Several extruded salty snacks and milled products based on identity preserved US white food sorghums are sold by Japanese food companies. Other countries are interested in using white food sorghums. It is possible to produce an array of expanded sorghum products directly from whole and ground, undecorticated white or brown sorghum grains using low-cost friction extruders (Acosta 2003; Maranphal 2003). These smaller extruders are often used in areas where infrastructure does not permit use of more costly sophisticated extruders and processes. The ability to produce snacks directly from whole clean grain is a distinct advantage for sorghum. Extrudates of 100% whole tannin sorghums have acceptable texture that can be used to produce whole grain snacks and ready to eat breakfast foods.

Whole or milled sorghums can be expanded directly by using low cost friction extruders (Fig. 4). Sorghum extrudates compared favorably with extrudates from rice and corn depending upon the decortication levels, particle size distribution and the moisture content. As the decortication level increased, the extrudates became whiter, more expanded, less dense, and more crisp. The extrudates made from coarse particle size materials had the most desirable characteristics compared to the other particle sizes used. Some sorghum products had a higher expansion ratio than both rice and corn with similar bulk density and texture characteristics.

White sorghum had excellent extrusion properties and can compete with rice and corn for expansion ratio. Different varieties of sorghum differ in expansion ratio. Heterowaxy and waxy varieties expanded more than normal, nonwaxy varieties (Gomez et al 1988).

Sorghum has been extruded with single and twin screw extruders to produce bland flavor, light color, highly expanded extrudates that carry mild flavors and seasonings similar to rice, at lower cost. For example, in some applications rice does not expand properly without use of potato starch or other expensive ingredients but sorghum can expand properly without the additives and the cost of the sorghum is often lower than rice. Obviously, it depends upon the kind of rice and the quality of the sorghum as well. Experience around the world consistently indicates that sorghum can be extruded into a wide variety of products quite efficiently. Extrusion appears to significantly reduce the degree of polymerization of sorghum tannins which may be beneficial in human foods (see section on Antioxidants in Special Sorghums).

IX. SORGHUM FLOUR AND GRAIN IN SPECIALTY PRODUCTS

Sorghum flour (SF) can be substituted for 100% of the wheat flour in a variety of products that are used in gluten free diets for Celiac-Sprue patients who are intolerant of wheat and other cool season cereals. Sorghum flour produces acceptable baked products with additives to substitute for its lack of gluten. Various prepared mixes, flours and other products containing sorghum have been introduced into specialty markets recently. Sorghum has excellent ethnic appeal to many African and Asian immigrants and can be increasingly found in specialty shops in the United States and Europe.

Sorghum can be used to produce couscous and other rice-like products. Whole grain can be cooked and added to soups to improve texture. An excellent whole grain salad can be made using cooked grain, with olive oil, lemon juice, feta cheese, and fresh basil or parsley. Whole grain can be popped and added to salads as a crouton-like product (Suhendro et al 1998).

X. SPECIAL BLACK AND TANNIN SORGHUMS

The tannin sorghums have high levels of proanthocyanidins (condensed tannins) that are known to be powerful antioxidants. The black sorghums are especially a rich source of anthocyanins that possess several therapeutic benefits and are also useful natural food pigments. These specialty sorghum varieties are generating a lot interest due to the increasing demand for natural therapeutic agents and functional foods.

A. Antioxidants in Special Sorghums

Antioxidant activities of specialty sorghums and their bran are equal to or higher than those of common high antioxidant fruits like blueberries and plums (Fig. 5). The high ORAC (oxygen radical absorbance capacity) levels in sorghum brans demonstrate their potential compared to fruits as a source of natural antioxidants and related phytochemicals.

Specialty sorghums and their products have high antioxidant activity when measured by different methods (Table II). The tannin and black sorghums and their brans had the highest levels of antioxidant activity (Awika et al 2003a). Since the phenols are concentrated in the outer layers of the sorghum kernel, the bran obtained by abrasive decortication or roller milling has 3-4 times the antioxidant activity of the whole grains.

The grain and bran fractions of the tannin and black sorghums make excellent quality breads that contain high levels of antioxidants, dietary fiber and a natural dark brown color (Gordon 2001). A blend of tannin sorghum bran, barley flour, flax seed and gluten produced an excellent quality, healthy bread (Rudiger 2003). Direct friction type extrusion produces whole grain snacks and ready-to-eat breakfast foods from these tannin or black sorghums. Cookies, tortilla chips and many other foods have been produced from these special sorghums (Leon-Chapa 1999; Zelaya 2001).

High temperature, high pressure extrusion and expansion change the molecular weight (MW) distribution of the tannins in sorghum significantly (Fig. 6). It causes the higher molecular weight polymers of the proanthocyanidins to break down into lower molecular weight constituents (monomers to tetramers) that are presumably more readily available for direct absorption. Other wet processes such as baking, and cooking did not produce a net increase in the lower MW proanthocyanidins as observed in the extrudates (Awika et al 2003b). This information should be confirmed by additional experiments, but extrusion seems to alter the MW distribution of the proanthocyanidins and potentially improves their bioavailability.

B. Levels of Tannins in Sorghum

Deshpande et al (1985) summarized methods used to quantify tannins and discussed limitations. The methods broadly fall under colorimetric (most common) and chromatography based assays (more recent). Gravimetric methods and techniques based on ability of tannins to precipitate proteins have also been used (Hagerman and Butler 1978; 1980; Reed et al 1985; Makkar, 1989).

Quantification of tannins from any source is complicated by lack of appropriate standards and difficulty in extraction; changes occurring during extractions are often time and solvent dependent. Many researchers fail to recognize that they are measuring total phenols and not just condensed tannins. The standards used, i.e., catechin, vary significantly and are valid for comparisons only in a given laboratory. Thus, many tannin-free sorghums are erroneously reported to contain significant levels of tannins.

The vanillin-HCl method originally reported by Burns (1971), and later modified (Maxson and Rooney 1972; Price et al 1978) is widely used for sorghums. The corrected vanillin-HCl method is generally more appropriate for tannins than the redox assays like the Folin-Denis or Prussian blue methods. With the vanillin-HCl method tannin levels of up to 68 mg/g have been reported for sorghum grains. However, factors like particle size, type of solvent, extraction time, temperature and standards significantly influence the measured tannin content. For example, Price et al (1978) reported, and we confirmed (Awika, 2003), that extraction for 2-24 hr with 1% HCl in methanol gave a 40-70% reduction in assayable tannins compared to 20 min extraction time. The tannins react with other components in the extract to form products that do not react positively in the Vanillin-HCl test.

C. Modern Analysis of Tannins

Quantitative assays of tannins based on HPLC to separate and analyze the high molecular weight proanthocyanidins, which are the most abundant forms of the tannins in sorghum are promising (Gu et al 2002; Hammerstone et al 1999). The advantage of the HPLC assay is that it determines the relative proportions of the various MW polymers present in condensed tannins. This provides useful information since polymer chain length affects organoleptic, antioxidant, and other properties of the tannins (Rigaud et al 1993; Tebib et al 1997; Lotito et al 2000). Hence information on relative proportions of the different proanthocyanidin oligomers and polymers may help predict their overall effectiveness as functional components of diet.

The HPLC analysis of sorghum proanthocyanidins (condensed tannins) indicated that more than 60% of the polymers had a degree of polymerization greater than 10 (Awika et al, 2003b). Different sorghum varieties show significant differences in MW distribution. The direct extrusion of tannin sorghums significantly reduced the polymer size of the proanthocyanidins and increased the percentages of oligomers with less than 5 units which may positively affect the biological significance of the antioxidants (Fig. 6). The type of processing is important since similar changes did not occur when the brans were baked into cookie and breads. It is likely that the high pressure and friction of extrusion caused fission of the tannin polymers. These findings must be confirmed by additional experiments, which are underway.

D. Composition and Structure of Tannins from Sorghum

Tannins of sorghum are almost exclusively of the condensed type. They are mainly polymerized products of flavan-3-ols and/or flavan-3,4-diols. Glycosylated and non-glycosylated polymers of flavan-4-ols with various substitution patterns were also reported in sorghum (Gujer et al 1986). No tannic acid or hydrolysable tannins have been detected in sorghum. Krueger et al (2003) observed the presence of DP2 – DP7 mixtures of proluteolinidin and proapigeninidin polyflavans, with eriodictoyl or eriodictoyl-*O*-ß-glucoside as the terminal units in sorghum. Significant heterogeneity also occurs in the polyflavans (proanthocyanidin) polymers in terms of interflavan linkages (A or B type) and the presence of gallocatechin/ epigallocatechin hydroxylation patterns (Krueger et al, 2003). HPLC analysis also suggested presence of epicatechin gallate as a significant component of the lower MW procyanidins of tannin sorghums (Awika 2003). Some of the tannins found in sorghum have been identified in other common foods, e.g., cocoa and blueberries (Hammerstone et al 1999; Gu et al 2002).

E. High Anthocyanin Sorghums

Special varieties of sorghum exist that have very high levels of anthocyanins. These sorghums have a thick pericarp with intense red pigments that turn deep black or purple when exposed to the sun during maturation. The genetics of the black pericarp are recessive. Gous (1989) reported the 3-deoxyanthocyanidins, luteolinidin and apigeninidin, as the major anthocyanidins from a black sorghum variety. These special black sorghums have very high levels of anthocyanins (3-deoxyanthocyanidins) that are relatively rare in nature (Clifford, 2000).

They lack an OH group at the C–3 position. These 3-deoxyanthocyanidins are more stable in acidic solutions compared to the other anthocyanidins commonly found in fruits and vegetables (Sweeny and Iacobucci, 1981). This suggests a potential advantage of sorghum as a viable commercial source of unique anthocyanins.

The black sorghums have been used to produce tortillas and tortilla chips, extruded snacks and baked products with dark purple or blue colors and high levels of phenols and antioxidants as measured by *in vitro* tests (Gordon 2001; Zelaya 2001). The black sorghum can be decorticated to yield bran that is high in anthocyanins because the pericarp is easily removed (Awika 2000).

Like tannins, effective quantification of anthocyanins is hampered by lack of appropriate standards, efficient extracting solvents and separation techniques. Awika (2003) showed that acidified methanol extraction gave higher anthocyanin values than aqueous acetone extraction for sorghum anthocyanins. Lu and Foo (2001) demonstrated that acetone, when used as a solvent, reacts with anthocyanins in a time dependent manner to form pyranoanthocyanins, which are spectrally different from anthocyanins. Anthocyanins are also pH sensitive and polymerize with other phenols to form structures that are hard to isolate or characterize (Remy et al 2000). The anthocyanins normally isolated may be mostly solvent-modified derivatives.

The pH differential method is still the most common spectroscopy method for crude anthocyanin estimation. The method is rapid and estimates both monomeric as well as polymerized anthocyanins. However, the values are greatly affected by the standard used. HPLC analysis has revolutionized anthocyanin analysis. The anthocyanin levels in black sorghums (2.3-2.8 mg/g in grain and 8.9-11.0 mg/g in bran) compare well to those of fruits and vegetables commonly used as commercial anthocyanin sources.

F. Phenolic Acids of Sorghum

In general, sorghums have levels of phenolic acids (PA) comparable to those of other cereals

(Hahn et al 1983; Adom and Liu 2002). The PA of sorghum largely exist as benzoic or cinnamic acid derivatives. Like other cereals, the sorghum phenolic acids are mostly concentrated in the bran and are esterified to cell wall polymers. Ferulic acid is the most abundant bound PA in sorghum (Hahn et al 1983) and other cereals (Adom and Liu 2002). The PA have good antioxidant activity *in vitro* and thus may contribute significantly to the health benefits associated with whole grain consumption. However, sorghum does not have any advantages over other cereals in terms of PA content.

G. Antioxidants in sorghum syrup or molasses

Sorghum syrup is composed of sucrose, glucose and fructose and contains significant quantities of phenolic acids, organic acids and other components that are present in the sap (Kwon and Kim, 2003). The ORAC values of sorghum syrups range from 35.0 to 81.3 umoles TE /g which means they are a significant source of antioxidants (Forberg 2003). The antioxidant activity is likely due to the extraction and concentration of phenolic acids and their derivatives from the stalks. More information is required to determine the potential of sorghum syrup as a source of antioxidants.

The stalks of special sweet sorghum varieties are crushed and the sap is concentrated by boiling to produce sorghum syrup or molasses as it is sometimes called. The syrup is a light amber, viscous liquid with a strong unique flavor. The flavor, color and viscosity are developed during boiling of the sap to concentrate the solids.

H. Other Phenolic Compounds from Sorghum

Several other phenolic compounds have been isolated from sorghum. Naringenin (a flavanone) was identified and quantified in our laboratory as a major phenolic component of a bright red sorghum (TX 2911) variety (0.95 mg/g of bran) (Rooney et al 2000; Awika 2003). The bright red sorghums have reported resistance to molds; naringenin could play a role in this resistance. Naringenin and its glucoside were previously reported in sorghum by Gujer et al (1986). Monomeric forms of proapigeninidin, apiforol, proluteolinidin, and luteoforol were identified in sorghum leaves and grain (Watterson and Butler 1983). Gujer et al (1986) also reported taxifolin and eriodictoyl and their glucosides in sorghum grain. No information on the role of these compounds in sorghum quality and/or properties is available.

I. Bioavailability of Sorghum Phenols

Currently antioxidant activity is the most common *in vitro* parameter used to assess or predict potential benefits of plant phytochemical compounds. However, correlations and relationships between *in vitro* antioxidant activity and actual health benefits are largely unknown. Additionally, antioxidant activity measured *in vitro* tells us nothing about release and uptake of the compounds, as well as their distribution and metabolism in the body. However, antioxidant activity provides useful information for screening plant materials and products with desirable compounds and properties that can be used for further biological testing. In sorghum, phenol content correlates strongly with antioxidant activity (Awika 2003; Awika et al 2003a).

Condensed Tannins. Tannins from sorghum show powerful antioxidant activity *in vitro* (Hagerman et al 1998; Riedl and Hagerman 2001). However, due to their large molecular size and binding with proteins and carbohydrates to form insoluble complexes, their bioavailability is greatly compromised. However, Riedl and Hagerman (2001) demonstrated that even when complexed with proteins, sorghum tannins retained at least 50% of their antioxidant activity. The protein-complexed tannins may serve as free radical sinks in the digestive system thus sparing other antioxidants. Available data indicates that the lower MW tannins (monomers, dimers, and to a limited extent trimers) can be directly absorbed in the small intestine (Ross and Kasum

2002, Deprez et al 2001). Additionally, Spencer et al (2000) reported that the interflavan bond in the procyanidins was unstable in a simulated gastric juice (pH 2) which degraded the higher molecular weight polymers to monomers and dimers. However, Rios et al (2002) reported that the procyanidins were actually stable during gastric transit in humans. Part of the non-absorbed tannins is degraded by colon microflora into phenolic acids that may be absorbed to provide additional benefits (Deprez et al 2000; Tapiero et al 2002).

Anthocyanins. We have not found any work reporting bioavailability of the 3-deoxyanthocyanidins commonly found in sorghum. This is probably because these relatively rare anthocyanins have not been considered of economic interest. The high antioxidant capacity of black sorghums and their brans was correlated with their anthocyanin contents. Hence anthocyanins may contribute significantly to any potential health benefits of these sorghums. Boveris et al (2001) demonstrated that a 3-deoxyanthocyanidin (apigeninidin) isolated from soybean had strong dose-dependent quenching ability against ascorbyl and lipid radicals. Anthocyanins from fruits possess several therapeutic benefits, including vasoprotective and anti-cancer properties (Lietti et al 1976, Karaivanova et al 1990). The sorghum anthocyanins should be investigated for health properties.

Other Compounds. Phenolic acids (PA) are more readily absorbed than other phenols from food due to their small molecular sizes (Scalbert et al 2002). The bound forms of phenolic acids were, until recently, considered unavailable for absorption. However, Andreasen et al (2001 a, b) demonstrated that human colonic esterases (mostly of microbial origin) are capable of releasing esterified diferulates and other hydroxycinnamic acids from cereal brans. This suggests that the bound PA are potentially bioavailable and the actual contribution of PA to health benefits associated with consumption of whole grains may be greater than previously assumed.

XI. PHYTOSTEROLS

Phytosterols are cholesterol-like compounds that are structural components of plant cell membranes. In grains they are extracted in the bran oil. These compounds promote cardiovascular health because they reduce serum cholesterol levels. Singh et al (2003) reported total phytosterol levels of 0.5 mg/g for sorghum grain, compared to 0.9mg/g for corn. The fiber fraction isolated from sorghum by a corn wet-milling procedure had 0.7-0.8 mg/g phytosterols. However, Singh et al (2003) reported that the wet milling procedure they used resulted in a loss of 53-73% of the phytosterols in the isolated sorghum fractions relative to whole grain. Additionally the values they reported were only for the hexane-extractable (non-bound) forms of the compounds. Actual phytosterol values for sorghum may be higher with hydrolytic or otherwise optimized extraction procedures. The phytosterols exist in free forms and as esters of fatty acids or hydroxycinnamic acids or conjugated with sugars (glucose). In sorghum, the free phytosterols include campesterol, stigmasterol, and sitosterol (Avato et al 1990). Sorghum contains esterified forms, with fatty acid chains of C14-C24 (Avato et al 1990) and ferulates (Singh et al 2003).

XII. POLICOSANOLS

Policosanols are a mixture of high molecular weight aliphatic alcohols (fatty alcohols) that are part of plant waxes. These alcohols have 24-34 C atoms, with the general chemical formula of CH_3-$(CH_2)_n$-CH_2OH. The compounds are currently commercially obtained from sugarcane wax by hydrolytic cleavage and further purification (Gouni-Berthold and Berthold, 2002; Pepping, 2003). In sorghum, wax comprises about 0.2-0.3% of the grain, generally higher than in other cereals. The policosanols represent 19% to 46% of the sorghum wax (Avato et al 1990). This translates to 38-92 mg of policosanols per 100g sorghum grain.

The policosanols may be the most valuable components of sorghum grain based on their current market value (Weller and Hwang 2003). They exist in high levels in distiller's dry grains, a co-product of ethanol production (Weller and Hwang 2003). The bloom types of sorghum have high levels of wax covering the leaves and stems which may be another source of these compounds. The policosanols are gaining popularity because they reduce cholesterol as effectively as statins (Gouni-Berthold and Berthold 2002). The policosanols are destined to gain importance as natural, safe, and effective dietary alternatives to statin medication. Efficacy and economic potential of the sorghum policosanols should be investigated.

XIII. DIETARY FIBER AND OTHER COMPONENTS

Most of the fiber is present in the pericarp and cell walls. Sorghum contains 6.5- 7.9% insoluble fiber, hemicellulose and cellulose, and 1.1-1.2% soluble fiber, composed primarily of beta-glucans and pentosans. Sorghum contains approximately 1.3% total pentosans, located mainly in the pericarp. Approximately 70% of these pentosans are alkali-soluble, and some 30% are water-soluble. Dietary fiber in cell walls of the aleurone and endosperm are associated with ferulic and caffeic acid. Dietary fiber in the pericarp provide structural and protective functions; therefore, fiber content of sorghum products depends on the extent of pericarp removal during milling. Abrasive decortication of 10-15% of the initial weight of the kernel produces bran with a dietary fiber content of 41-48% depending upon the sorghum (Table IV).

Sorghum dietary fiber contains more associated proteins than dietary fiber from other cereals. Insoluble dietary fiber increases during food processing due to increased levels of bound protein (mainly kafirins) and enzyme resistant starch (Knudsen and Munck, 1985). In tannin sorghum, cooking also forms insoluble polyphenol-protein complexes which hence increases dietary fiber.

Sorghum bran fed to human subjects increased stool weight, decreased intestinal transit time, and increased the frequency of evacuation. Klopfenstein et al (1981) compared several sources of cereal fibers and found that sorghum bran was effective in lowering serum and liver cholesterol levels in guinea pigs. Rooney et al (1992) decorticated white and brown sorghums to remove approximately 7.5% of the caryopsis. The resulting pericarp rich tissue (bran) contained 47.8 and 35.1% insoluble dietary fiber and 1.6 and 1.0% soluble fiber, respectively. Sorghum brans were excellent bulking agents in rats. Brown sorghum bran (containing tannins) had better bulking ability than white sorghum bran.

The bran of tannin sorghum is also high in phytates and natural brown or black pigments that impart attractive colors to baked products such as cookies and multigrain breads. A healthy bread that contains modest levels of high tannin sorghums as a source of antioxidants is currently being sold by a commercial bakery in Wisconsin. A bread mix containing brown or black sorghum bran with flax seed, gluten, barley and wheat flour was developed (Rudiger 2003). The bread has excellent flavor, texture and high levels of dietary fiber, antioxidants, lignans and omega 3 fatty acids with a natural brown color. Black sorghum bran in breads resulted in appearance, texture, color and specific volume (cm^3/g) similar to commercial specialty or dark rye breads.

XIV. SORGHUM PHYTOCHEMICALS AND HUMAN HEALTH

A. Cardiovascular Disease (CVD)

Various epidemiological data indicate that whole grain consumption significantly lowers mortality from CVD (Kushi et al 1999; Slavin et al 2000; Anderson 2003). The phytosterols in the cereal brans are believed to contribute to these beneficial effects. Other components of the whole grains, including polyphenols and fiber also play a role in CVD prevention.

CVD are scarce, but there are biomarker studies. Klopfenstein et al (1981) reported a cholesterol-lowering effect of low-tannin sorghum grain fed to guinea pigs at 58% of the diet. This effect was greater than that produced by wheat, rolled oats or pearl millet. More recently, Cho et al (2000) found that sorghum and proso millet hexane extracts inhibited rat liver microsomal 3-hydroxy-3-methylglutaryl CoA (HMG-CoA) reductase in a dose-dependent manner. They observed that fecal bile acid excretion and HDL cholesterol levels were increased, without a change in total cholesterol, when whole sorghum, proso millet or buckwheat were fed to rats at 30% of diet. Lee and Pan (2003) demonstrated that tannin-sorghum distillery residues inhibited 63-97% of hemoglobin-catalyzed oxidation of linoleic acid in cultured mullet fish compared to soybean (13%) and rice bran (78%). The sorghum residues significantly improved blood-thinning and erythrocyte membrane integrity of the fish blood cells during winter; they attributed the prevention of RBC hemolysis to the antioxidant activity of the tannins and other polyphenols present in the sorghum residue.

In general, several epidemiological studies show that red wine and tea consumption correlate with reduced risk of CVD (Chung et al 1998; Higdon and Frei 2003). The effects are largely attributed to the tannins and other polyphenols in these food products. There is no epidemiological data on tannin-sorghum consumption and CVD in humans probably because CVD is not a major problem in populations that consume high levels of sorghum . The unique tannins and anthocyanins in sorghum (discussed earlier) are likely to produce beneficial effects.

A hypoglycemic effect of sorghum has also been demonstrated (Lakshmi and Vimala 1996), which might contribute to lower risk of CVD. This and the above animal data suggest that a controlled clinical trial is warranted.

B. Obesity

Tannin sorghums may help depress weight gain in humans as observed in animals. Most of the negative press on sorghum originated from the fact that the high tannin sorghums have reduced calorie value relative to corn, and thus depressed livestock growth/weight gain compared to corn and other cereals.

Tannin-sorghums reduce nutritive value by binding food proteins and carbohydrates into insoluble complexes that cannot be easily broken down by digestive enzymes. Another mechanism involves the direct binding of digestive enzymes including sucrase, amylases, trypsin, chymotrypsin, and lipases (Al-Mamary et al 2001), thus inhibiting their activity. Inhibition of intestinal brush-border bound amino acid transporters by sorghum tannins has been reported (King et al 2000). There is evidence that the higher DP tannins are more involved in these interactions than the low DP ones (Sarni-Manchado et al 1999).

Effects of the sorghum tannins on animal weight gain depend on levels fed as well as animal species. Numerous reports on reduced weight gain of rats, pigs, rabbits and poultry fed high tannin sorghum are available (Cousins et al 1981; Lizardo et al 1995; Al-Mamary et al 2001; Muriu et al 2002). Al-Mamary et al (2001) found a high tannin (3.5% CE) sorghum diet markedly decreased live weight gain and feed conversion ratio in rabbits, whereas a 1.4% CE sorghum had no effect. Cousins et al (1981) reported a 10% reduction in feed efficiency (relative to corn) when high tannin (3.1-3.4% CE) sorghums were fed to pigs. A low tannin sorghum had feed efficiency similar to corn. Lizardo et al (1995) also observed a 10% reduction in weight gain when pigs were fed tannin-sorghum diet compared to corn. Broiler chicks fed low tannin sorghums (0.6-0.9% CE) had weight gain and feed efficiency similar to corn (Ambula et al 2001). However, tannin sorghums (2.7-3.5% CE) significantly reduced the weight gain of broilers.

The differential response of animals to sorghums with different tannin levels may be due to adaptation of animals to dietary tannins by release of proline-rich salivary proteins (Mehansho et al 1983, Mole et al 1990). Hence there appears to be a tannin-level threshold for every animal species. There are no reports on how tannin-sorghums might be used to lower calorie intake in human diets. Epidemiological data on humans is lacking, probably because obesity is not common in locations where tannin sorghums are consumed. With the growing problem of obesity in certain parts of the world, potential of tannin sorghums to control weight should be explored.

C. Cancer

Positive effects of sorghum and/or millet consumption on cancer have been documented. Van Rensburg (1981) reported that sorghum consumption consistently correlated with low incidences of esophageal cancer in various parts of the world (including several parts of Africa, Russia, India, China and Iran) whereas wheat and corn consumption correlated with elevated levels. These regions also had deficiencies of certain minerals and vitamins in their diets. In attempting to explain this phenomenon, the author proposed that nutrient deficiencies were responsible for the high esophageal cancer incidences, and that sorghum and millet consumption promoted resistance to esophageal cancer . Chen et al (1993) reported similar results for epidemiological data from Sachxi Province, China. These authors studied 21 communities within the province over a period of 6 years. The regions that consumed the highest amounts of sorghum, and to a lesser extent millet, had 1.4-3.2 times lower mortality from esophageal cancer than areas that mainly consumed wheat flour or corn. Consumption of other foods like alcohol, tea, meats and vegetables did not contribute significantly to esophageal cancer mortality. These findings suggest the presence of anticarcinogenic compounds in sorghum that are either lacking or are not present in significant quantities in wheat or corn.

In vitro studies have also demonstrated the anticarcinogenic properties of sorghum. Grimmer et al (1992) found antimutagenicity of sorghum polyphenol extracts. The high MW procyanidins (tannins) had the highest antimutagenic activity compared to the lower MW tannins. Gomez-Cordovez et al (2001) showed that sorghum tannins had anticarcinogenic activity against human melanoma cells, as well as positive melanogenic activity. Similar melanogenic activity in red wine extracts was not detected. On the other hand, Parbhoo et al (1995) reported that sorghum procyanidin extracts may induce cytochrome P-450, a protein that is capable of converting certain promutagens to mutagenic derivatives, in rat liver. These conflicting findings are typical of these endeavors. More work on sorghum is required to validate these reported anticarcinogenic properties.

There is plenty of literature available (often conflicting) on properties of various polyphenol-rich foods, especially tea and red wine/grapes in relation to various types of cancer in humans (reviewed by Chung et al 1998; Higdon and Frei 2003). The overall trend suggests polyphenol-rich products are anticarcinogenic, but a consensus on their efficacy is currently lacking. For example, even though tea is reported as anticarcinogenic in many *in vitro* and epidemiological studies, Higdon and Frei (2003) concluded that available data does not support the notion that tea is protective against cancer. Yang et al (2001) also provided useful insight on the limitations of various cancer-related studies.

For sorghum, available data on cancer is too limited to draw meaningful conclusions. However, the corroborative epidemiological evidences reported by Van Rensburg (1981) and Chen et al (1993) against esophageal cancer warrant further investigation. Additional *in vitro* data as well as controlled animal studies are necessary to understand how the levels and composition of polyphenols in sorghum affect cancer, and which specific components are responsible.

XV. SUMMARY

Sorghum varies from the white food hybrids that have excellent properties for use in a wide variety of processed foods to brown high tannin and black high anthocyanin types containing high levels of antioxidants. The white food types have functionality similar to rice with a bland flavor and light color and they can be extruded, flaked, and made into a wide variety of food products. Moreover, these new hybrids have excellent yields and are widely adapted.

Tannin and black sorghums have a diversity of phytochemicals with potential significant impact on human health. The sorghum phytochemicals show high antioxidant activities against different free radicals *in vitro* that compare favorably with high antioxidant fruits and vegetables. The tannin sorghums can be processed into bran that can be used to produce foods rich in antioxidants and desirable phenolic compounds. The sorghum brans are also rich in phytosterols and policosanols which are known to promote cardiovascular health. More information on how sorghum phytochemicals affect human health is required. However, current overall epidemiological evidence suggests special sorghums have anticarcinogenic properties, promote cardiovascular health and may reduce caloric availability of foods.

The brown (tannin) sorghum brans produce baked products with dark natural color, acceptable flavor and improved levels of antioxidants and dietary fiber. The protein complexed with condensed tannins has the potential to slow digestion and reduce caloric content of foods. These special sorghums are available in high yielding cultivars and hybrids. The grain can be stored indefinitely and processed into brans and extracts to produce an array of useful products for health foods and related products. Knowledge of sorghum genetics permits designing special types of sorghum with even greater variation in phenol type and contents. The combination of high anthocyanins and tannins is a promising option.

XVI. ACKNOWLEDGEMENT

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TABLE I

Physical Properties and Composition of Food and Feed Sorghum Hybrids Grown Over Four Years at Four Locations in Texas, Kansas, and Nebraska.

Pedigree	Type	Hardness Index	Decortication Yield (%)	Grain L Value	Grit L Value	TKW (g)	Diameter (mm)	Density (g/cc)	Protein[1] (%)	Fat[1] (%)
ATx378*RTx430	RP	83.4 bc	75.9 cd	47.7 d	65.3 b	30.0	2.22	1.376 cd	11.5	3.8
ATx623*RTx430	WP	83.0 c	74.9 cd	59.5 c	68.2 a	29.0	2.17	1.373 cd	10.0	3.5
AOK11*RTx2741	WP	70.6 e	70.7 d	60.4 bc	68.2 a	25.9	1.97	1.368 d	9.5	3.5
ATx635*RTx436	WT	94.9 a	85.8 a	63.1 a	68.2 a	23.2	1.97	1.396 a	11.0	3.8
888Y	WT	90.3 ab	86.4 a	59.5 c	67.8 ab	25.8	1.92	1.396 a	11.2	3.9
ATx631*RTx436	WT	89.9 ab	79.1 bc	63.8 a	69.6 a	25.6	2.07	1.381 bc	11.1	3.9
ATxArg-1*RTx436	WT	91.5 a	82.7 ab	62.6 ab	69.6 a	22.6	1.83	1.389 ab	10.8	3.6
LSD (P<0.05)		7.2	5.9	2.3	2.4	4.0	0.22	0.011	1.3	0.3

[1]Expressed on dry weight basis

RP: red grain, purple plant; WP: white grain, purple plant; WT: white grain, tan plant.

Means with same letters not significantly different.

The first three sorghums are feed sorghums typical of the commercial production of sorghum in the United States. The last 4 samples of grain are hybrids that produce food type sorghums.

TABLE II

Phenol Contents and Antioxidants (mMol TE/G Sample, Dry Wt) in Sorghum and Sorghum Products Measured by Three Methods.

Sorghum	ORAC[a]	ABTS[b]	DPPH[c]	Phenols[d]
White grain	22	6	6	0.8
White bran	64	28	21	4.8
Red grain	140	53	28	6.6
Red bran	710	230	71	19.9
Black grain	220	57	41	6.4
Black bran	1,000	250	184	26.0
Hi Tannin grain	450	108	118	12.3
Hi Tannin bran	2,400	512	495	54.9
Sumac grain, brown	870	226	202	19.8
Sumac bran, brown	3,100	768	716	66.3
CV%	6.8	3.5	5.3	5.97

[a]ORAC = Oxygen radical absorbance capacity, fluorescein used as a probe. [b]ABTS = 2,2′-azinobis (3-ethyl-benzothiazoline-6-sulfonic acid); activity was measured in pH 7.4 phosphate buffer saline.

[c]DPPH = 2,2-diphenyl-1-picrylhydrazyl; activity was measured in methanol.

[d]Phenols, mg GAE/g (Folin-Ciocalteu method).

Samples were extracted in 70% aqueous acetone.

Adapted from Awika et al, 2003b.

TABLE III

Proanthocyanidin Content[a] of Brown Sorghums Compared to Those of Freeze-Dried Cocoa and Blueberry[b]

DP[c]	Sumac Grain	Suman Bran	Cocoa[d]	Blueberry[d]
1	0.18	0.33	14.24	0.18
2	0.40	1.33	8.57	0.46
3	0.51	1.61	8.10	0.38
4	0.69	2.32	8.89	0.50
5	0.74	2.51	8.86	0.47
6	1.10	3.61	9.99	0.69
7	0.79	2.56	6.38	0.48
8	0.74	2.29	5.97	0.61
9	1.17	3.48	7.36	0.93
10	0.55	1.52	3.22	UI[e]
P[f]	15.09	36.87	16.17	15.28
Total	21.97	58.44	97.76	19.99
% oligo[g]	31.31	36.33	83.45	23.51
CV (%)	2.0	10.2	5.4	2.1

[a]mg/g, obtained by normal phase HPLC with fluorescence detection. [b]Awika et al. (2003a).
[c]Degree of polymerization.
[d]Gu et al. (2002).
[e]nd – not detected.
[f]Mixture of polymers with DP>10.
[g]Oligomers (DP<10) as a percent of total

TABLE IV

Composition of Special Sorghum Brans (%) (dry matter basis)

Bran	Crude protein	Crude fat	Ash	NFE	Crude fiber	Dietary fiber
Wheat	17.2	4.7	6.4	71.6	-----	47.5
White sorghum	13.2	8.3	3.5	65.0	9.9	41.3
Tannin sorghum	12.7	10.4	5.1	63.8	8.0	45.0
Black sorghum	15.0	4.4	3.8	68.3	9.7	43.4

Sorghum brans obtained using a PRL decorticator at 12-15% yield (Gordon 2001)

LIST OF FIGURES

Figure 1. Fluorescence photomicrograph of sorghum bran cross-section, showing structural differences between a non-tannin sorghum without a testa (left) and a tannin sorghum with a pigmented testa (right). Al: aleurone layer, CW: cell wall, E: endosperm, En: endocarp, Ep: epicarp, M: mesocarp, T: pigmented testa. Earp, et al. (2004).

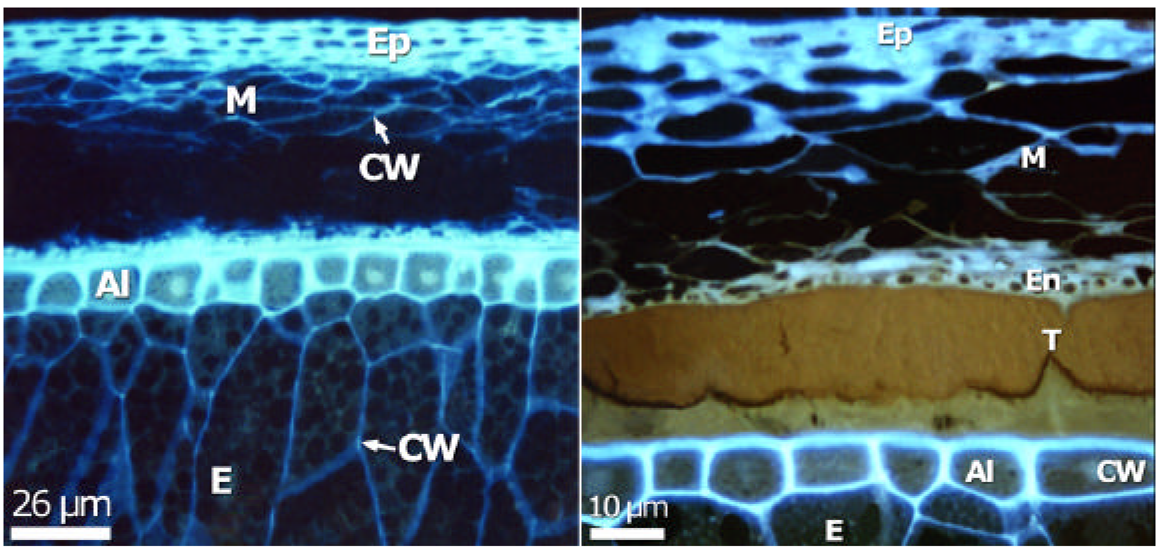
Figure 2. Relationship between L value and decorticated yields of food and non-food sorghums over time. Note the reduced yield of the non-food sorghums (Cargill Alt. And Dreyfus I. varieties) relative to the food sorghums at comparable lightness value. Unpublished data, Cereal Quality Lab, Texas A&M Univ., 2004.

Figure 3. Decorticated grain yield of food (white) and commercial feed (red) sorghums adjusted to an L value of 67 (CV = 3.5%). The L value of 67 was demonstrated to produce flour of commercially acceptable lightness (Awika et al. 2002). You can see significant differences among the white food type sorghums vs. the red commercial samples. Source: Value Enhanced Sorghum Grains. US Grains Council 2002.

Figure 4. Decorticated food sorghum (A) direct-expanded extrudate (B) characteristics compared to corn meal (C) and rice (D) extrudates. Samples were extruded through a short barrel, high friction type Maddox extruder.

Figure 5. Antioxidant (ORAC) levels in different sorghum brans compared to wheat bran and fruits (dry basis) (modified from Awika et al 2003a).

Figure 6. Change in tannin sorghum procyanidin distribution due to extrusion. 'P' represents polymers with DP>10. Normal phase HPLC method was used to quantify proanthocyanidins. Modified from Awika et al. (2003b).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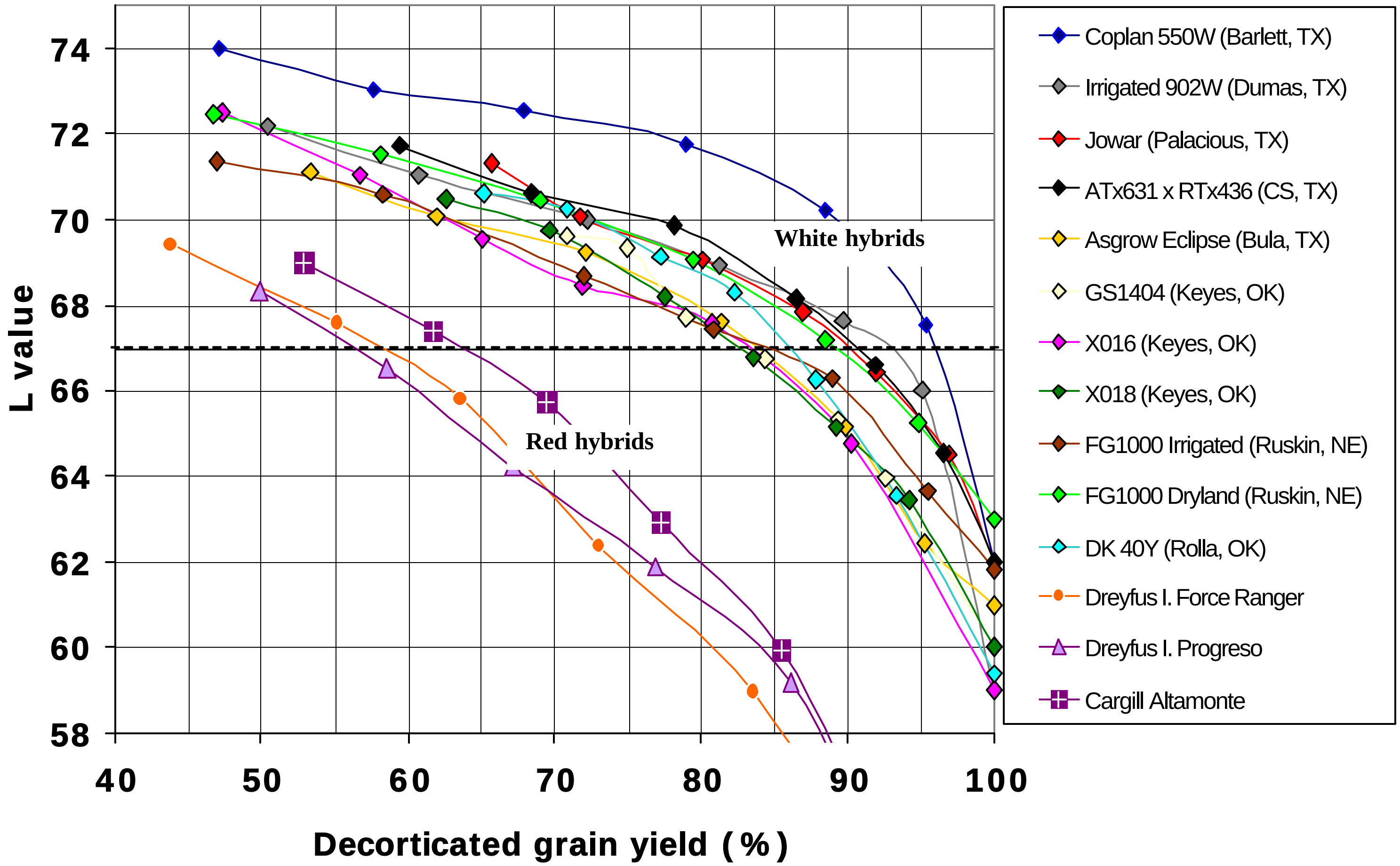
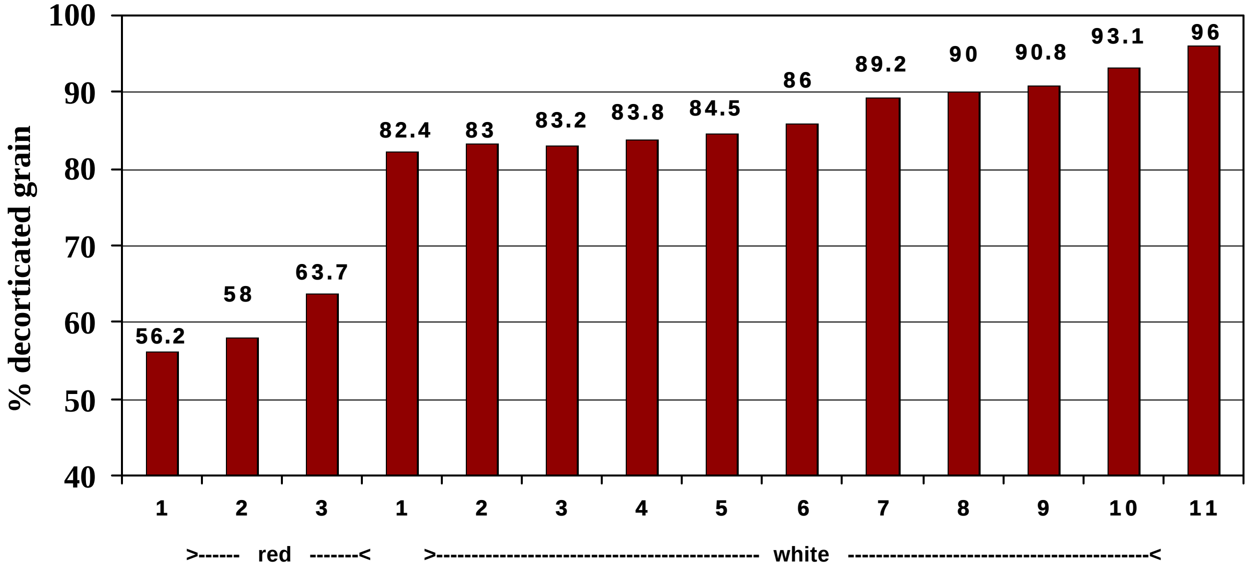
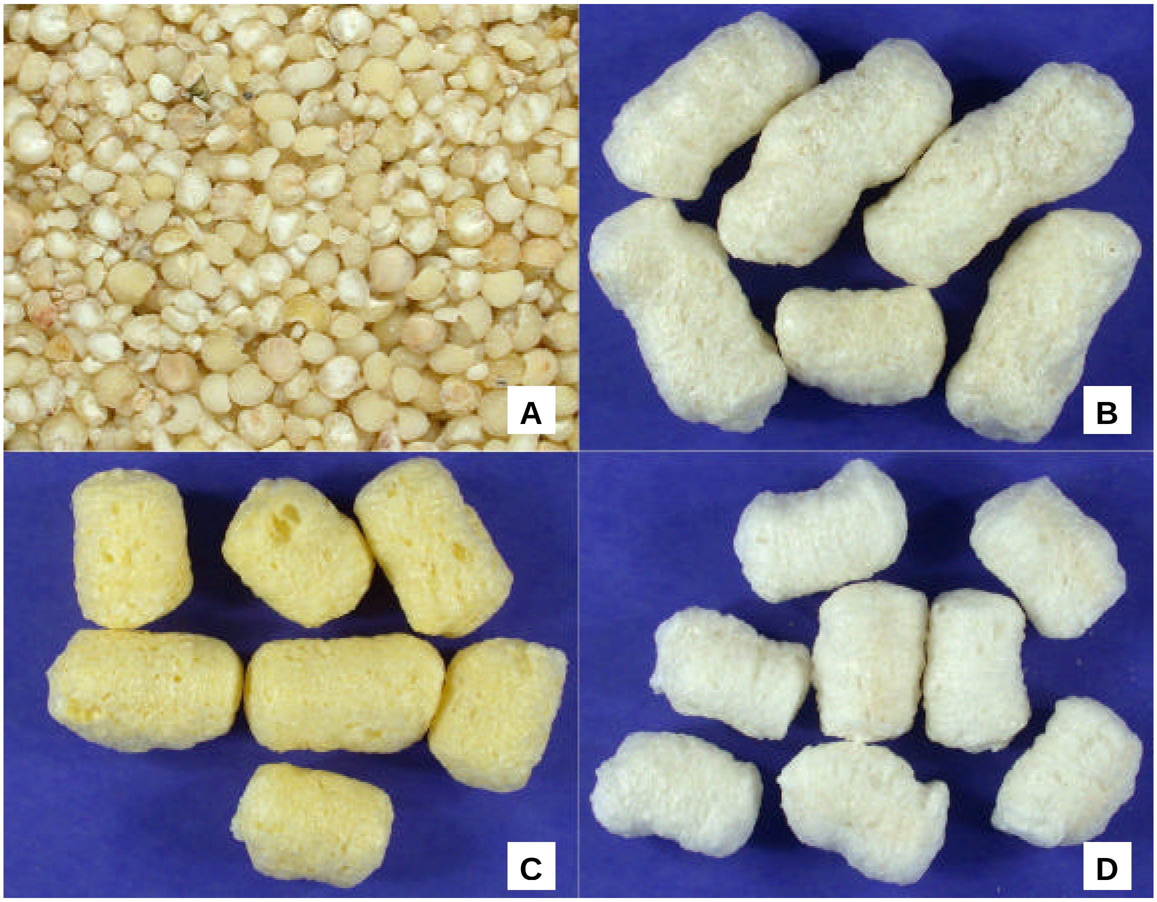
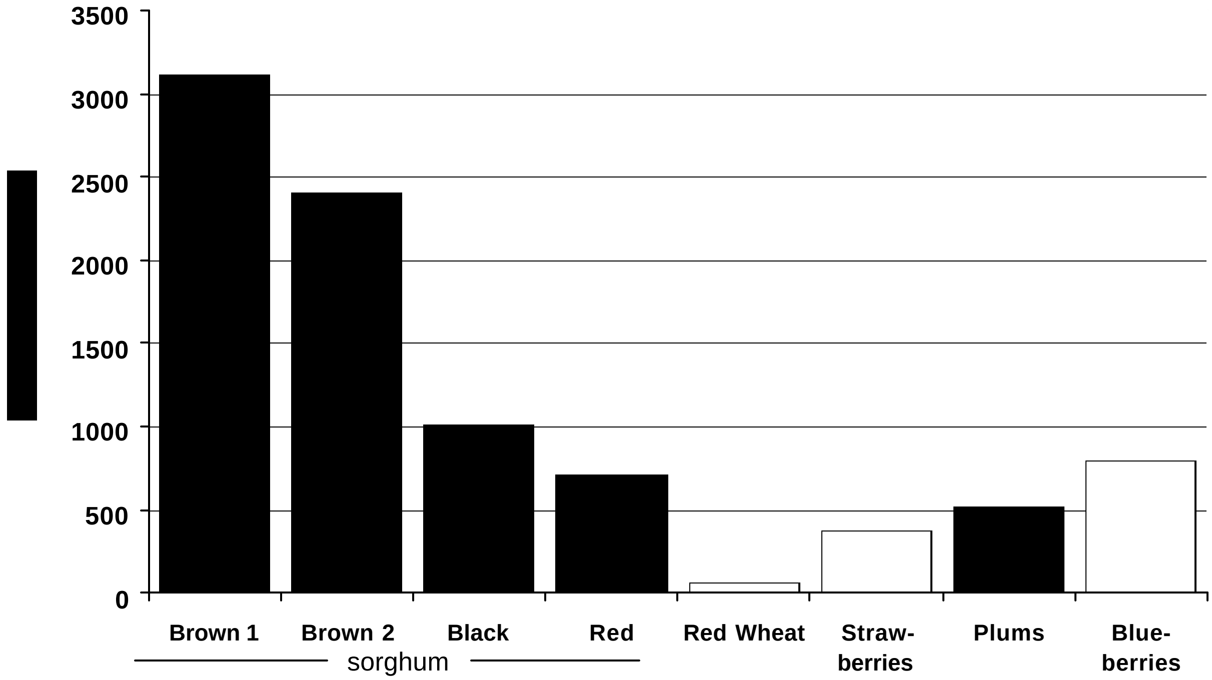
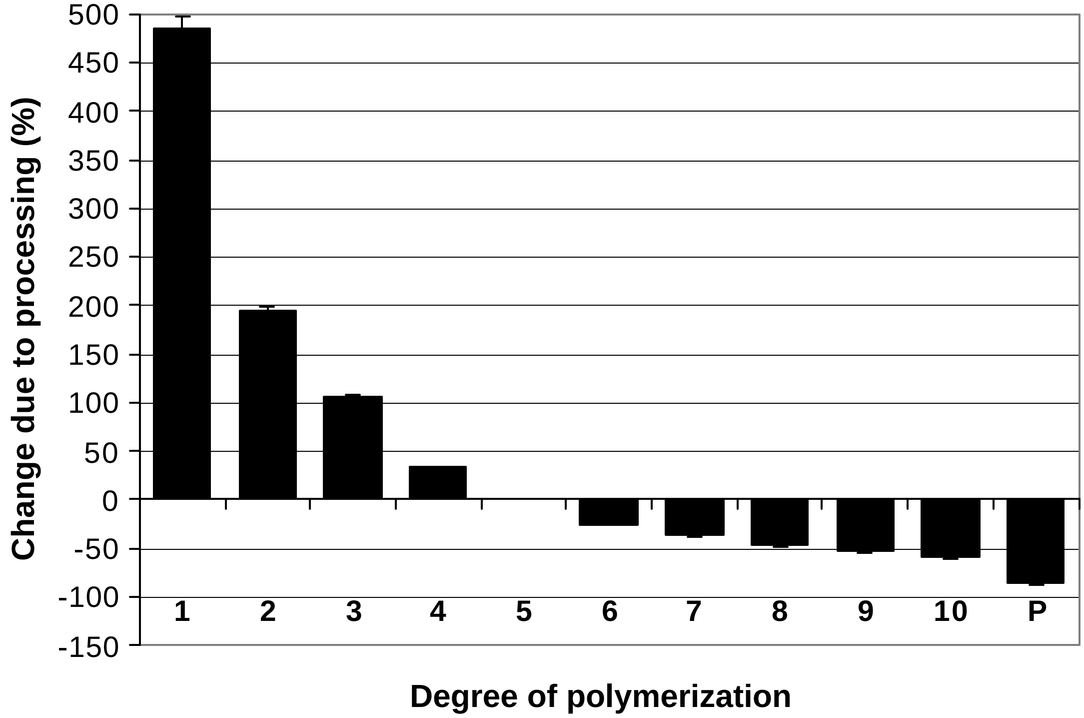


L value
Decorticated grain yield (%)
White hybrids
Red hybrids
Coplan 550W (Barlett, TX)
Irrigated 902W (Dumas, TX)
Jowar (Palacious, TX)
ATx631 x RTx436 (CS, TX)
Asgrow Eclipse (Bula, TX)
GS1404 (Keyes, OK)
X016 (Keyes, OK)
X018 (Keyes, OK)
FG1000 Irrigated (Ruskin, NE)
FG1000 Dryland (Ruskin, NE)
DK 40Y (Rolla, OK)
Dreyfus I. Force Ranger
Dreyfus I. Progreso
Cargill Altamonte


% decorticated grain
100
90
80
70
60
50
40
56.2
58
63.7
82.4
83
83.2
83.8
84.5
86
89.2
90
90.8
93.1
96
1 2 3 1 2 3 4 5 6 7 8 9 10 11
>------ red -------<
>-- white --<


A
B
C
D


[redacted]
3500
3000
2500
2000
1500
1000
500
0
Brown 1
Brown 2
Black
Red
sorghum
Red Wheat
Straw-
berries
Plums
Blue-
berries



Change due to processing (%)
500
450
400
350
300
250
200
150
100
50
0
-50
-100
-150
1
2
3
4
5
6
7
8
9
10
P
Degree of polymerization