THE USE OF SPECIALTY SORGHUMS FOR EXPANDED SNACK FOOD PROCESSING

A Thesis

by

DUANE LAWRENCE TURNER

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2004

Major Subject: Food Science and Technology

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Approved as to style and content by:

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ABSTRACT

The Use of Specialty Sorghums for Expanded Snack Food Processing. (May 2004)

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The physical, chemical, and antioxidant properties of extrudates prepared from specialty tannin sorghum (CSC3xR28) and Tx430 black sorghums were evaluated. White food type sorghums (ATx631xRTx436) and commercial corn meal were also extruded. Sorghums were extruded as whole kernels or cracked (broken) kernels through a Maddox MX-3001 high-friction extruder. Cracked sorghum fortified with bran (0 -50%) derived from decortication or roller-milling were also extruded.

Tannin sorghums extruded similarly to white food-type sorghums, with very little difference in extrudate quality. Cracking the sorghums produced lower feed rates, higher specific mechanical energy (SME) and extrudates that were less dense, more expanded, and softer than whole kernel extrudates. Whole and cracked sorghum materials had feed rates similar to corn meal, but lower SME. Corn meal extrudates were less dense, more expanded, and softer than sorghum extrudates. Cracked and whole black sorghum extrudates were less expanded than hi-tannin and white sorghum extrudates, due to the black sorghum’s soft endosperm and thick, fibrous pericarp.

With increased fiber, all extrudates had decreased SME and expansion, with increased bulk density and breaking force with the addition of bran. These effects, were

more pronounced in extrudates containing decorticated bran vs. roller-milled bran. The decorticated bran had smaller particle size, higher density, lower endosperm content, and greater dietary fiber content than roller-milled bran. Also, increases in dietary fiber content in the extrudates were strongly correlated to increases in bran fortification in the raw feed stock.

Tannin and black bran extrudates showed increased phenol, tannin (high-tannin), and antioxidants where bran was added. Phenols, tannins, and antioxidants in tannin extrudates ranged between 10.3-30.9 mg GAE/g, 7.1-55.2 CE mg/g, and 68.3-212.2 umol TE/g, respectively. Phenols and antioxidant activity in black sorghum extrudates ranged from 4.2 -7.8 mg GAE/g and 39.7 – 73.3 umol TE/g, respectively.

Specialty tannin and black sorghums can be used to produce extruded snacks high in fiber and antioxidant activity. Optimum product characteristics, along with nutraceutical benefits, will need further determination.

DEDICATION

I would like to first dedicate this whole endeavor to my Lord and Savior Jesus Christ, without whom none of this would be possible. I also want to dedicate this to my mom and dad for their consistent support and concern. I thank them, as well as all my family and friends, for their prayers.

ACKNOWLEDGEMENTS

Where do I begin? First of all, I want to thank everyone in the Cereal Quality Lab. I wish I could have been as helpful to everyone individually as they have been to me. Special acknowledgement goes to Dr. Rooney and Dr. Waniska for their patience in guiding me through the program. You've always encouraged my progress and reminded me to stay on track. I hope to learn from my experiences: the mistakes, as well as the accomplishments, and use those memories as focus points for future growth. I would also like to acknowledge Dr. Cisneros-Zevallos for serving on my committee and Dr. Mian Riaz for being accommodating and allowing me (as well as others) to use his facilities. Also, without the help of Marc Barron, this project would not have been possible.

I also thank Dr. Joseph Awika for always being willing to take in my questions about my project and taking the time to walk me though intricate concepts. You have been a valuable asset to this work. A huge thanks goes to Lisha Xu for her assistance on the phenolic and antioxidant assays and values used in this thesis.

I also want to thank Cassandra McDonough for the much appreciated help in the visual aspects of my project and her continuous willingness to fit my requests somewhere into her work. My gratitude also goes to Mrs. Littlejohn for her day to day assistance.

And last but not least, I just want to send out an appreciation to all the CQL grad students and student workers. If I've forgotten to mention you, just know you're appreciated.

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CHAPTER I

INTRODUCTION

Sorghum (*Sorghum bicolor* (L.) Moench) is the world's fifth leading grain in production and is a staple food for many in the arid, dry climates of Africa and Asia (Suhendro et al. 1998). These continents use sorghum to produce many traditional foods, such as t^o, ogi, chapti, and injera. However, in the western hemisphere, much of the sorghum produced is for animal feed purposes. The food market for sorghum in North and Central American is still developing.

Certain sorghums have very high antioxidant potential (Awika 2000). Specialty sorghums, such as tannin and black sorghums, have brans high in antioxidant activity that exceed that of blueberries, strawberries, and red wine on a dry weight basis (Awika 2003). The abundance of antioxidants in sorghum is important due to the potential benefits of these compounds to human health. Oxidative compounds in the human body, when out of balance, can cause cellular destruction at the molecular level, which can lead to degenerative diseases such as Parkinson's disease, arthritis, cancer, and cardiovascular disease (Smythies 1998). Antioxidants react with these oxidative compounds to halt, impede, or prevent oxidative chain reactions.

Sorghum bran is also a good source of dietary fiber (Rooney et al. 1992). Dietary fiber aids in gastrointestinal health through bulking fecal matter, decreasing

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This thesis follows the style and format of Cereal Chemistry.

constipation, and reducing the absorption of carcinogenic metabolites (Kahlon et al. 2001). Research also shows that dietary fiber aids in lowering plasma and liver cholesterol levels, and may be a significant factor in treating coronary heart disease (Kahlon et al. 1990, 1993, 1996; Maier et al. 2000).

Because of increased consumer health concern and awareness, the demand for natural, health promoting foods and additives, often referred to as nutraceuticals or functional foods, is growing. The functional food world market was estimated at $ 32 billion US dollars in 1999 (New Nutrition 2002), with about half from U.S. sales alone (Bhaskaran and Hardley 2002). In 2010, functional food retail sales in the United States is estimated at $34 billion in US dollars, with the nutraceuticals sector growing at 9 to 10 percent, annually (Bhaskaran and Hardley 2002).

Tannin sorghum bran is an excellent source of antioxidants and fiber in bread (Gordon 2001) and cookies (Mitre-Dieste et al. 2000) with good product quality. Awika (2003) found that bread and cookies fortified with tannin bran retained approximately 60 and 78% of their original antioxidant activity, respectively, after processing. Awika also found that extruded tannin expanded-snack type products retained 89% of their original whole-grain antioxidant potential.

This factor is important as extrusion processing is gaining interest because of its material-to-product cost effectiveness, processing & time efficiency, and adaptability (Ilo et al. 1999; Alonso et al. 2000). Extrusion processing is used to produce various expanded snack and food products and allows for a simplified raw material to product conversion, with very few steps involved. These beneficial factors have kept extrusion-cooking technology at the forefront of the snack food and cereal industries (Huber 2001).

Various studies have been conducted to determine the functional food qualities of whole-grain and bran fortified extruded products. The physical, chemical, nutritional and sensory attributes of extrudates containing brans derived from corn, wheat, and barley have been examined (Lue et al. 1991; Berglund et al. 1994; Mendonca et al. 2000). However, very little data is available on sorghum. Specialty sorghum can be used to produce healthy, value-added expanded snacks. Whole unground tannin sorghum can have beneficial attributes for nutraceutical snacks.

Therefore, the objectives of this study were:

1. To characterize specialty sorghum extrudates in comparison to white food-type sorghum and corn meal extrudates.

2. To determine the physical, antioxidant, and fiber contents of specialty sorghum extrudates fortified with 0-50% sorghum bran.

CHAPTER II

LITERATURE REVIEW

Functional Foods and Nutriceuticals

"Functional foods" or "nutraceuticals" are "food or food components that collectively impart a physiological benefit that can enhance overall health, including disease treatment and/or prevention" (Hasler 1998). Thomas and Earl (1994) also state that functional foods "may provide health benefits beyond that of the traditional nutrients it contains." Functional foods are not strictly defined, but entail dietary supplements, engineered "designer" foods,"pharma" medical foods, enriched or fortified foods, processed cereal, soup and beverage products, and isolated nutrient and phytochemicals components (Kwak and Jukes 2000; Andlauer and Furst 2002).

Functional foods originated in Japan in the mid-1980's, based on the concept that foods and drugs have the same origin (Goldberg 1994). Since there is no strict regulatory framework for functional foods, they are regulated as foods in the U.S., although guidelines for health claims (Kwak and Jukes 2001) and safety (Kruger and Mann 2003) are being established. Also, the U.S. FDA states that for a functional food substance to remain a "food", it must be consumed in part for taste, aroma, nutritive value, or other specific effects (Clydesdales 1998).

Functional food production has steadily increased in the U.S. market. Sales in functional foods reached an estimated $ 16.5 and $ 17.2 billion, in 2000 and 2001, respectively, and are predicted to exceed $22 billion by 2006 (Obesity, Fitness, &

Wellness Week 2002). Increased onset of nutrition related diseases such as cardiovascular disease and diabetes as well as increased knowledge on health, have caused many food consumers to shift their thinking towards using foods for disease prevention at low cost and low involvement, in addition or opposition to drugs and medical treatments (Clydesdale 1998). In 1995, a Food Marketing Institute (FMI) prevention survey on specific health benefits of foods, showed that 93, 88, and 86% of those surveyed felt that diet could control "cholesterol", onset of heart disease, and blood pressure, respectively (FMI/Prevention 1995).

Also, studies in recent years have increase interest in various foods such as fruits, vegetables, and cereal grains because of their potential cancer preventative effects. With this in mind, specialty sorghum grains show promise as functional food components because of their high fiber and phytochemcial content (Rooney et al. 1992; Awika 2003). Specialty sorghums have already been used to produce products with desirable qualities (Mitre-Dieste et al. 2000; Gordon 2001; Rudiger 2003).

Sorghum

Sorghum [Sorghum Bicolor (L.) Moench] is the world's fifth most important cereal, after wheat, rice, maize, and barley (Serna-Salvador and Rooney 1995), and is successfully grown in Africa, India, and China due to the profitable cultivation of sorghum in climates too dry for maize production (FAO and ICRISAT 1996). Almost a decade ago, (1992-94), the worldwide utilization of sorghum was close to 63.5 million tons. 42% of this sorghum was used for human food mainly in semi-tropical locations in Asia and Africa (FAO and ICRISAT 1996).

While the United States currently leads the world in sorghum production, sorghum is used mainly for feed purposes. Sorghum has attractive value as feed, as the total digestible nutrients (TDN) found in sorghum are about 95% of those found in maize. Also sorghum crop yields are similar to maize, and international prices for sorghum are slightly lower (FAO 2003). These factors, plus possible health promoting, high phenolic sorghums (Awika 2003) and ongoing research on food-type sorghums (Acosta-Sanchez 2003), may open up interest in sorghum to U.S. health and food markets.

Sorghum Composition

Sorghum contains approximately 7-16% protein, 55-75% starch, 0.5-5% lipids 1-6% crude fiber, and 1-4.5 % ash, on a dry weight basis (Serna-Saldivar and Rooney 1995). Approximately 80%, 16%, and 3% of the protein is contained in the endosperm, germ, and pericarp, respectively (Taylor and Schussler 1986). Starch, the major grain component, comprises 80-82% of the endosperm, and has similar composition to that of cornstarch granules (Serna-Saldivar and Rooney 1995). Sorghum starch contains 70-80% branched amylopectin and 20-30% amylase. Waxy, glutinous sorghum have almost 100% of its starch as amylopectin with properties similar to waxy corn (Serna-Saldivar and Rooney 1995). Starch endosperm hardness in sorghums is determined by grain genetics and environment (Rooney 2004). Hard, corneous-type endosperm contains starch granules that are tightly bound in a rigid protein matrix, and is translucent in appearance and is more resistant to milling. Floury soft endosperm, on the other hand, has starch granules that are loosely spaced and loosely surrounded by protein bodies, is opaque in appearance, and is more easily broken during processing (Rooney 2004).

Various genetic factors also affect sorghum grain color and appearance. R and Y genes control pericarp color, and combinations of these genes produce red (R_ Y_), lemon-yellow (rrY_), and white (R_yy or rryy) pericarp coloring. The intensifier gene (I) affects pericarp color intensity (Hahn et al. 1984). Grain color appearance is influenced by the presence of a pigmented testa and a spreader gene. Dominant B_1_B_2_ genes result in a pigmented testa with condensed tannins, however homozygous recessive genes ($b_1b_1b_2b_2$, B_1_b_2b_2, $b_1b_1B_2$_) will cause the testa to be absent (Serna-Saldivar and Rooney 1995). When a pigmented testa is present, a dominant spreader (S) gene causes increased tannin and polyphenol levels in the seed testa and pericarp layers producing a high-tannin, brown colored sorghum (B_1_B_2_S_1_) (Rooney et al. 1982).

Sorghums are categorized based on the presence and structure of tannins. Type I sorghums have low phenol levels and no pigmented testa or tannins. Both type II and III sorghums have tannins and pigmented testas. However, type II sorghums (recessive S gene), have tannins that can only be extracted by acidic methanol and, while type III (dominant S gene) sorghums can be extracted by methanol or acidic methanol (Hahn et al. 1984). Most bird resistant, brown sorghums are type III (Rooney et al. 1982). These sorghums produce tannins as a defense mechanism, which give an astringent taste when highly concentrated.

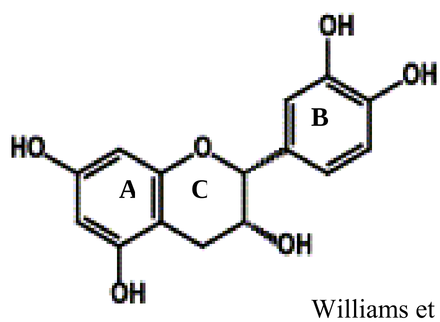
In sorghum, flavonoids such as catechins, proanthocyanidins (tannins), and anthocyanins are the most abundant phenolic compounds, depending on sorghum type and variety (Awika 2000) and are the most important antioxidant compounds found in sorghum. Tannins - produced in some sorghum varieties as a defense mechanism against pest and fowl (Hahn et al. 1984) - are located in the testa layer, just beneath the sorghum pericarp layer. Type III brown sorghums have thick pigmented testa layers, are rich in tannins, and dominate all other sorghum types in total phenols, tannin content, and antioxidant activity (Awika 2003). Anthocyanins are predominantly located in the pericarp layer of sorghum, and black sorghum varieties are the highest in anthocyanin pigments, followed by brown and red sorghum verities (Awika 2000). Type I red and white sorghums have no pigmented testas. Red sorghums contain low levels of phenols and anthocyanins (Nip and Burns 1869). White sorghums contain opaque pericarps, which result in these sorghums having very little, if any flavonoid content (Nip and Burns.

Sorghum Phenolic Antioxidants

Sorghum, as other cereal grains, fruits, and vegetables, have phytochemical phenolic compounds, which have been heavily studied for their antioxidant properties. These compounds are usually secondary metabolites biosynthesized throughout the plant kingdom as a defense mechanism against pathogens and pests (Hollman and Katan 1997). Phenols are valuable antioxidants that contribute to the natural body defense system in scavenging free radicals (molecules like ${}^{1}O^{2}$, $O^{2\cdot-}$, $NO^{\cdot}$), chelating metals ($Fe3^{+}$), and repairing lipids, proteins, and DNA (Kehrer and Smith 1994). Also, phenols complement other natural antioxidant compounds such as vitamin C and E, by helping to regenerate or spare these molecules in the body (Smythies 1998). Phenolic compounds also provide flavor and color characteristics to fruit juices, wines, and candy sources such as peppermint, licorice and chocolate (Kuhnau 1976; Peterson and Dwyer1998).

Phenolic compounds can be divided into (a) phenolic acids and derivative compounds and (b) flavonoids. Phenolic acids are grouped into either cinnamic (C7) or benzoic (C6-C3) categories. These compounds occur as free acids, soluble, and insoluble esters located in the outer layer of the grain. Ferulic acid (3-methoxy-4-hydroxy-cinnamic acid) is the most abundant phenolic acid in sorghum and exists mostly in bound form.

Flavonoids (Fig.1) are divided into several classes, and flavans and flavan-3-en-ols are the most significant group found in sorghums (Gous 1989).



Williams et al. 2004.

Fig.1 Basic flavonoid (catechin) structure.

Flavin structures based upon the combination of leucoanthocyanins and catechins are commonly known as proanthocyanidins or condensed tannins (Ribereau-Gayon 1972). Tannins are water-soluble phenolic compounds that have molecular weights between 500 and 3,000 daltons; react in a similar manner as other phenolic compounds, and have the ability to bind with proteins and other macromolecules (Jimenez-Ramsye et al. 1994;

Santos-Buelga and Scalbert 2000). Another category of tannins called hydrolysable tannins, which are derivatives of gallic acid esterified to a core polyol, like glucose. Phenolic groups surrounding the polyol may be further esterifed or crossed-linked oxidatively to produce larger hydrolysable tannin molecules (Santos-Buelga and Scalbert 2000).

Tannins are strong antioxidants (Hagerman et al. 1998; Awika 2003). Tannins have highly effective radical quenching ability due to high molecular weight and the proximity of their aromatic rings and hydroxyl groups (Hagerman et al. 1998). Tannins can chelate metals at low pH (Hagerman et al. 1998) and can scavenge aqueous peroxyl and hydroxyl radicals by donating a proton from the phenolic B ring (Santos-Buelga and Scalbert 2000). The unpaired electron is then delocalized on the phenolic ring and forms a stable semiquinone radical (Santos-Buelga and Scalbert 2000). Tannins have also shown beneficial antimutagenic, anticarcinogenic, and antimicrobial properties (Chung et al. 1998). This is evident in the inverse correlation between intake of tannins in green and black teas and carcinogenic tumors found in rat and human cells (Cao et al. 1996; Katiyar and Muktar 1996).

Concerns over tannin interactions with nutrients have been reported. Tannins complex with proteins, minerals, and other compounds making them more resistant to digestion in the stomach (Jimenez-Ramsye et al. 1994). However, tannins may spare other antioxidant compounds (Hagerman et al. 1998) and protect nutrients from oxidative damage during digestion (Marshall and Roberts 1990).

Anthocyanidins (flavan-3-en-3ols) are flavonoid groups, which commonly exist as glycosides and acylglycosides known as anthocyanins. Anthocyanins are responsible for producing the blue and red colorations in fruits such as berries, cherries, and plums, vegetables such as red cabbage and radishes, and some grains, including sorghum (Herman 1976; Gous 1989). Data on anthocyanins in most cereals is limited, however, anthocyanin compounds such as apigeninidin-5-glucoside and luteolinidin-5-diglucoside (Nip and Burns 1969, 1971) have been isolated from white and red sorghums; apigeninidin and luteolinidin in black sorghums (Gous 1989).

Anthocyanin color is pH influenced: anthocyanins give off a red pigmentation at pH 3.5, and as the pH increases, anthocyanin coloring shifts to blue (Pierpoint 1986). Anthocyanins also contribute some of the beneficial effects of consuming fruits and vegetables (Wang et al. 1997). Anthcyanins are vasoprotective (Lietti et al. 1976) and can decrease the onset of diabetes (Karaivanova et al. 1990). Anthocyanins also have anti-inflammatory (Lietti et al. 1976), anti-cancer, and chemo protective properties (Karaivanova et al. 1990). Proanthocyanins Tannins, anthocyanins, and other flavonoids are partially absorbed in the human body (Pietta 2000; Ross and Kassum 2002). Tannins can be absorbed in the small intestine, but only as small oligomers (Deprez et al. 2000). Most flavonoids are not absorbed directly, but are primarily degraded by large intestine microflora. Bacterial enzymes are able to cleave flavonoids and produce several phenolic acids which can be absorbed through the large intestine and enter circulation (Pietta et al. 1997 and Deprez et al. 2000). This information suggests that tannins and anthocyanins may be digestible and bioavailable to the human body as antioxidants.

Effects of Thermal Processing on Proanthocyanidin and Anthocyanin Compounds

Current research shows that most processes decrease assayable proanthocyanidin retention in final products; although at varying levels (Campbell and Van der Poel 1991; Sze-Tao et al. 2001; Awika 2003). Van der Poel et al. (1991) reported that various thermal processes (reconstitution, extrusion, and reconstitution /extrusion) on faba beans all similarly reduced assayable tannin levels by 50% (Folin-Denis phenol assay according to Swain and Hillis 1981). However, condensed tannins determined with the vanillin sulphuric acid method described by Kuhla and Ebmeier (1981), showed retention in samples ranging from 55 to 90%. Sze-Tao et al. (2001) showed that roasting (204 C for 5 min), microwave heating (double-deionized water), and blanching (100 C for 2 min), caused a 14, 93-98, and 98%, reduction of assayable walnut tannins, respectively. Alonso et al. (2001) showed that extrusion cooked peas and kidney been seed meals retained only 8 and 30 % of their assayable tannin levels, respectively. Tannins in both Sze-Tao et al. (2001) and Alonso et al.'s (2001) studies were extracted with absolute methanol (kidney beans in acidified methanol) and analyzed using the .5% vanillin assay (Broadhurst and Jones 1978; Deshpande et al. 1986). Awika (2003) reported that high tannin type III sorghum extrudates retained only 21% of their original assayable tannin content and 89% of their original antioxidant activity. Tannins were assayed with vanillin-HCL method of Price et al. (1978). This previous data shows that processing may structurally alter tannins, without significantly hindering antioxidant potential, particularly in tannin sorghums. Awika (2000) reported that tannin sorghums have the highest ORAC antioxidant activity and phenolic content among sorghums followed by black, red, and white sorghums, respectively.

Reduction of detectable tannins in thermal processing can be attributed to structural break down and chemical rearrangement. Awika et al. (2003) reported that extrusion decreased the degree of polymerization (DP) in proanthocyanidins, in comparison to their raw grain material. HPLC proanthocyanidin profiles showed increased levels of monomers (478%) and tetramers (29%) in extrudates, compared to the raw grain. Thermal food processing causes polyphenols to form insoluble complexes with proteins, vitamins, and minerals (Jimenez-Ramsye et al. 1994). This in turn decreases nutrient bioavailability and tannin extractability (Barroga et al. 1985; Kataria et al. 1989). In this respect, tannins may also be beneficial in binding surplus nutrients (proteins, sugars, etc.) lowering caloric intake, which could help in fighting obesity and diabetes.

Much less has been reported about the effects of processing on anthocyanins. Kaack and Austed (1998) reported that anthocyanin pigments in fruit juices were highly susceptible to oxidation during processing and storage. Also, anthocyanins can polymerize with other phenolic compounds, such as ascorbic acid, resulting in decreased color and pH (Garcia-Viguera et al. 1999). Natural plant enzymes such as polyphenol oxidase (PPO), oxidize and degrade anthocyanin pigments (Kadar et al. 1997). However, blanching fruits and fruit juices at low or moderate temperatures greatly retains anthocyanin content and radical-scavenging activity (Cheftel 1995; Rossi et al. 2003).

High thermal processing of black, anthocyanin sorghums show moderate retention of anthocyanins and antioxidant activity. Awika (2003) found that bread and cookies fortified with black sorghum bran, retained 57 and 72% of the original bran antioxidant activity, respectively. Black sorghum extrudates from two locations (Tx430 2001, Tx430 2002) showed retention levels for anthocyanins at 54 and 49%, phenols at 72 and 70%, and antioxidant activity levels at 81 and 70%, respectively (Awika 2003).

Dietary Fiber and Bran

Dietary fiber is divided into insoluble and soluble fiber. Insoluble dietary fibers are compounds (primarily found in the bran or seed coat of grains) that cannot be broken down by digestive enzymes in the small intestine, but can be fermented by bacteria in the large intestine. Thus, insoluble fiber increases fecal bulk and decreasing fecal transit time through the large intestine (Stockwell 1998; Nelson 2001 a). Soluble fibers included pectins, gums, and beta-glucans and have effects similar to insoluble fiber in the small intestine. Soluble fibers slow down nutrient absorption and can be fermented by gut microflora. Bacterial microflora can then produce compounds (short-chain fatty acids), which are thought to aid in lowering serum and LDL cholesterol, glycemic response, and insulin levels (Stockwell 1998; Nelson 2001 a).

Fiber (crude fiber) values were commonly obtained in the past by determining the percentage of plant residue remaining after acid and alkaline hydrolysis of animal feeds (Van Soest and McQueen 1973). In this experiment, crude fiber values were determined by near infrared spectrophotometry (NIR), based on sorghum grain standards. Dietary fiber content, however, is often determined on human food sources by enzymatic processing (which mimics the human digestive process) and gravimetric methodology (Prosky et al. 1988). Because of differences in methodology, crude fiber values only give a fraction of the actual cellulose, hemicellulose, pectins, lignin, and other components determined by dietary fiber analysis (Scaller 1978; Chen et al. 2003).

Dietary fiber has gained increased recognition in recent years as essential to the diet. Low dietary fiber has been associated with diverticular diseases, diabetes, coronary heart disease, and bowl cancer (Pomeranz et al. 1977). In recent years, the American Dietetics Association (ADA) recommended that adults consume 20 - 35 g of dietary fiber per day. However, most Americans are currently only consuming 12 -17 g of dietary fiber per day (Ohr 2004). Because of these factors, there has been increased push for the production of whole-grain and bran fortified products in the cereal grain industry (Slavin et al. 2001). Many current food labels carry daily reference values (DRV) for dietary fiber which has been established at 25 grams per day. Also, the FDA has allowed health claims for food products that contain 10 to 20% of the RDA for dietary fiber per serving (Miraglio 2003).

Cereal Bran is a rich and common source of dietary fiber (Nelson 2001 a), as well as various vitamins and minerals. Bran fortified foods have improved nutritional properties, and enhanced physical characteristics by acting as a gelling agent or improved storage oxidative resistance (Guillon and Champ 2000). Literature shows that brans from cereals such as wheat, rice, oat, and barley are highly effective sources of dietary fiber in animal and human studies. Kalon (2001) preformed a study in which diets containing different percentages of cellulose or hard red winter wheat bran (at varying particle sizes) where fed to rats. Results showed heavier fecal bulking and longer cercal lengths in rats fed wheat bran diets in comparison to cellulose diets, with coarser bran producing higher digestibility and passage. This function of fiber is important for gastrointestinal health, not only for preventing constipation, but also by decreasing or diluting the absorption of toxic or carcinogenic metabolites (Stockwell 1998).

Kahlon et al. (1990, 1993, and 1996) did several studies using rats and golden hamsters to determine the nutritional effects of diets containing varying amounts of rice, oat, barley, and wheat brans including combinations and/or modifications of these sources. They showed that high-fiber diets rich in these brans significantly lowered plasma and liver cholesterol levels, increased excretion of fat, neutral sterols, and bile acids in comparison to control cellulose diets. Rieckhoff et al. (1999) found similar effects in hamsters fed diets containing varying combinations of wheat, oat, barley, and rye brans. In human studies, the physiological and nutritional effects of dietary fiber in bran-rich diets were similar (Meyer and Calloway 1977; Maier et al. 2000).

Sorghum Bran

Hahn and Rooney (1986) demonstrated that decortication, air-separating, and sifting of sorghum material could produce reasonably pure bran fractions, which contained phenols several times greater than whole sorghum. Awika (2000) found that bran fractions (10% removal from brown sorghums) had the most tannin (17.5 mg CE/100mg). Fifteen percent removal of bran from black sorghum gave fractions richest in anthocyanins (318.3 abs/g/ml) (Awika 2000). Similar results were also found by

Taylor (2002), who reported that 10% decortication of white and red sorghums produced brans that were darker, lower in protein, and higher in fat, crude fiber, ash, and total polyphenols, than white and red sorghums decorticated at 25%.

Specialty sorghum brans have beneficial attributes, such as high fiber and antioxidant potential. Rooney et al. (1992) reported that sorghum bran fractions contained on average 36-50% total dietary fiber and 35-48% insoluble dietary fiber on a dry-weight basis. Rudiger (2003) also showed that bread fortified with 15% high-tannin sorghum bran contained higher phenols, antioxidant activity, and fiber, than flaxseed and barley flour fortified in the bread at the same percentages. Awika (2003) also reported that brown tannin and black sorghum brans contained higher ORAC antioxidant activity (2,400 and 1,008 umol trolox equivalent/g dry basis, respectively) than several high-antioxidant fruits, such as blueberries (87-873 umol TE/g) , plums (450-600 umol TE/g), and strawberries (356-400 umol TE/g) on a dry weight basis (shown in Table I). However, there is very little known about how other methods of bran production, such as roller-milling, would effect bran composition and functionality.

Extrusion Processing

Extrusion cooking is a high-temperature-short-time (HTST) process that has various applications, such as cooking, forming and expanding cereals, as well as texturizing proteins (O' Conner 1987) Extrusion minimizes time, energy and material costs, while allowing innovation in product manufacturing. Extrusion snack processing is shown in Table II.

TABLE I

Phenol Contents and Antioxidant Properties of Sorghum, Sorghum Products, Fruits, and Wheat Bran Measured by Three Methods[a]

Sample	ORAC[b]	ABTS[b]	DPPH[b]	Phenol[c]
White grain	22	6	6	3
White grain extrudate	26	7	6	3
White bran	64	28	21	6
Red grain	140	53	28	7
Red bran	710	230	71	20
Black 2001 grain	219	57	41	6
Black 2001 extrudate	94	37	32	5
Black 2001 bran	1,008	250	184	26
Hi Tannin grain extrudate	286	90	74	6
Hi Tannin bran	2,400	512	495	55
Sumac (brown) grain	868	226	202	23
Sumac bran	3,124	768	716	66
Blueberries[d]	87-873	--	--	--
Plums[e]	450-600	--	--	--
Strawberries[e]	356-400	--	--	--
Red winter wheat bran	80	--	--	--

[b]ORAC = oxygen radical absorbance capacity; ABTS = 2,2'-azinobis (3-ethyl-benzothialine-6-sulfonic acid); DPPH = 2,2-diphenyl-1-picrylhydrazyl; mmol TE/g DM basis

[c]mg GAE/g DM basis (Folin-Ciocalteu method)

[d]Blueberries – Moyer et al. 2002; ePlums & Strawberries – Wu 2000

[a]all values dry weight basis, Awika 2003

TABLE II

The Physiochemical Changes in Feed Material During Extrusion

Pressure	Extruder Zones	Action
ATM	Preconditioning	water uptake
	Feeding	compression/remove air/ add $H_2$0 - steam
5 – 10 ATM	Melting and Kneading	gelatinization/melting disruption of starch/ protein matrix
10^+ ATM	Final cooking	amorphous/ elastic dough with steam trapped in melted starch/ proteins
ATM (Drop in Pressure)	Die	expansion of steam/ cell structure development

Rooney 2001.

The fortification of extruded material with fibrous material to enhance product nutritional quality has been studied. Such studies include barley cereal blends with rice or wheat flour (Berglund et al. 1994), corn bran with corn meal (Mendonca et al. 2000) or wheat flour (Onwulata et al. 2001), sugar beet fiber and corn meal (Lue et al. 1991), and cassava bran with cassava starch (Hashimoto 2003). Fortified extrudates show increased soluble fiber content due to the degradation of non-starch polysaccharides (Guillon and Champ 2000; Rinaldi et al. 2001; Slavin et al. 2001) and the retention or increase of their original hypocholesterolemic effect (Kahlon et al. 1998).

Unfortunately, bran fortified extrudates have less desirable physical characteristics such as decreased expansion and increased bulk density at particular levels (Jin et al. 1994; Rinaldi et al. 2000). Bran-fortified extrudates usually have smaller air cells and thicker cell walls (Nelson 2001 b) than standard corn meal extrudates. Increased fiber to an optimum level reinforces extrudate structure and increases resistance to breakage (Nelson 2001 b; Rinaldi et al. 2001). However, adjusting levels of bran and extrusion conditions can increase product quality (Mendonca 2000; Hashimoto 2003).

An alterative to bran or fiber fortified extruded snacks, would be the use of whole grain cereals for extrusion. Although some studies have used whole- grain flours in extrusion (Dahlin and Lorenz 1992; Plavnik and Sklan 1995; Bjorck et al. 2003), there is very little data on whole grain extrusion for expanded snack processing. However, Acosta-Sanchez (2003) has reported that whole kernel white food-type sorghum can be used for producing successful snack food products. Whole sorghum kernels were extruded with less power and processed faster than corn meal. Also, sorghum tempered at 14% moisture produced whole sorghum extrudates closest to corn in expansion (Acosta-Sanchez 2003).

Summary

Specialty sorghums, which are rich sources of dietary fiber and antioxidants, have great potential for use in producing nutraceutical expanded snack products. Brown tannin and black sorghum brans have shown good product and sensory qualities in cookies and bread, yet there is little information on the use of specialty brown tannin and black sorghums for expanded snack processing. Whole kernel brown tannin and black sorghums have shown high antioxidant retention in extrusion processing. However, there have been no studies on the physical characterization of specialty sorghum extrudates in comparison to white food-type sorghum and corn meal extrudates. Specialty sorghums may produce extrudate snacks with acceptable, physical, and organoleptic qualities. Also, sorghum bran fortification of extruded specialty sorghums may produce value-added high fiber, high antioxidant snacks.

CHAPTER III

MATERIALS AND METHODS

Sorghum Samples

Raw samples - whole sorghum and corn meal. Tannin (CSC3xR28), black sorghum (Tx430), and white food grade sorghum (ATx631xR Tx436) varieties used in this study were grown at Texas A&M University in College Station, TX in 2001. These samples were extruded whole as whole kernels. Commercial snack corn meal (ADM, Chicago, IL) was used as a control. All grains were cleaned to remove chaff and stored in a freezer until used.

Processed samples – cracked sorghum and bran. Cleaned sorghum from each of the three sorghum varieties was used to produce cracked sorghum and bran. Sorghum from each variety was cracked into large grits using an attrition grinder (Glen Mills Inc., Maywood, N.J.). The grinder dial was closed at the reading of 11.25. The dial was slowly turned, until the ground material became coarser. The average dial setting for cracking the sorghums was one full turn and 15.25. Slight variations were made with the dial, so that the majority of sorghum kernels (depending on type) were just broken, not ground.

The cracked sorghums were then sieved for particle size distribution and all particles above No. 30 sieve were used for extrusion. Material loss for all cracked sorghum varieties for both experiments was less than 10% of total material.

Bran treatments used for the extrusion processes were obtained from both roller-milling (Chopin mill - Perten, Springfield, IL) and pericarp decortication (PRL Dehuller

- Nutana Machine Co., Saskatoon, Canada) processes**.** Sorghum kernels were tempered to 18% moisture to increase bran separation during roller-milling. Sorghum kernels were decorticated 2 to 2.5 min. to obtain optimal bran fraction.

Extrusion Processing and Experimental Design

The extrusion process flow chart is shown in Fig. 3. The production of bran and cracked sorghum materials and their use in the extrusion process shown in Fig.2. Moisture content (AACC method # 44-19, 1999) of whole sorghum, cracked sorghum, and bran materials were determined and used to temper each fraction to the desired percent moisture (AACC method# 26-95, 1999). Whole sorghum materials that were initially above 14% moisture, were dried in a circulation, baking oven at 50^{o}C for 12 hr; cracked sorghum and brans were dried at 50^{o}C for 5 hr. Extrudates were also dried in a circulation baking oven at 100^{o}C for 30 min and packaged in metallic packaging.

Experimental Design

1) Three kg samples of cracked tannin and white sorghums where substituted (% w/w) with exact percentages (0, 15, 30, and 50%) of bran (roller-milled or decorticated) and extruded. The extrudates were analyzed for physical, compositional, and phenolic characteristics. Four kg samples of whole sorghums were also extruded to compare whole and cracked extrudate physical characteristics, as well as to serve as a control. Corn meal was also used as a standard. Moisture content of all sorghum materials and corn meal was tempered to 13.5%.

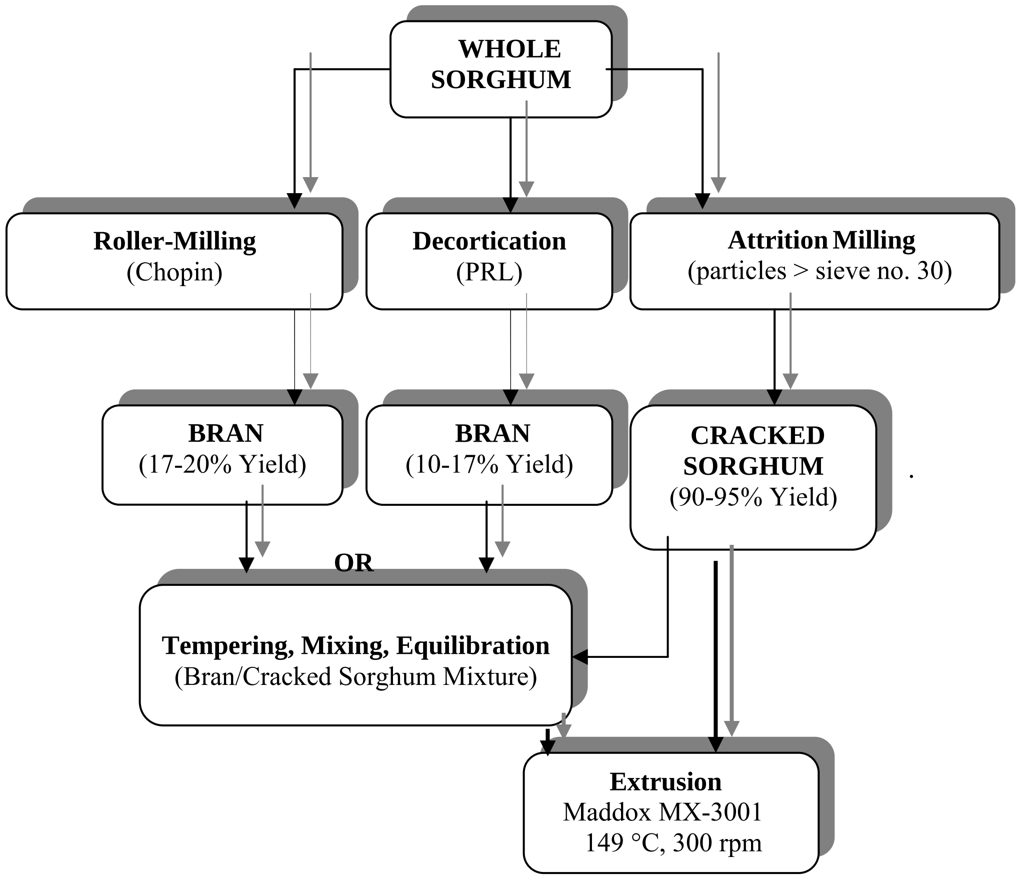


Fig. 2. Flowchart of bran and cracked sorghum production**.** Note: Bran and cracked sorghum tempered separately, then mixed and equilibrated.

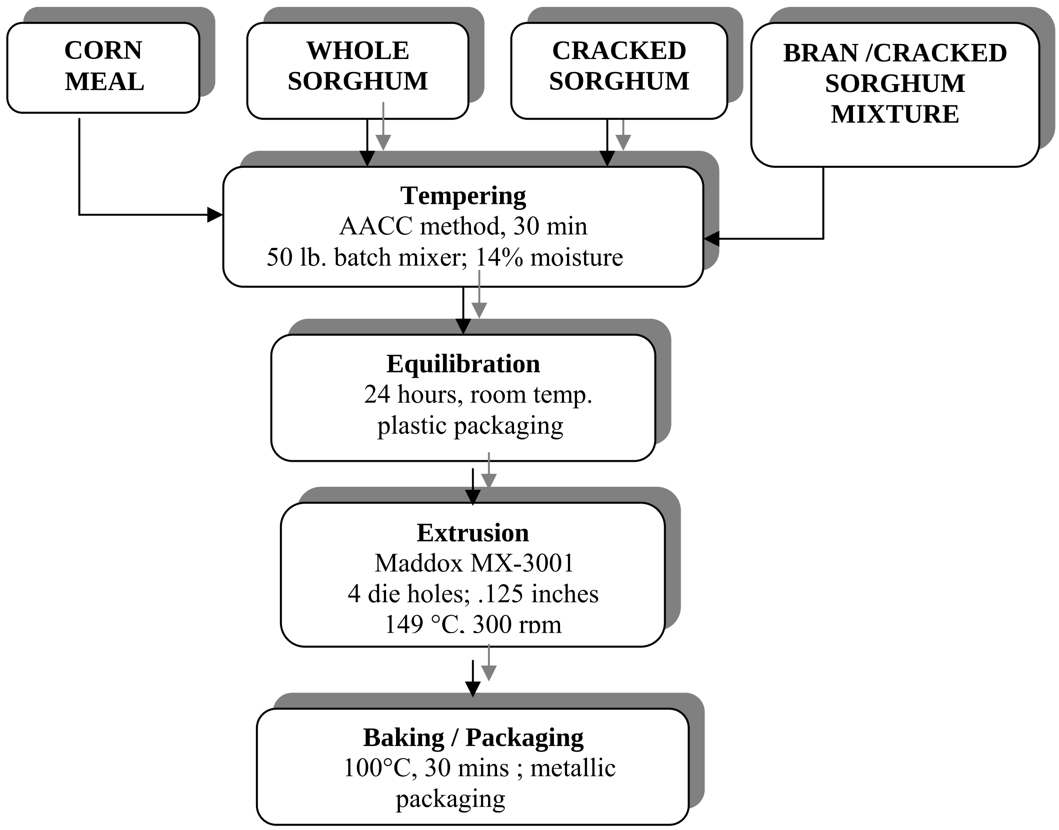


Fig. 3. Extrusion process flowchart.

2) Ten kg samples of whole and cracked tannin, black, and white sorghums were tempered to 14% moisture and extruded in duplicate. Cracked tannin and black bran fortification for this extrusion process was modified: instead of using direct weight percentage, bran was added using a baker's percentage. Four kg (40%) of bran was added to a 10 kg base (cracked sorghum) of the respective type. The actual percentage of bran found in the total 14 kg bran/cracked sorghum mixture was 28.5%, which was chosen as an "optimal" bran percentage. Corn meal was extruded as a standard. Moisture contents of all sorghum materials and corn meal was tempered to 14.0%.

Analysis of Raw Materials

Physical Dimensions of Sorghums. Tannin, black, and white sorghum kernels were evaluated using the Single Kernel Hardness Tester (Model SKCS 4100, Perten Instruments Inc., Reno, Nevada). Three hundred individual sorghum kernels were selected out and evaluated for average weight (mg), diameter (mm), hardness index, and class. Measurements were taken in triplicate for each sorghum type.

True Density. The densities of the whole sorghums were determined using the multipycnometer nitrogen displacement apparatus (Quanta Chrome, Syosset, N. Y.). Eighty grams of the grains were weighed and placed into the sample cell. Pressure readings were taken before and after nitrogen was introduced into the sample cell. Volume (cm^3) was determined with the following equation:

(1) $$\text{Volume } (cm^3) = Vc - [\ Vr\ a\ (P1/P2) - 1\ ]$$

Vc = Large sample cell vol. = 149.81; Vr = Large reference vol. = 71.6
P1 = Pressure reading 1; P2 = Pressure reading 2

True density values were reported in grams/cubic centimeter (g/ cm^3). Bulk density of whole and cracked sorghum material and bran were determined as described in (4 - page 28), primarily with test weight apparatus. Measurements were done in triplicate for each sorghum type and reported in kilograms/hectoliter (kg/hL).

Tangential abrasive decorticating device (TADD) Hardness. Whole kernel sorghum samples were separated into 12, 20 gram replicate samples. All samples were placed in the TADD (Model 4E – 115, Creative Technologies, I.C., Utah) simultaneously and decorticated for 4 mins. Samples were then re-weighed and percent removal was calculates as:

(2) % Removal = { [(Int. w – Dec. w)/ Int. w] a100 } a CF

Int. w = Initial sample weight; Dec. w. = decorticated kernel weight
CF = correction factor (original standard TADD hardness/new TADD hardness)

*Moisture. R*aw materials were ground in a UDY cyclone mill (model 3010-030, Udy Corporation, Fort Collins, CO), through a 1 mm opening screen. Moisture content of all raw materials, (as well as extrudates) was determined by modification of the AACC Method 44-19 (AACC 1999). Duplicate samples were dried at 130 °C for 24 hr in a forced air oven.

Proximate Analysis. Composition of sorghum grains and other sorghum fractions, whole unground sorghum, cracked sorghum, and decorticated bran were analyzed for crude protein (N x 6.25). Crude fiber and lipid content of each of these samples were evaluated using NIR (near-infrared reflectance). Sorghum dietary fiber was determined using the Prosky method (2000).

Particle Size Distribution. The particle size distribution of all bran and cracked sorghum fractions was determined in triplicate using U.S. standard testing sieves (Seedburo Equipment Company, Chicago, IL), no. 6, 8, 10, 12, 16, 18, 25, and 30. Sieve number 25 was not included in experiment 1 and sieve number 18 was not used for cracked tannin sorghum in experiment 1.

Analysis of Extrudates

Feed Rate. The feed rate of the extrusion material was determined by dividing the initial weight of the extrusion material by time needed for the material to pass completely through the extruder bin. Feed rate was reported in kilograms per hour (kg/ hr).

Specific Mechanical Energy. The specific mechanical energy (SME) was determined from this calculation:

(3) $$\text{SME} = (2\prod \text{ x T x RPM})/ \text{ feed rate}$$

∏ has the value 3.14. Torque is a measurement of force times distance and is expressed as pounds per feet (lb/ft) or newtons per meter (n/m). A U.S. electrical motor chart was used to convert amps recorded during the extrusion process to torque. The extruder revolutions per minute (RPMs) were held at a constant value of 300. Feed rate was determined as mentioned above. SME was reported in joules per gram (j/g).

Bulk Density. Extrudate bulk density (g/l) was determined in triplicate using this formula:

(4) $$\text{Bulk density} = \frac{(\text{container + sample weight - empty container weight})}{\text{container volume}}$$

Expansion Ratio. Extrudate radial expansion (cross section) width was measured in mm with the use of electronic calipers divided by the die diameter value (.125 inches or 3.18 mm). 15 individual extrudate measurements were taken of each extrudate type.

Texture Measurement. Extrudate texture were evaluated using the texture analyzer model TA.xT2 (Texture Technologies Corp., Scarsdale, NY/Stable Micro Systems, Godalming, Surrey, UK). The force in compression test was conducted with a metal needle probe. Post and pre test speeds were conducted at 0.5 mm/s, for a test distance of 15 mm, with a force of 1.49N. Extrudate hardness and force to break were determined.

Color Determination. The color of ground extrudates and their raw materials were obtained in duplicate using a hand-held colorimeter (CR-310, Minolta Col., LTD. Ramsey, NJ).

The standard tile: L = +97.48, a = -.89 and b = -0.86. Scale values are as follows:

L= 100, white	+a = red	+b = yellow
L= 0, black	-a = green	-b = blue

Environmental Scanning Electron Microscopy (ESEM). ESEM (Cereal Quality Laboratory, Texas A&M University, College Station, TX) pictures were taken of cross sections of cracked and whole tannin extrudates, and tannin extrudates containing 50% decorticated or roller-milled bran.

Analytical Procedures

Phenols. A modified Folin-Ciocalteu method (Kaluza et al., 1980) was used to determine total phenols in sorghum grains samples. A 0.2 ml aliquot of the sample supernatant was reacted at room temperature with 0.4 ml Folin-Ciocalteau reagent and 0.9 ml of 0.5 M ethanolamine for approximately 20 min. The absorbance of each sample solution was measured by scanning through a UV/VIS spectrophotometer (Cary 300 Bio, Varian Co., Walnut Creek, Ca) at 600 nm, and expressed as mg gallic acid (used in standard curve) per 100 g (dry weight basis).

Condensed Tannins. A modified vanillin-HCL method (Price et al. 1978) was used to determine tannin content. A 1.0 ml aliquot of the sample supernatant were mixed with 5 ml of vanillin reagent and a duplicate with 5 ml of 4% HCl in methanol (the blank), were reacted for 20 min. in a 30 °C water bath. Absorbance was read at 500 nm and sample values were determined by subtracting the blank readings from the sample readings. Results were expressed as mg of catechins (used in standard curve) equivalent per gram of sample (dry weight basis).

Antioxidant Activity Using the DPPH (2,2-diphenly-1- diphenly-1-picrylhydrazly) Method. The DPPH method of Brand-Williams et al. (1995) was modified by Awika (2003) for this assay. Half gram samples were extracted with 15ml of 70% acetone for 30 mins. decanted, and re-extracted (x2). The aqueous acetone samples extracts (150 ul) were mixed with 2850 ul of DPPH Samples were allowed to react for 8 hours, and absorbance was read at 515. Results were expressed as mg Trolox equivalents (used in standard curve) per gram of sample dry weight.

Statistical Analysis. SAS (SAS Institute Inc., Cary, NC) software was to determine Fisher's (LSD), and coefficient of variation (CV). Means and standard deviations were reported for some values.

CHAPTER IV

RESULTS AND DISCUSSION - PHYSICAL CHARACTERISTICS AND PROXIMATE ANALYSIS OF SORGHUMS

Physical Dimensions of Whole Grains

White (Tx631xTx436), tannin (CSC3xR28), and black Tx430 sorghum varieties varied in their physical kernel dimensions (Table III). Pictures of grains and cracked sorghums are shown in Fig. 4. Tannin sorghum kernels were lighter and smaller in diameter than white or black sorghums. Both white and tannin sorghums were classified as "hard" by the single kernel hardness tester. Chroma values show that white sorghums (ground), are lighter than tannin and black sorghum materials, respectively, which can be seen from natural observation. Black sorghums were classified as "mixed" by using the single kernel hardness tester, indicating that the black sorghum consisted of kernels varying from soft to hard endosperm.

White, tannin, and black sorghum kernels were also cut in half and examined subjectively, to determine endosperm structure. White sorghum kernels appeared to contain a large portion of corneous endosperm, surrounding a tightly packed soft endosperm center. Black sorghum kernels contained a large amount of soft, floury endosperm, and whole tannin sorghum contained an intermediate mixture between the two types. These factors were also reflected in the grains' true densities and decortication yields. White sorghum kernels were more dense and more resistant to

TABLE III
Physical Dimension of Sorghums[a]

Sorghum variety	Kernel[a] Weight (mg)	Diameter (mm)	Color[b] L Chroma	Moisture[c] (%)	Hardness Index	True Density (g/cm^3)	TADD Grit Decortication %	Class[d]
White Tx436xTX631	29.2b	2.2b	78.9a	10.4a	67.9a	1.39a	79.2a	Hard
Tannin CSC3xR28	26.4c	1.9c	66.1b	10.4 a	60.0b	1.38ab	76.5b	Hard
Black Tx430	37.8a	2.5a	60.1c	9.8 b	46.4c	1.37b	73.7c	Mixed
LSD (α = 0.05)[e]	1.2	0.05	0.0	0.4	0.7	0.02	2.5	-----

[a] Based on an average of 300 selected sorghum kernels

[b] Based on whole ground (1 mm screen) sorghum values

[c] Determined after grains were dried for 12 hr at 50°C in an forced air oven

[d] Classification of kernel hardness, based on hardness index with single kernel hardness tester.

[e] All means with similar letters in columns were not significantly different.

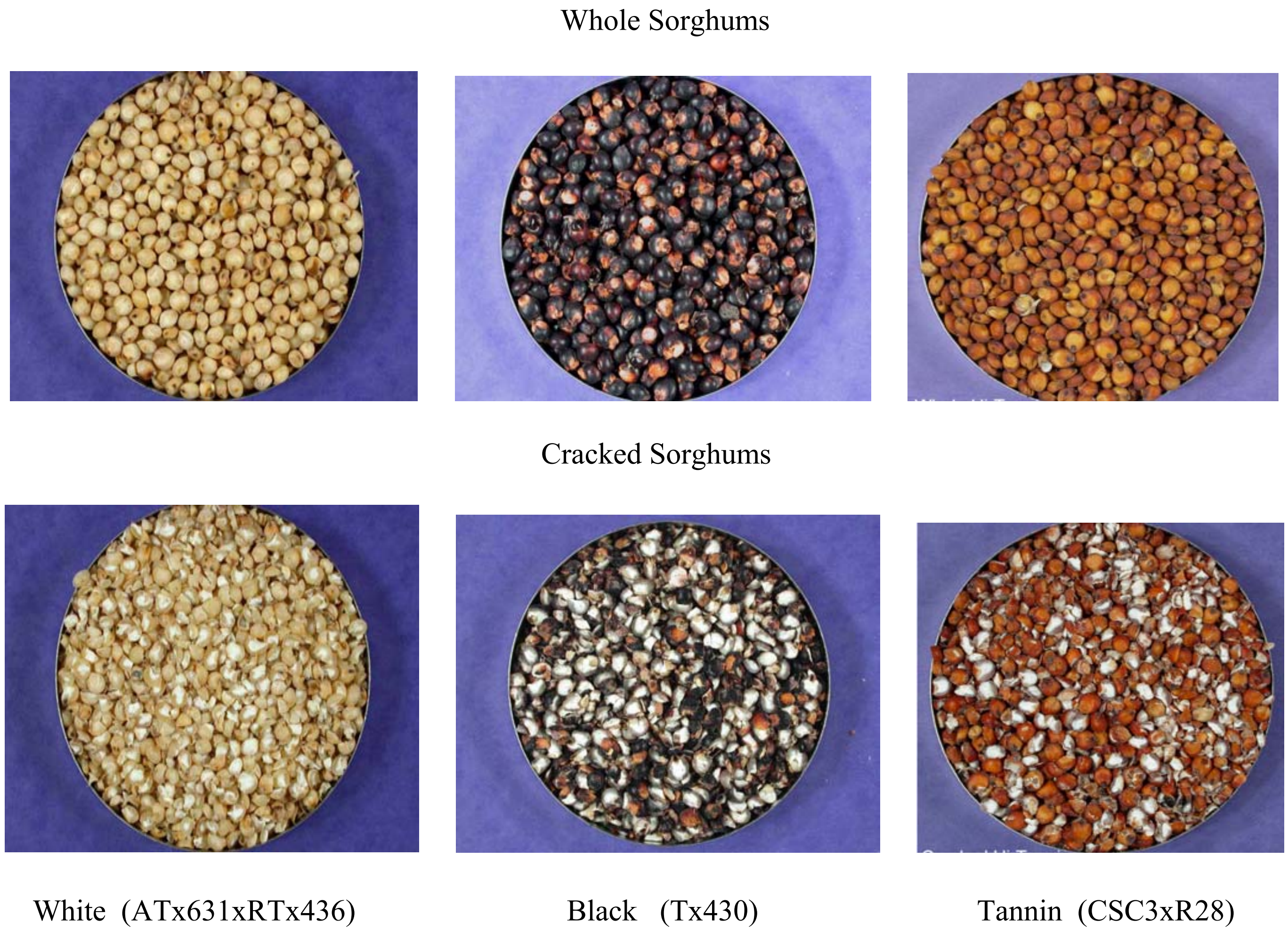


Fig. 4. Whole and cracked samples of white, black, and tannin sorghum varieties.

decortication than tannin and black sorghums, respectively. Awika (2000) reported that College Station grown white, tannin, and black sorghums have pericarp thicknesses of 2, 3, and 5 respectively, with a pericarp thickness number of 1=thin to 5=thick. Thicker pericarps such as contained in black sorghum kernels, are more easily removed during decortication, which increases decortication yield.

Bulk Densities of Whole and Cracked Sorghums

Cracking reduced the bulk density in material, in comparison to whole sorghum kernels (Table IV). The bulk densities of whole sorghums followed trends similar to their grain true densities, with white sorghums having higher bulk densities than tannin or black sorghums. The bulk densities of white and tannin cracked sorghums were statistically similar. Black cracked sorghum had the lowest bulk density of the grains, also confirmed by the grain's true density.

Particle Size Distribution of Cracked Sorghums

Grain hardness and kernel size may have affected the particle size distribution of cracked sorghums used in experiment 1 (Table V) and experiment 2 (Table VI). Attrition milling produced cracked white sorghum with a greater percentage of larger fractions than the cracked tannin sorghum. The total fines discarded during cracking of sorghums in experiment I were 8.3 for tannin sorghum and 3.3% for white sorghum, respectively, of their total materials. There was greater break-up of softer endosperm within the tannin kernel, which increased losses of fine particles.

In experiment II (Table VI), cracked sorghum was produced and sieved using the same procedure described in experiment I. However, sieve no. 25 was placed between

TABLE IV
Bulk Densities (kg/hL) of Cracked Sorghum Materials[a]

Treatment	Tannin	Black Tx430	White Tx436xTX631
Whole Sorghum	78.4a	71.3b	79.3a
Cracked Sorghum	66.7cd	63.9d	69.3bc

[a]All means with similar letters in columns were not significantly different. at LSD ($\alpha = 0.05$) = 3.2 kg/hL.

TABLE V
Particle Size Distribution (%) of Cracked Sorghum[a]
(Extrusion Experiment I)

Sieve Number	Tannin	White
No. 6	2.1	8.4
No. 8	55.4	67.1
No. 10	22.8	14.0
No.12	11.1	6.5
No. 16	8.6	4.0
Total	100	100
%Fines discarded	8.3%	3.4%

[a]Note: All small particles through sieve no.16 were discarded.

TABLE VI
Particle Size Distribution (%) of Cracked Sorghum [a]
(Extrusion Experiment II)

Sieve Number	Black	Tannin	White	LSD (α= 0.05) [b]
No. 6	20.6b,A	4.2e,B	0.6e,C	2.4
No. 8	53.5a,A	47.4a,B	51.9a,A	3.9
No. 10	14.1c,C	24.1b,B	28.1b,A	1.2
No.12	6.1d,B	12.0c,A	11.7c,A	1.1
No. 16	3.5e,C	8.3d,A	6.1d,C	1.2
No. 18	0.8ef,AB	1.6f,A	0.6e,B	0.8
No. 25	1.2f,AB	2.2f,A	0.6e,B	1.2
Total	100	100	100	
LSD (α = 0.05) [b]	2.4	1.5	1.0	
%Fines discarded	0.5%	2.7%	2.0%	

[a] Note: All small particles through sieve no. 30 were discarded.

[b] All means with similar letters in columns (lowercase) and rows (capitalized) were not significantly different.

However, sieve no. 25 was placed between sieve no. 18 and 30 to improve measurement of particle size distribution. According to the current American Association of Cereal Chemist definition of whole grain foods and ingredients, whole grain products must retain the same proportions of brain, germ, and endosperm as the original grain (AACC 2004). All cracked sorghum fractions through sieve no. 25 were discarded.

Losses from sifted cracked white, tannin, and black sorghums were 2.0, 2.7, and 0.5%, respectively. Black cracked sorghum was coarse compared to tannin and white sorghums, due to their larger kernel size. White cracked sorghums were slightly coarser than tannin sorghums, possibly due to larger kernel size and/ or harder endosperm.

Bulk Densities of Roller-milled and Decorticated Brans

The densities of the sorghum brans were affected by the type of process in which they were produced (Table VII). Decorticated brans were more dense than roller-milled brans. White sorghum brans (roller-milled and decorticated) were more dense than tannin brans, while the densities of tannin and black decorticated brans were statistically similar. White sorghum brans, in general, had higher bran density than tannin and black sorghum brans, because of it's brittleness and it's tendency to break into small pieces, that packs together tightly (Awika 2000).

Particle Size Distribution of Roller-milled and Decorticated Brans

The particle size distributions of the decorticated and roller-milled brans produced for extrusion experiment I (Table VIII) differed in their percentages of fine and coarse particles. The roller-milling process (Chopin) produced bran with a larger percentage of coarse particles than the decortication process (PRL Dehuller). Tannin and white sorghum decorticated bran (PRL Dehuller) yields were 14.4 and 10%, respectively, while the roller-milled (Chopin) bran yields for tannin and white sorghums were 22.6 and 15.1%. While the decortication process uses abrasive disks to "sand" off the outer pericarp, seed coat, and aleurone layers (the bran), the roller-milling process crushes the sorghum kernel during the first roller break, producing separate bran and

TABLE VII
Bulk Densities (kg/hL) of Brans Prepared by Roller-Milling or Abrasive Decortication[a]

Treatment	Tannin	Black Tx430	White (Tx436xTX631)
Decorticated Bran	36.8b	37.0b	38.2a
Milled Bran	30.3d	------	35.9c

[a]Means with similar letters were significantly different at LSD ($\alpha = 0.05$) = 0.6 kg/hL.

endosperm fractions. However, roller-milled bran may still contain a considerable amount of endosperm, unless it's sent through additional breaking steps for purification (Hoseney 1998).

Both processes showed that tannin sorghum produced higher yield of bran than white sorghum. The thinner pericarp fraction of the white sorghum produces less bran (in weight) than the tannin sorghum for equal amounts of sorghum.

Also, grains with high percentages of corneous endosperm, have pericarps that more cleanly separate from intact endosperm (Rooney & Miller 1982). Grains with

TABLE VIII
Particle Size Distribution (%) Among Brans From Different Processing Methods Used in Extrusion Experiment I

	Tannin Sorghum Bran		White Sorghum Bran		
Sieve Number	**PRL[a]**	**Chopin[b]**	**PRL[a]**	**Chopin[b]**	LSD(α = 0.05)[c]
No. 6	0.05f,A	0.0f,A	0.0d,A	0.0c,A	0.1
No. 8	0.6f,B	0.8f,AB	0.9d,A	0.4c,B	0.4
No. 10	0.4f,B	4.1e,A	1.1d,B	1.0c,B	1.6
No.12	6.5e,B	23.8b,A	10.1c,AB	13.0b,B	8.7
No. 16	36.1a,B	53.5a,A	52.2a,A	57.8a,A	10.5
No. 18	17.9c,A	4.3d,B	3.5d,B	3.9c,B	5.7
No. 30	25.1b,AB	10.8c,C	20.1b,AB	17.4b,B	5.9
Bottom	13.4d,A	2.7e,B	12.1c,A	5.9c,B	5.2
Total	100	100	100	100	
LSD (α = 0.05)[c]	4.5	1.4	4.4	7.0	
% Yields[d]	15.1%	22.6%	10.0%	14.4%	

[a]Denotes bran derived from kernel decortication (PRL Dehuller).
[b]Denotes bran produced by roller-milling process (Chopin mill). Milled sorghum kernels were initially tempered to 18% moisture.
[c]Means with similar letters in columns (lowercase) or rows (capitalized) are not significantly different.
[d]Yields of bran derived from decortication and roller-milling.

floury endosperm, however, tend to break during decortication, giving a higher percentage of fine endosperm particles mixed in with the bran fraction (Eggum et al. 1982). This may explain the higher yields for tannin bran compared to white sorghum bran.

In experiment II (Table IX), the black sorghum bran had similar particle distribution to tannin sorghum bran. Decorticated bran yields for tannin and black sorghums were 11.0 and 16.8%, respectively. The larger, more readily removable pericarp fraction of the black sorghum (Awika 2000) contributed to a high yield. Again, factors such as sorghum endosperm composition, pericarp thickness, and milling process can affect bran particle size, density, and yields. Bran treatments are shown in Fig. 5.

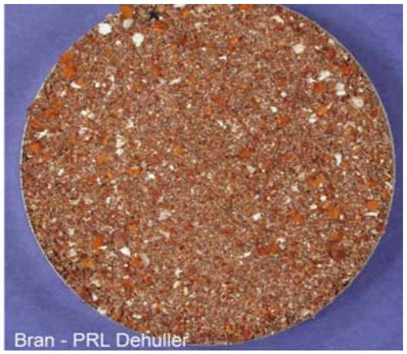
Proximate Analysis and Dietary Fiber of Raw Sorghum Materials

Protein and lipid contents (Table X) of the white, tannin, and black whole sorghums agree with values reported by Awika (2000) and Zelaya-Montes (2001). White sorghum materials were lower in ash, crude fiber, and dietary fiber than black and tannin sorghums, respectively. However, black decorticated bran showed slightly higher values over tannin decorticated bran for ash, crude fiber and dietary fiber components. Decorticated brans of white and tannin sorghums were higher in ash, crude fiber, and dietary fiber (tannin only), than their roller-milled brans.

TABLE IX
Particle Size Distribution (%) of Black and Tannin Bran Used in Extrusion Experiment II

Sieve Number	Black	Tannin	LSD (α = 0.05)[a]
No. 6	0.2fe,A	0.2c, A	0.3
No. 8	2.3fe,A	0.9bc,B	0.4
No. 10	7.9dc,A	3.2bc,A	5.6
No.12	41.4a,A	40.7a,A	12.5
No. 16	33.5b,A	40.4a,A	20.2
No. 18	4.1de,A	4.6bc,A	5.6
No. 25	9.4c, A	8.5b,A	1.9
No. 30	0.1e, A	0.1c,A	0.1
Bottom	1.1e, A	1.4c,A	1.5
Total	100	100	
LSD (α = 0.05)[a]	3.9	8.1	
%Yield [b]	16.8%	11.0%	

[a]Means with simular letters in columns (lowercase) or rows (capitalized) are not significantly different.
[b]Yields of bran derived from decortication.



Tannin Decorticated Bran

Black Decorticated Bran

White Decorticated Bran

Tannin Roller-milled Bran

Corn Meal

White Roller-milled Bran

Fig. 5. Photos of sorghum types and roller-milled and decorticated brans and corn meal.

TABLE X

Percent (%) Proximate Analysis Values and Dietary Fiber Levels for Raw Sorghum Materials[a] (DMB)

Sample and Treatment	Protein[b]	Lipids[c]	Ash[c]	Dietary Fiber[d]	Crude Fiber[c]
White sorghum, whole	10.1g	3.3c	1.0h	6.3	2.0e
Tannin sorghum, whole	12.0d	3.2cd	3.6e	11.1	4.1d
Black sorghum, whole	15.5b	3.1d	3.5e	9.8	2.2e
White sorghum, cracked	9.3h	3.4bc	1.4h	---	2.4e
Tannin sorghum, cracked	10.8f	3.5b	3.7e	10.2	4.8d
Black sorghum, cracked	16.0a	3.1d	3.1f	---	2.1e
White sorghum, roller-milled bran	12.0d	3.7a	2.6g	---	6.0c
Tannin sorghum, roller-milled bran	11.6e	2.8e	8.2c	29.4	7.6b
White sorghum, decorticated bran	13.8j	3.3c	4.9d	38.3-41.3	6.4c
Tannin sorghum, decorticated bran	8.8i	2.7e	10.5b	40.3-45.0	11a
Black sorghum, decorticated bran	13.8c	2.7e	12.6a	43.4-45.3	11.2a
LSD $(\alpha = 0.05)$[e]	0.4	0.2	0.3	----	0.8

[a]All values are given on a dry matter basis (DMB) for sorghums from the 2001 cultivars.
[d]Determined by Dumas Nitrogen
[c]Determined by Near Infrared Spectrophotometer (NIR)
[d]Determined by Prosky method (2000); certain values given in the dietary fiber ranges for brans were obtained from Gordon (2001).
[e]All means with similar letters are not significantly different.

CHAPTER V

RESULTS AND DISCUSSION –EXTRUSION EXPERIMENT I

Extrusion Characteristics of Whole; Cracked Sorghum and Corn meal Extrudates

Acosta-Sanchez (2003) mentioned in his work with white food-type sorghum, that the Maddox MX-3001 high-shear extruder has the ability to produce quality extrudates directly from whole, unground sorghum kernels. Tannin and white sorghums kernels were also cracked to determine if extrusion efficiency of the whole would be increased. The cracked sorghum also acted as a carrier for bran in the extrusion process

Extrusion process data gathered from whole and cracked sorghums are shown in Table XI. Whole unground sorghums had higher feed rates than cracked sorghums. However, the whole sorghums generated less specific mechanical energy than the cracked sorghums. The residence time of extruded materials is affected by the material feed rate and extruder screw speed (Ilo et al. 1999; Guha et al. 2003). In this experiment, the extruder screw speed was held at a constant 300 rpm and the material was fed manually into the extruder. The cracked sorghum material probably had a higher volume which increased residence time in the extruder. The increased specific mechanical energy of the cracked sorghum increased specific mechanical energy, which in turn increased the degree of starch gelatinization in the extrudate. The increased residence time of the cracked sorghum in the extruder caused more complete breakdown and gelatinization of the starch granules than in the whole sorghum kernels.

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TABLE XI
Feed Rate (kg/hr) and Specific Mechanical Energy (SME) of Whole and Cracked Sorghums[a] for Extrusion Experiment I

	Feed Rate (kg/hr)		SME (J/g)	
Sorghum/Treatment	**Whole**	**Cracked**	**Whole**	**Cracked**
White	160.1	148.1	227.7	275.5
Tannin	151.9	143.7	215.8	320.4
Mean[b]	156.0	145.9	221.8	298.0
Standard Dev.	5.8	3.1	8.4	31.7

[a]Values based on single observation from single extrusion run.
[b]Mean is the average under treatment type (whole or cracked).

The slight differences in the whole kernel and cracked sorghum feed rates and specific mechanical energy affected their extrudates' (Fig. 6) bulk densities, expansion ratio, and breaking force (Fig. 7-9). Values for corn meal extrudates are also included for standard comparison. Sorghum extrudates were more dense, less expanded, and harder than cornmeal extrudates. The cornmeal was highly refined (lower ash, pericarp, lipids, etc.) composed predominately of starch for maximum starch gelatinization and extrudate expansion.

Cracked sorghum extrudates were less dense, more expanded, and required less force to break, than whole sorghum extrudates. Besides SME, it is also possible that the increased physical exposure of cracked sorghum endosperm to extrusion conditions, increased granule gelatinization and expansion. ESEM micrograph pictures (Fig. 10) reveal that whole (unground) extrudates contain more ungelatinized endosperm, while cracked extrudates contain larger air cell and cell wall formation. The enclosed endosperm content of the whole sorghum may not have been efficiently and thoroughly heated, in comparison to pre-processed and broken, cracked sorghum kernels. Breaking the sorghum kernels allowed fewer starch granules to be "hidden" and unprocessed during extrusion.

Tannin and white sorghum extrudates (whole and cracked treatments) had similar values for bulk density and expansion ratio measurement. However, the break force of extrudates varied more. Again, the specific mechanical energy of the extruder while forming the extrudate, gives insight to these characteristics. Studies on rice (Guha et al.

White Whole Extrudate

Corn Meal Extrudate

Tannin Whole Extrudate

White Cracked Extrudate

Tannin Cracked Extrudate

Fig. 6. Extrudates prepared from whole or cracked, white or tannin sorghums and corn meal.

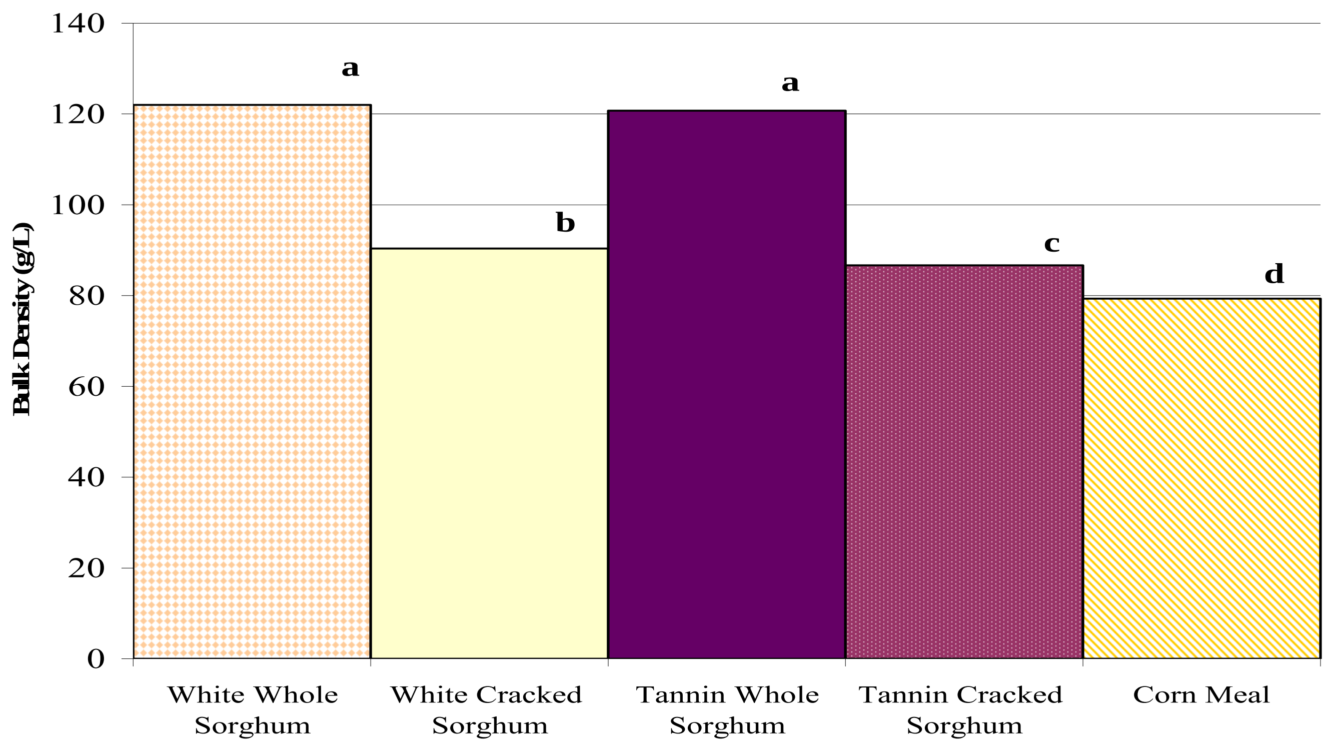


Fig. 7. Bulk density (g/L) of extrudates prepared from white or tannin, whole or cracked sorghums; corn meal. Note: LSD ($\alpha = 0.05$) = 2.0 g/L; means with same letters are not significantly different.

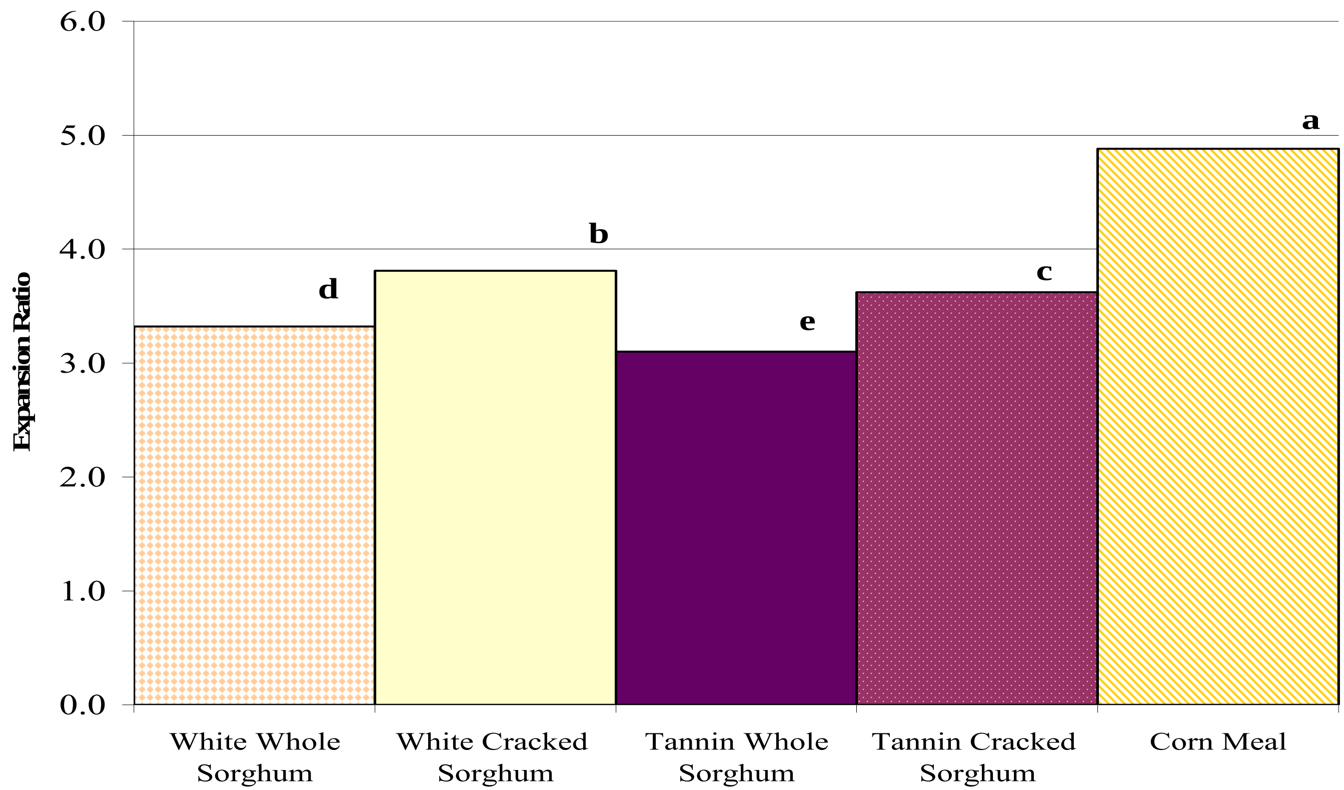


Fig. 8. Expansion ratio of extrudates prepared from white or tannin, whole or cracked sorghums; corn meal. Note: LSD ($\alpha = 0.05$) = 0.2; means with same letters are not significantly different.

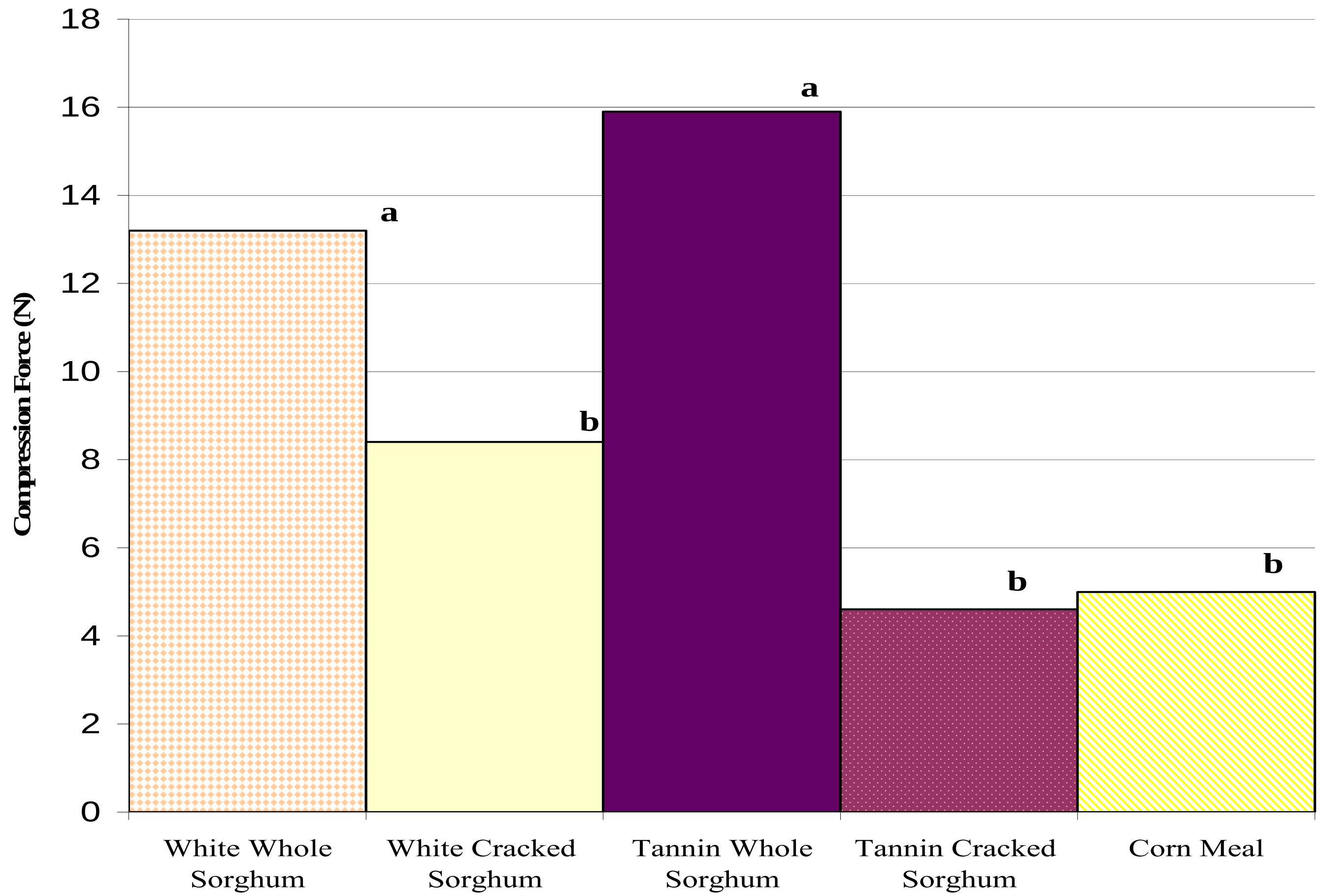
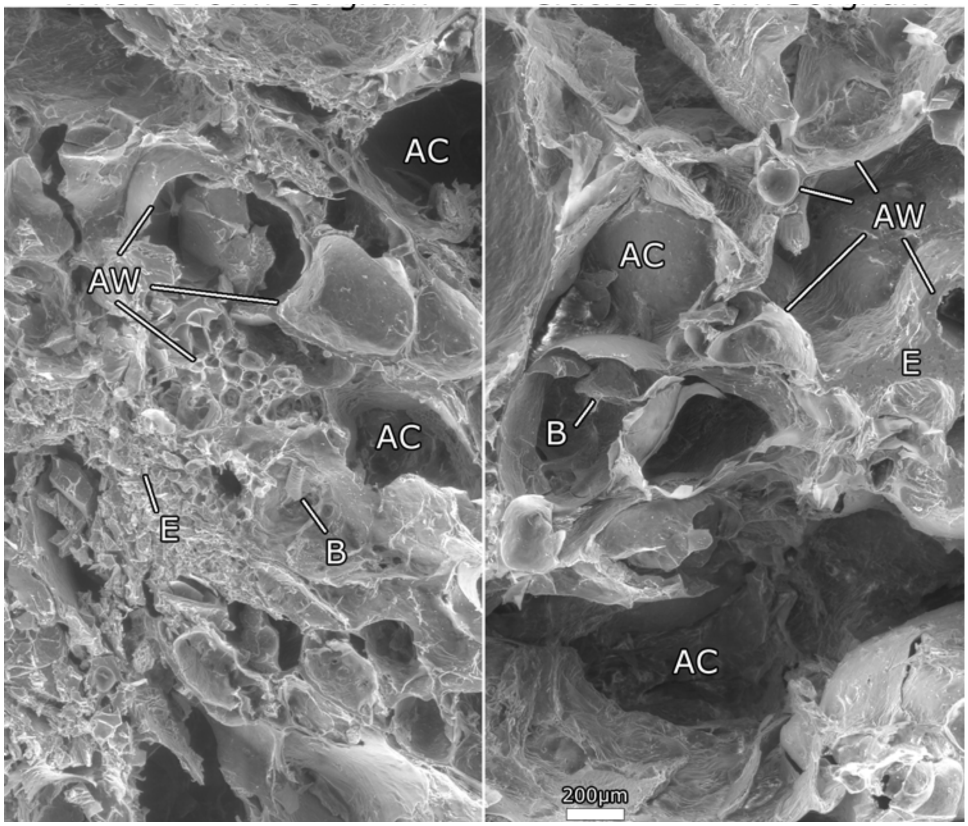


Fig. 9. Compression force (N) of extrudates prepared from white or tannin, whole or cracked sorghums; corn meal. Note: LSD ($\alpha = 0.05$) = 4.0 N; means with same letters are not significantly different.



Whole (Unground) Sorghum Extrudate Cracked Sorghum Extrudate

Fig. 10. ESEM micrograph photos of interior cross sections of tannin extrudates. Note: AC = air cell, AW = air cell wall, B = bran (pericarp), E = endosperm.

2003) and barley flours (Baik et al. 2004) have shown that extruded grain materials with high SME generate high pressure and barrel temperature, which in turn lowers product density and increases extrudate expansion. Thus, extrudate break force (force of compression) is often directly correlated to extrudate bulk density (Ilo and Berghofer 1999) and is inversely correlated to extrudate expansion ratio (Camire et al. 1991; Onmulata et al. 2000).

Extrusion Characteristics of Bran Fortified Sorghum Material and Extrudates

Cracking the sorghum increased desirable extrudate characteristics; therefore, cracked sorghum kernels were used when bran was added. Only tannin and white sorghums were used in this experiment. Cracked sorghums were blended in weight percentage with their respective roller-milled and decorticated brans at 0, 15, 30 and 50%. Thus, the 50% level contained 50% bran and 50% cracked grain.

Table XII shows the feed rate of the extruded material. Tannin roller-milled and decorticated brans were added to equal portions of tannin cracked sorghum, and the same was done for the white cracked sorghums and brans. Cracked tannin and white sorghum material as “0% Bran” had no bran added; they are same materials as shown in Fig. 7-9; Table XI. The feed rates of the extruded material decreased with bran addition. The feed rate of the bran blends decreased mainly due to increased bulk of the feed stocks.

The SME of the bran fortified materials, also decreased with the addition of increased bran levels (Table XIII). Almost any non-starch such as lipids (Ilo et at 1999), proteins (Onwulata et al. 2001), fiber and emulsifiers (Hu et al. 1993) decrease SME,

TABLE XII
Feed Rate (kg/hr) of Bran Substituted Sorghum Material[a]

	Bran Substitution			
Treatment	**0%**	**15%**	**30%**	**50%**
[b]Wht. + Wht. Milled Bran	148.1	155.2	140.6	120.0
Wht.+ Wht. Dec. Bran	148.1	135.8	----	----
[b]T + T. Milled Bran	143.7	135.3	142.9	120.0
T + T Dec. Bran	143.7	131.4	141.7	120.0
Mean[c]	145.9	139.4	141.7	120.0
Standard Dev.	2.5	10.7	1.2	0

[a]Values based on single observation from single extrusion run.
[b]Wht = white sorghum; T = tannin sorghum; Dec = decortication-derived bran
Each bran is added to its own respective sorghum type.
[c]Mean is the average of sorghum blends at a particular percentage of bran substitution.

TABLE XIII
Specific Mechanical Energy (J/g) of Bran Substituted Sorghum Material[a]

	Bran Substitution			
Treatment	**0%**	**15%**	**30%**	**50%**
Wht. + Wht. Milled Bran	206.8	197.4	207.3	124.2
Wht.+ Wht. Dec. Bran	206.8	223.3	----	----
T + T. Milled Bran	247.7	210.5	139	121.4
T + T Dec. Bran	247.7	230	179.9	151.8
Mean [b]	227.25	215.3	175.4	132.5
Standard Dev.	23.6	14.4	34.4	16.8

[a]Values based on single observation from single extrusion run.
[b]Wht = white sorghum; T = tannin sorghum; Dec = decortication-derived bran
Each bran is added to its own respective sorghum type.
[c]Mean is the average of sorghum blends at a particular percentage of bran substitution.

when all other extrusion factors are held constant. Hu et al. (1993), Singh et al. (1998), and Ilo et al. (1999) all give indications these materials decrease the melt viscosity in the extruder, which in turn, decreases torque, which is highly correlated to SME. Melt viscosity should not be confused with intrinsic viscosity: Intrinsic viscosity involves the internal breakdown and degradation of starch granules, while melt viscosity describes the shearing, mixing, and pressure involved in cooking the extrusion material. Tannin roller-milled and decorticated bran fortified extrusion materials had decreased SME at each level of bran substitution, with the greatest decrease in SME occurring between 15 and 30% of bran substitution for tannin treatments.

Physical characteristics of the bran fortified extrudates (shown in Fig.11 and 12), where affected predominately bran dietary fiber and endosperm starch content and inherent grain composition. Dietary fiber values were calculated from values for grains and bran shown in Table X. Values for tannin extrudates fortified with 28.5% decorticated tannin bran from extrusion experiment II were also compared with bulk density, expansion ratio, and break force data (Fig. 13, 14, and 15) gathered from experiment I fortified extrudates.

Bulk densities of all sorghum extrudates (Fig. 13) increased with increasing fiber content. Extrudates containing tannin roller-milled bran had the lowest overall bulk densities, followed by those containing white roller-milled, tannin decorticated, and white decorticated bran, respectively. Roller-milled bran seemed to aid in forming and supporting the extrudate cell wall structure (Nelson 2001 b), due to less fiber content to interrupt air cell formation. A combination of lower fiber and higher starch content in the roller-milled treated brans, allowed the roller-milled bran fortified materials more to gelatinize more fully than the feed blends produced from the decorticated bran. The decorticated bran packed together tightly while the extrudate was forming, reducing air cell and cell wall formation, resulting in a more dense extrudate mass (Fig. 16).

It is uncertain why the tannin extrudates had lower bulk densities than white sorghum extrudates for both roller-milled and decorticated bran treatments; the initial densities of the grains and starch content in the brans may have been a factor. All sorghum extrudates had higher bulk densities than the corn meal extrudates. The composition of the corn meal is predominately starch, which when expanded, produces an extrudate with a large network of air cells that is very light. Whole sorghum contains more oil and fiber with less starch which increases the bulk density of the sorghum extrudates. However, the bulk density for whole white sorghum extrudates decrease with increased decortication up to 20% (Acosta-Sanchez 2003). Although decortication would decrease extrudate density, it would also remove the bran, which is responsible for the dietary fiber and antioxidant content found in tannin and other sorghum types. Oddly, the extrudates of tannins substituted with 28.5% decorticated bran had very low bulk density similar to the corn meal extrudate, and lower than all other bran fortified extrudates.

Several studies have shown that the expansion ratio of the extrudates (Fig. 15) decrease with increasing fiber content (Berglund et al. 1994; Rinaldi et al. 2000; Hashimoto and Grossman 2003). Cracked sorghum extrudates (at 0% bran addition), had initial expansion ratios greater than whole sorghum extrudates, however, all treatments

Whole Unground Sorghum (Wht.)

Cracked Sorghum (WC)

85% WC/ 15% Wht. Milled Bran

85% WC/ 15% Wht. Dec. Bran

70% WC/ 30% Wht. Milled Bran

70% WC/ 30% Wht. Dec. Bran

50% WC/ 50% Wht. Milled Bran

50% WC/ 50% Wht. Dec. Bran

Fig. 11. Cracked white sorghum extrudates substituted with roller-milled and decorticated white sorghum bran.

Whole Unground Sorghum (T)

Cracked Sorghum (TC)

85% TC/ 15% Tannin Milled Bran

85% TC/ 15% Tannin Dec. Bran

70% TC/ 30% Tannin Milled Bran

70% TC/ 30% Tannin Dec. Bran

50% TC/ 50% Tannin Milled Bran

50% TC/ 50% Tannin Dec. Bran

Fig. 12. Cracked tannin sorghum extrudates substituted with roller-milled and decorticated tannin sorghum bran. Note: In pictures, C = Chopin mill (brans derived from the chopin mill), and P = PRL Dehuller (for decorticated bran).

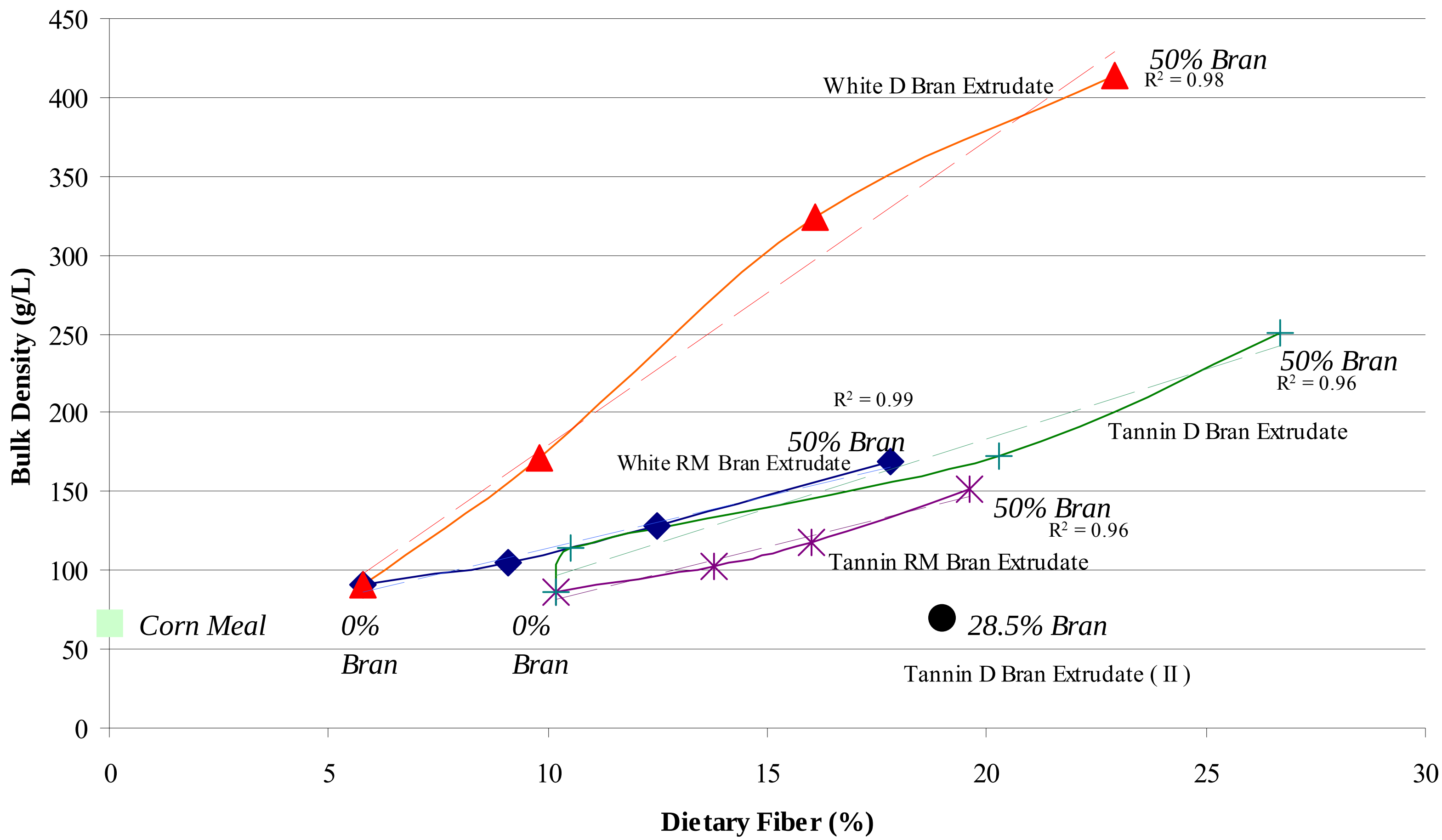


Fig. 13. White and tannin extrudate bulk density (g/L) corresponding to the addition of dietary fiber with 0-50% bran (roller-milled = RM) or (decorticated =D) fortification. Note: All brans added are derivatives of their sorghums; overall LSD (α = 0.05) = 4.2 g/L; tannin bran fortified extrudate (experiment II) data also shown; corn meal extrudate bulk density: 79.3 g/L.

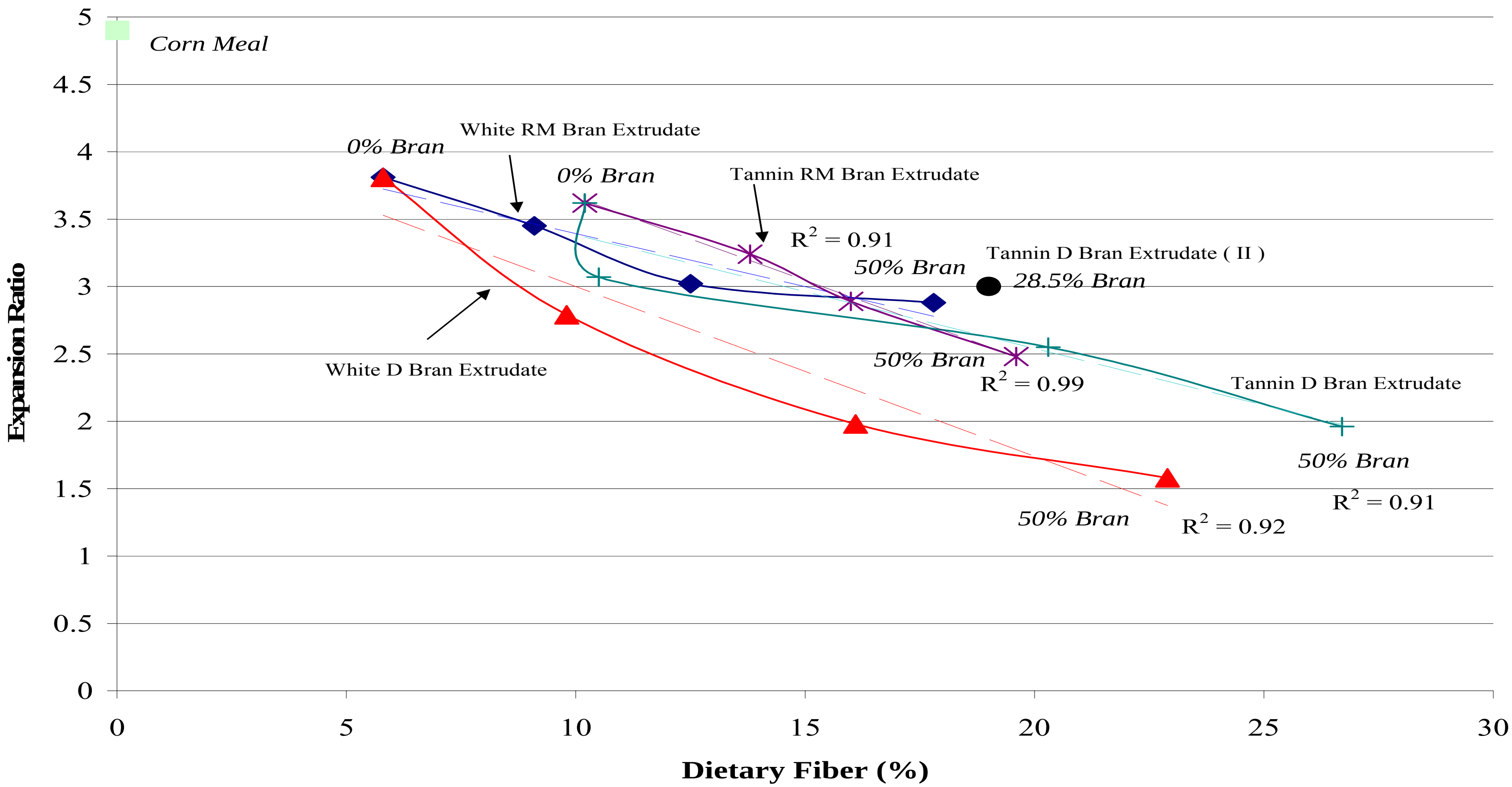


Fig. 14. White and tannin extrudate expansion ratio corresponding to the addition of dietary fiber with 0-50% bran (roller-milled = RM) or (decorticated = D) fortification. Note: All brans added are derivatives of their sorghum; overall LSD (a < 0.05) = 4.2; tannin bran fortified extrudate (experiment II) data also shown; corn meal extrudate expansion ratio: 4.9.

showed that extrudates decreased in expansion linearly (average r^2 value = 0.96) with increased fiber in the blends. White roller-milled bran fortified extrudates showed the greatest expansion, followed by tannin roller-milled, tannin decorticated, and white decorticated bran extrudates, respectively.

Decorticated bran's higher percentage of fine particles also may compound the decrease in extrudate expansion with bran. de Kock (1999) found that brown bread made with the addition of bran with fine particles, also decreased bread loaf volume. The lower density and/or larger, flaky, shape of the coarse bran helped encapsulate air during bread making, allowing for a more open structural formation and volumetric expansion, as compared to the dense, concentrated action of fine-particle bran. Ozboy and Kokshel (1997) also reported that coarse wheat bran had a strengthening effect on dough rheology and baking quality. However, the tannin extrudates fortified with 28.5% decorticated bran had very low bulk density, which did not follow the trends seen in experiment one.

Similar explanations can be given for the extrudates' bulk densities can also be applied to their expansion. Bran particle size aside, white sorghum extrudates produced from blends of roller milled bran, had the lowest fiber content of all the sorghum treatments, and thus had the greatest expansion followed by extrudates containing tannin roller-milled bran, and those containing tannin decorticated bran, and white sorghum decorticated bran, respectively.

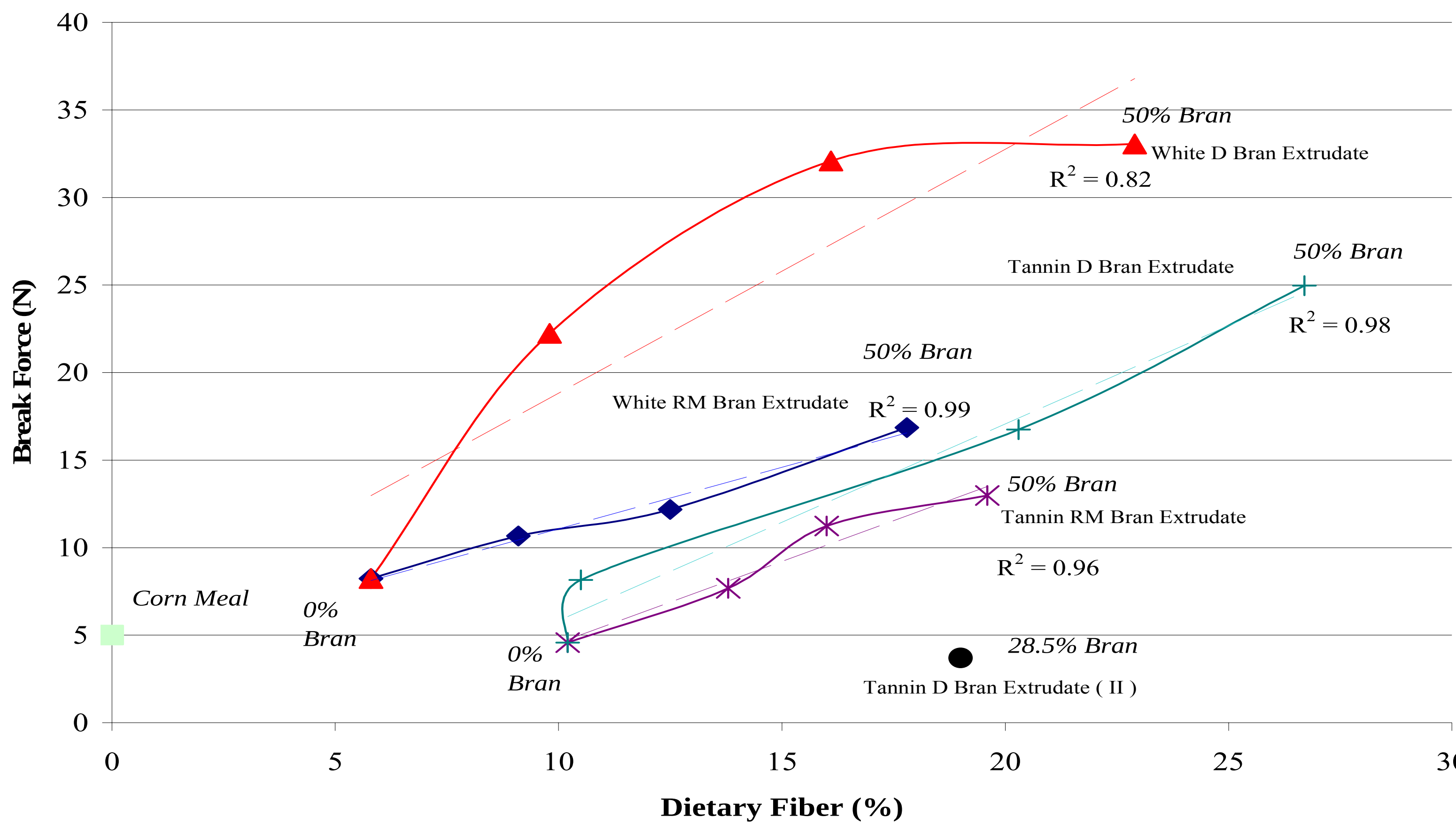
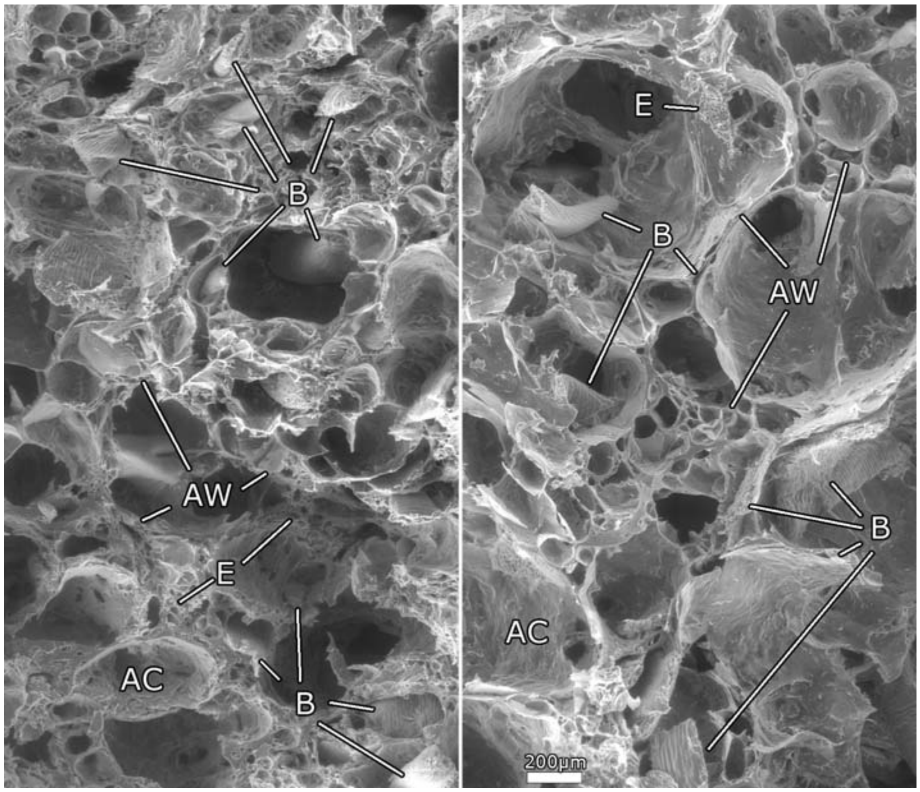


Fig. 15 White and tannin extrudate break force (N) corresponding to the addition of dietary fiber with 0-50% bran (roller-milled = RM) or (decorticated = D) fortification. Note: All brans added are derivatives of their sorghums; overall LSD (α = 0.05) = 4.2 N; tannin bran fortified extrudate (experiment II) data also shown; corn meal extrudate break force: 5.0 N.



Decorticated Bran Extrudate Roller-milled Bran Extrudate

Fig. 16. ESEM micrograph photos of interior cross sections of tannin extrudates containing 50% bran by weight. Note: AC = air cell, AW = air cell wall, B = bran (pericarp), E = endosperm.

Interestingly, white sorghum extrudates produced from decorticated bran blends, (which had slightly lower dietary fiber content than the tannin extrudates produce with decorticated bran) had very severe decreases in expansion with a fiber content between 16 and 23 % (30 and 50% bran), while tannin decorticated bran extrudates retained better expansion even with fiber content between 20 and 27% (30 and 50% bran).

While the tannin decorticated bran contains slightly more fiber than the white decorticated bran (Table X), it also contains more endosperm starch that acts to weakly counter the decreasing effect that added fiber has on expansion. According to Lai et al. (1989), the addition of extra flour (starch + gluten) is often a remedy used to compensate for the "bran effect" in bread making. Increasing starch content in extruded grain/bran blends may also compensate for decreased expansion caused by fiber content. White sorghum decorticated bran contained very little starch, because it's endosperm is more resistant to breakdown, than the tannin sorghum. Factors in composition of the white decorticated sorghum bran, other than endosperm starch or fiber, such as lipids and protein (Table X) may also account for decreased extrudate expansion.

As with the trends shown for extrudate bulk density and expansion, extrudate break force increased with increased fiber content (Fig. 15). Several studies show that increased bran (or fiber) content increases extrudate strength (Anderson et al. 1981; Mendonca et al. 2000; Rinaldi et al. 2000). Less force was required to rupture extrudates prepared using roller-milled vs. decorticated bran. Extrudates containing tannin roller-milled bran had the lowest breaking force for all treatments at each level of bran. Break force increased for extrudates containing white roller-milled, tannin roller-milled, tannin decorticated, and white decorticated bran extrudates, respectively. Factors such as original grain endosperm hardness, bran fiber and starch content, and bran particle size affect the hardness of extrudates.

Again, experiment II tannin extrudates substituted with 28.5% decorticated bran, give results differing from the trend, with a very low break force in comparison to all other bran fortified treatments. Experiment II extrudates were produced with 10 kg of material, rather than 3 kg used in experiment I, thus allowing the bran be homogenously worked through and dispersed throughout the cracked sorghum material, producing a better process product. Other factors such as bran particle size, may also have affected extrudate characteristics, which is discussed in chapter VI.

Color L, a, b Characteristics of Tannin Extrudates Containing Roller-milled and Decorticated Bran

The L, a, and b values of tannin bran extrudates are shown in Fig. 17-19, respectively. Extrudates became darker (L) and more reddish (a) in color with the increased bran. Gordon (2000) reported that the crust and crumb sections of tannin bran fortified breads became increasingly darker and reddish with increased bran addition. The increased tannin content in the bran acts as a natural colorant when added to the base flour or whole sorghum materials. Decorticated bran extrudates were darker than roller-milled bran extrudates with increased bran substitution, which also increased indications that decorticated tannin bran not only had higher tannin concentration than roller-milled bran, but also contained less endosperm starch and more dietary fiber.

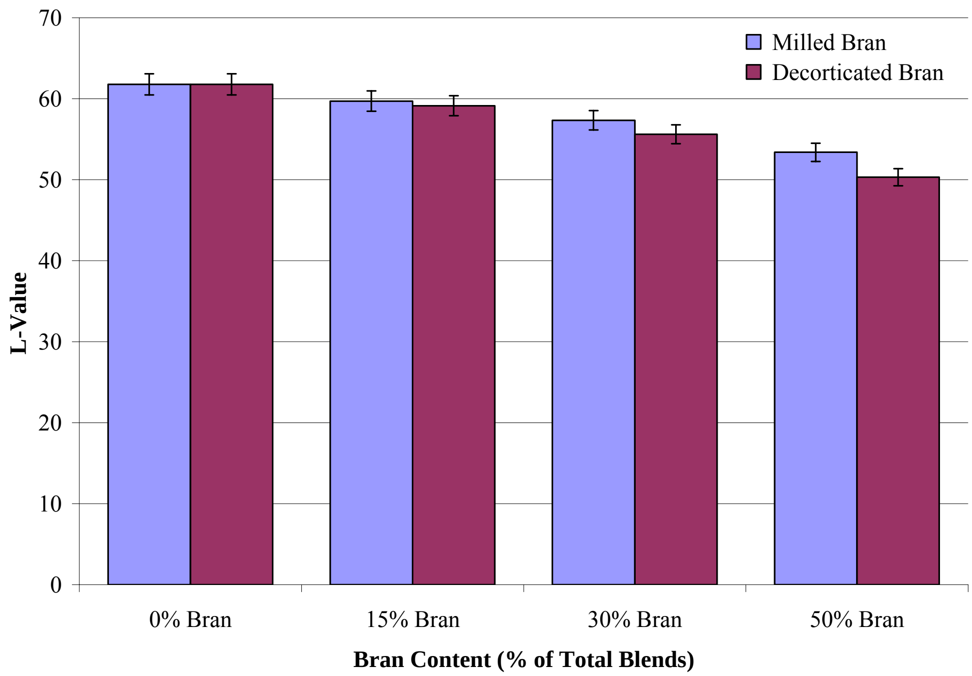


Fig.17. The L-values of tannin extrudates containing roller-milled and decorticated bran. Note: Coefficient of variation (a = 0.05) = 2.1%.

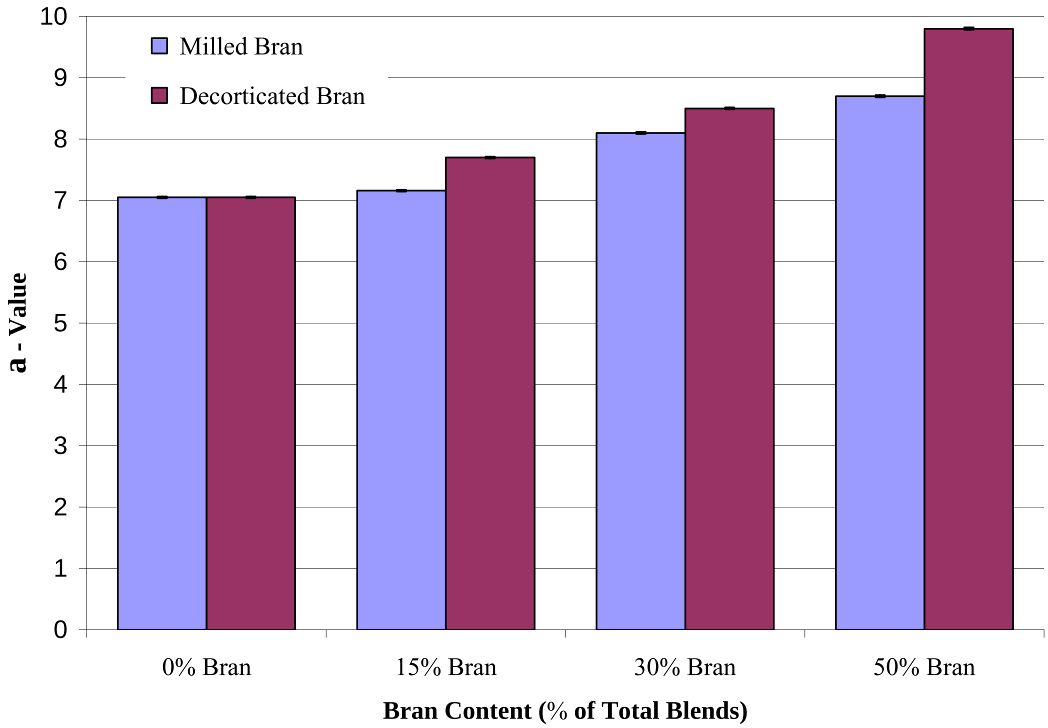


Fig. 18. The a-values of tannin extrudates containing roller-milled and decorticated bran. Note: Coefficient of variation (a = 0.05) = 0.2%. Numerical values are listed in appendix

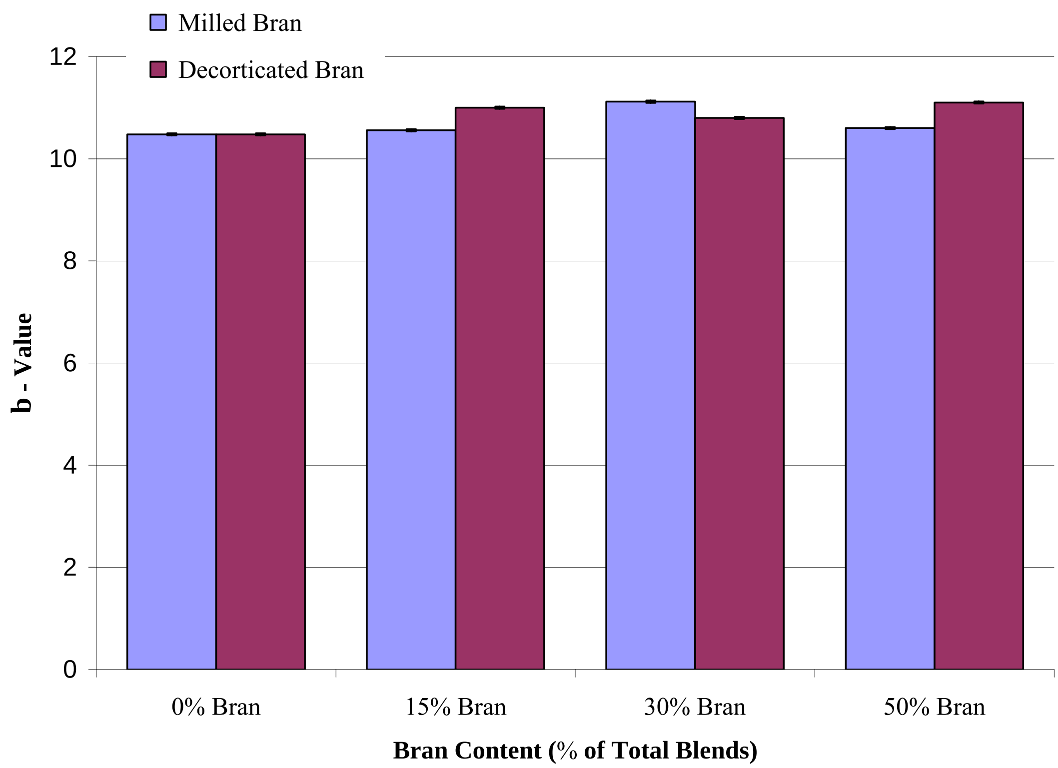


Fig. 19. The b-values of tannin extrudates containing roller-milled and decorticated bran. Note: Coefficient of variation (a = 0.05) = 0.2%.

From looking at the color of bran fortified extrudates, the decortication process seems to aids in concentrating dietary fiber in the bran, more so than roller-milling. For example, colorimeter values of white cracked (0% bran), 50% roller-milled, and 50% decorticated bran extrudates were also measured. The 50% white bran substituted extrudates were darker ($P < 0.05$) than the white cracked extrudates (L= 79.5), but extrudates fortified with the white decorticated bran at 50%, (L= 68.7, a = 2.8, and b= 15.8), were of a darker, reddish huge of yellow ($P < 0.05$) than the white roller-milled bran extrudates (L= 72.2, a = 2.3, and b = 16.1). The “b” values for the tannin bran substituted extrudates did not give conclusive results, probably because the tannin extrudate color does not specifically fall into the yellow (+) to blue (-) color spectrum.

Correlation of Dietary Fiber to Bran Content in Tannin; White Sorghum Extrudates

The dietary fiber contents of extrudates correlation to bran content (Fig. 20) increased in dietary fiber with increased bran fortification, however, their percentages depended on the composition of the bran and the grain. Tannin extrudates fortified with 28.5% decorticated bran (experiment II) had a similar dietary fiber percentage (19%) in comparison to the tannin extrudates produced in the 1st extrusion experiment fortified with 30 percent bran (20.3%). Tannin extrudates fortified with decorticated bran extrudates had greater increases in dietary fiber than extrudates with roller-milled bran, due to greater dilution of fiber with endosperm in the roller-milled bran. This difference was also seen among the white sorghum decorticated and roller-milled brans. White sorghum extrudates, though initially lower dietary fiber, also show great increases in dietary fiber with bran addition, and white sorghum extrudates produced with decorticated bran have a greater percentage of dietary fiber at 50% bran addition (22.3%) than those produced from roller-milled bran fortified at the same percentage (20.3% at 50%) at same percentage.

However, dietary fiber values for the extrudates were calculated based on the dietary values of the raw grain and bran materials (Table X), and not actual Prosky (1998) determination. Actual tannin extrudate material containing 50% decorticated bran, was analyzed for dietary fiber, and gave a value of 18% dietary fiber (dmb), as opposed to the calculated 26.7%. This indicates that a loss in insoluble dietary fiber may have taken place during the extrusion process, which conflicts with several sources that have reported that extrusion increases soluble fiber content compared to starting materials (Ralet et al. 1993; Rinaldi et al. 2000; Nelson 2001 b). However, tannin content in the bran may complex with fiber just as it is known to complex with protein (Hamaker et al. 1986). Prosky dietary fiber analysis on the bran fortified extrudates is needed to in order to determine the actual percentage of dietary fiber in the bran, and if the dietary fiber in sorghum extrudates actually increases or decreases upon extrusion. .

Total Phenols, Tannins, and Antioxidant Activity of Tannin Extrudates Containing Decorticated Bran

Taylor (2002) reported that increased decortication from 10 to 25% of a red sorghum (NK 283), resulted in more protein, less fat, crude fiber, ash and polyphenols, and lighter color in comparison to 10% bran. Tannin roller-milled bran extrudates were lighter in color and lower in fiber content than those containing decorticated bran.

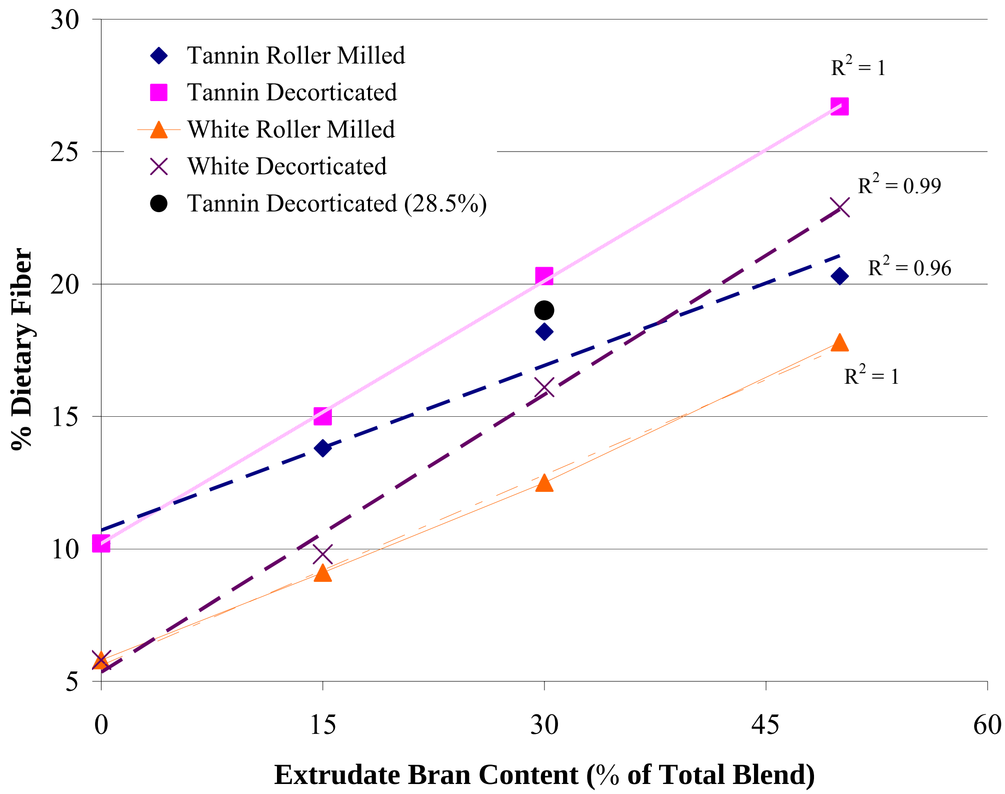


Fig. 20. Correlation of calculated dietary fiber content in tannin and white sorghum extrudates containing roller-milled or decorticated bran. Note: dietary fiber content was calculated based on dietary fiber values for grains and brans shown in Table X; value for tannin extrudate containing 28.5% bran (19.0% dietary fiber) is shown.

Decorticated tannin bran was higher in phenols, tannin content, and antioxidant activity than tannin roller-milled bran. Therefore, only extrudates containing decorticated bran were analyzed.

Phenol, tannin content, and antioxidant potential for raw materials and extrudates containing decorticated bran are shown in Fig. 21-23, and levels for tannin extrudates containing 28.5% decorticated bran (experiment II) for comparison. Phenols, tannins, and antioxidant potential in raw materials and extrudate samples increased with increasing bran substitution. Awika's (2003) also reported simular increases in antioxidant activity in breads and cookies fortified with increasing amounts of tannin and black sorghum bran. The average recoveries of phenols, tannins, and antioxidant activity in the extrudates containing bran were 61.5, 42.1, and 66.8 % respectively. Extrudates containing with 50% tannin bran retained the highest percentage of tannins and antioxidant activity at 49.2 and 82.6%, respectively, because they were the least modified by the extrusion process.

Several studies have shown that polyphenolic compounds, such as tannins, are decreased during to processing, depending on the feed stocks and process (Campbell and Van der Poel 1991; Sze-Tao et al. 2001; Alonso et al. 2001; Awika 2003). The bran fortified extrudates showed moderate recovery of antioxidant activity and total phenols, while tannin retention was lower. Tannin whole sorghum extrudates retained 21 and 89% of the original grain tannin content and antioxidant activity, respectively (Awika 2003). Tannins may retain their antioxidant functionality throughout processing,

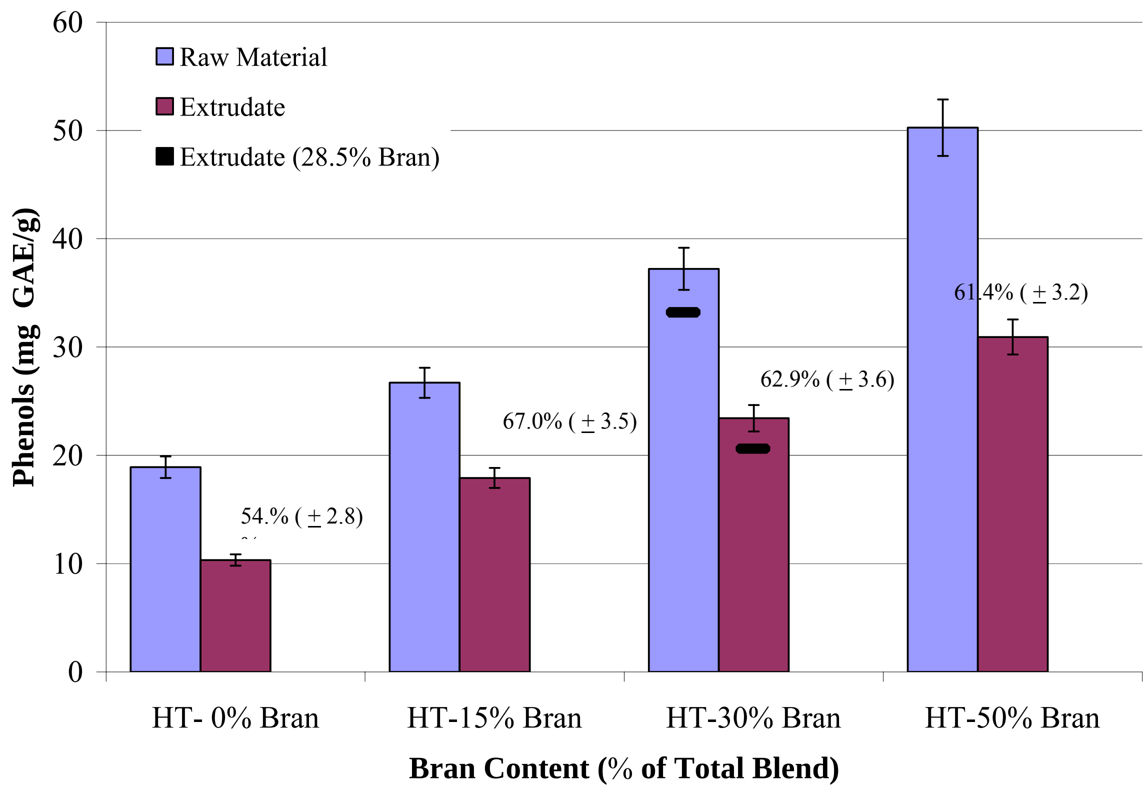


Fig. 21. Phenolic content of tannin sorghum raw materials and extrudates substituted with decorticated bran. Note: Values above columns shows percentage of tannin retention in extrudates; tannin bran fortified extrudate (experiment II) data also shown; Coefficient of variation (a = 0.05) = 5.3%.

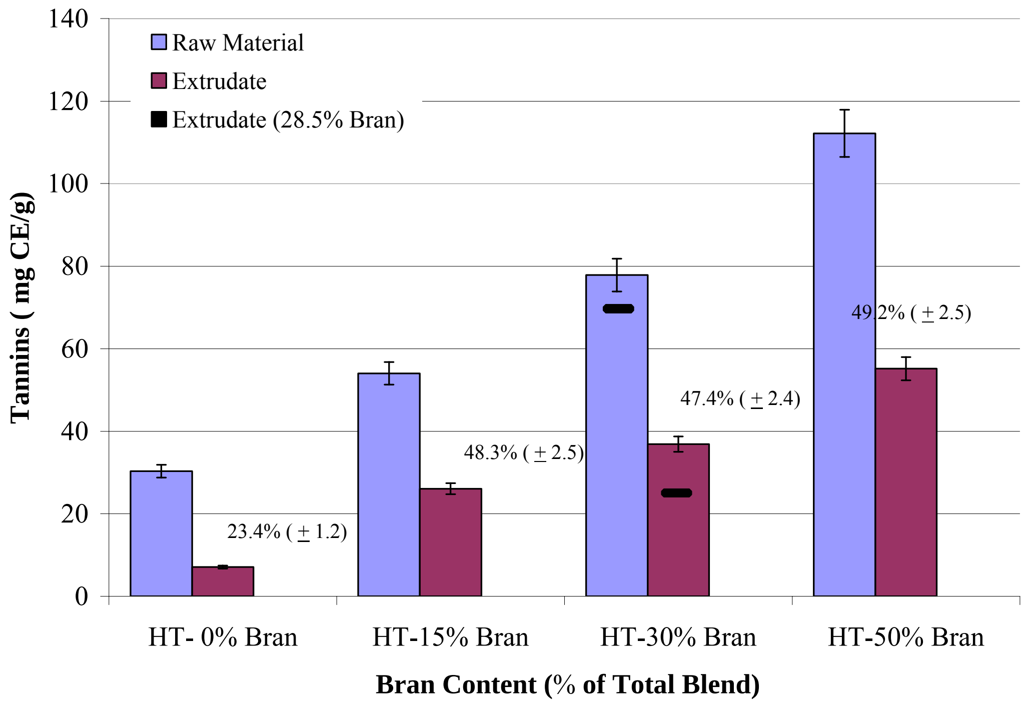


Fig. 22. Tannin content of tannin sorghum raw materials and extrudates substituted with decorticated bran. Note: Values above columns shows percentage of tannin retention in extrudates; tannin bran fortified extrudate (experiment II) data also shown; coefficient of variation (a = 0.05) = 5.1%.

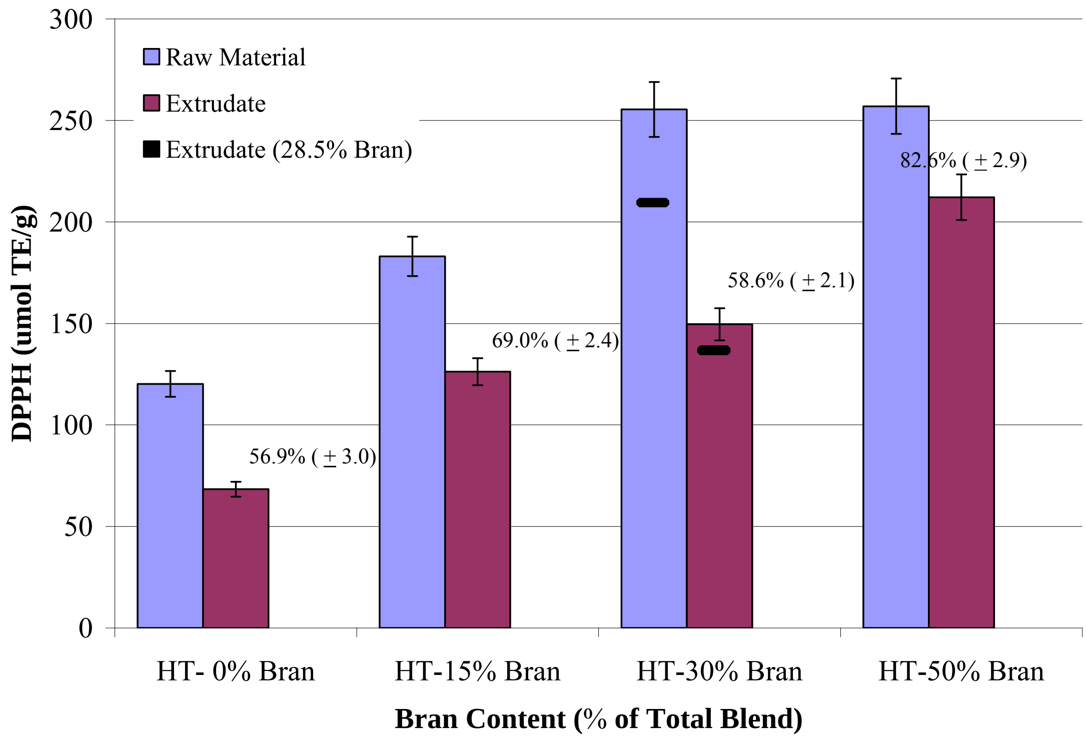


Fig. 23. Antioxidant activity of tannin sorghum raw materials and extrudates substituted with decorticated bran. Note: Values above columns shows percentage of antioxidant activity retention in extrudates; tannin bran fortified extrudate (experiment II) data also shown Coefficient of variation (a = 0.05) = 5.2%.

however the extrusion/ cooking process may alter the structure of tannin compounds. Tannins complex with proteins and carbohydrates rendering them more difficult to extract and/or detect through the simple vanillin HCL antioxidant activity, respectively Awika's (2003). Also, the reduction in detectable tannin content may not mean these compounds are destroyed. They may be depolymerized to smaller oligomers that have different biological value (Awika et al. 2003).

Phenols, tannin, and antioxidant activity percentages in extrudates increased with bran levels. In fact, phenol content, tannin content, and antioxidant activity increased as much as 68, 87, and 67 % in extrudates containing 50% bran. Extrudates of cracked tannins without bran had antioxidant activity similar to tannins of the whole extrudate reported by Awika (2003) were 120.2 umol/g vs. 125 umol/g. Phenols, tannins, and antioxidant activity increased by 42.4, 73.2, and 45.4 %, respectively, for extrudates with 15% tannin bran. This gives an indication that increased bran content (as little as 15%), can produce extrudates with nearly a 50% increase in phenols, tannins, and antioxidants.

Also, tannin extrudates and raw materials containing 28.5% decorticated bran were slightly lower in phenol (18.0 mg GAE/g), tannin (23.6 mg CE/g), and antioxidant values (133.1 umol TE/g), compared to extrudates containing 30% bran (23.4 mg GAE/g, 36.9 mg CE/g, and 149.6 umol TE/g, respectively).

CHAPTER VI

RESULTS AND DISCUSSION – EXTRUSION EXPERIMENT II

Extrusion Characteristics of Whole, Cracked, and Bran Fortified Specialty Sorghums, White Sorghum and Corn Meal

In the second experiment, black TX430 sorghum was extruded along with tannin (CSC3xR28) and white (ATx631xRTx436) sorghums. Black sorghum, high in anthocyanin and antioxidant compounds (Awika 2003), was included to determine physical/ chemical antioxidant characteristics of extrudates across specialty/high phenolic sorghum varieties. Sorghums were processed and extruded (in 10 kg duplicates) for three treatments: whole, cracked, and bran fortified. White sorghums were extruded only as whole sorghum and cracked sorghum extrudates: there were no white sorghum bran fortified extrudates due to the low phenolic/ antioxidant potential value of white bran (Awika 2000). ADM corn meal was also extruded along with samples for comparison purposes.

The feed rates of the cornmeal and sorghum extrudates were not statistically different (Fig. 24). White and tannin whole kernel sorghums had similar feed rates, while cracked sorghum had slightly lower feed rates, though values were not significantly different. This slight decrease in the feed rate of cracked sorghum compared to whole sorghum kernels was observed in experiment 1, though differences were greater. Black whole and cracked sorghums had much lower feed rates than the corn meal and other sorghums. The bran fortified cracked sorghum blends had the lowest feed rates of all the sorghum treatments, which confirmed results of experiment 1

(Table XII). Cracked sorghum extrusion material had decreased feed rate with increased bran substitution.

The SME generated by the sorghum materials was lower than corn meal (Fig. 25), yet SME values were not significantly different among sorghum treatments. Whole and cracked sorghum materials had similar SME values, with cracked sorghums (white and tannin) generating slightly higher energy values. Tannin bran fortified material had SME similar to whole kernel and cracked sorghum material. Black bran fortified material, however, extruded with much less energy efficiency than whole and cracked black sorghum material. The high fiber content of the black bran fortified feed stocks significantly reduced extrusion cooking/energy efficiency, increasing the need for energy input into the extruder to produce a product (Hu et al. 1993).

The corn meal extrudates had a lower bulk density (66.7 g/L) than the sorghum extrudates, due to the highly refined process of cornmeal degermination and pericarp removal (Fig. 26). Cracked extrudates were slightly less dense than those of whole kernels. These results mimicked those found in experiment 1 (Fig. 13) Black sorghum bran fortified extrudates had significantly higher bulk densities than all other extrudates, which was expected in light of results from experiment 1. In contrast, extrudates containing tannin bran had the lowest bulk density of all the sorghum extrudates; its value was similar to that of the corn meal extrudate (70.0 g/L vs. 66.7 g/L). The particle size distribution of the tannin bran might be a contributing factor. The decorticated tannin bran, had larger particles than the roller-milled and decorticated brans used in the last experiment. These larger particles may aid in the

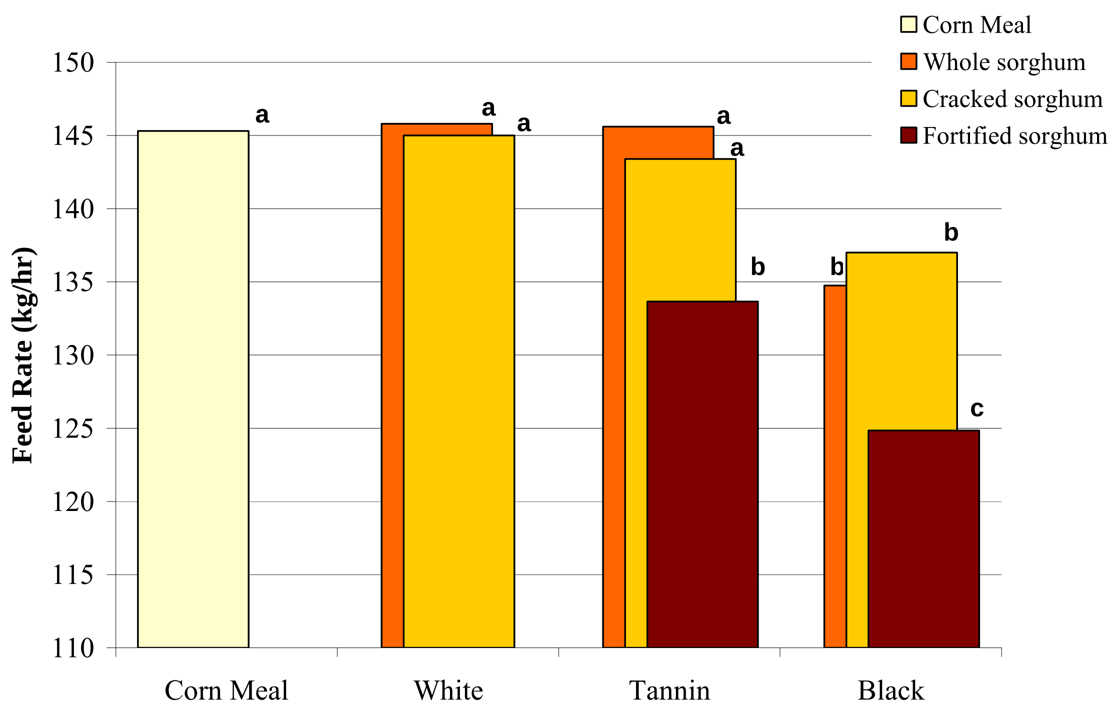


Fig. 24. Feed rates of various whole, cracked, and bran fortified sorghum materials and corn meal. Note: LSD (α = 0.05) = 6.7 kg/hr; means with similar letters were not significantly different.

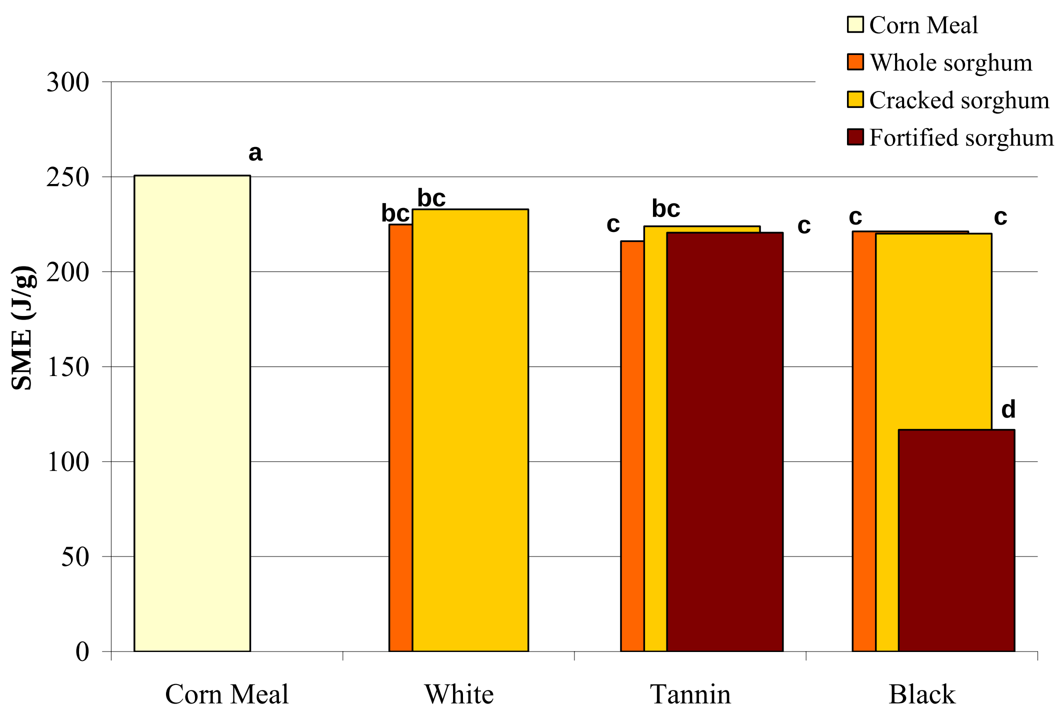


Fig. 25. SME of various whole, cracked, and bran fortified sorghum materials and corn meal. Note: LSD (α = 0.05) = 9.6 J/g; means with similar letters were not significantly different.

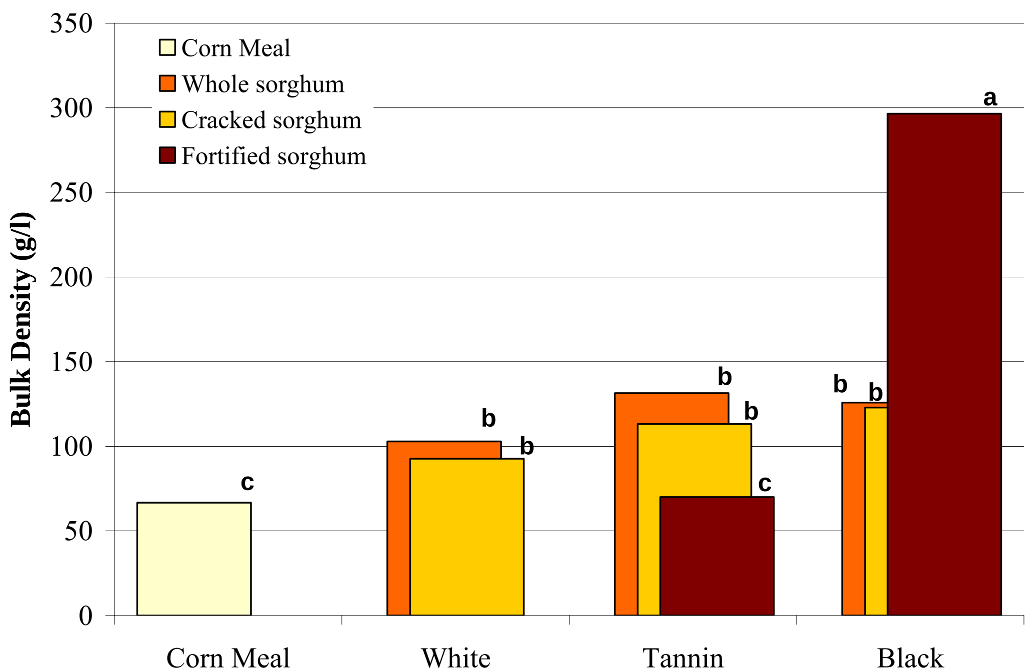


Fig. 26. Bulk density of various whole, cracked, and bran fortified sorghum and corn meal extrudates. Note: LSD ($\alpha = 0.05$) = 41.6 g/L; means with similar letters were not significantly different.

formation of the extrudate and were more highly incorporated into the extrudate structure than in experiment 1. Many of previously fortified extrudates had deposits of bran right in the center of the extrudate (Fig.14), increasing the density and hardness of extrudates.

Corn meal extrudates had greater expansion than all sorghum extrudates (Fig. 27). Cracked sorghum extrudates had similar expansion over whole sorghum extrudates, confirming experiment 1 data. Whole unground and cracked black extrudates had the least expansion of the whole and cracked sorghum extrudates. The black sorghum's thick pericarp and soft endosperm may be characteristics that adversely affect expansion.

Gordon (2000) reported that breads containing black sorghums were very dense, with sparse air cell formation in the crumb. ESEM pictures revealed that breads and doughs fortified with black sorghum bran contained sharp, hair-like pieces and large, angular pieces not present in the doughs and breads fortified with other sorghum brans. These fractions were pieces of the black sorghum glume that tightly adhered to the pericarp. They adversely affected bread loaf volume by shredding gluten proteins during mixing and puncturing the dough during rising. Gordon's findings are similar to findings by Gan et al. (1989, 1992) that the outer layers of bran containing epicarp hairs were responsible for bread loaf volume depression. .

The black sorghum pericarp/glume fractions may physically hinder air cell formation and expansion during the extrusion process. The glumes of the black TX430 sorghums blended in very well with their dark grain color and structure and were not

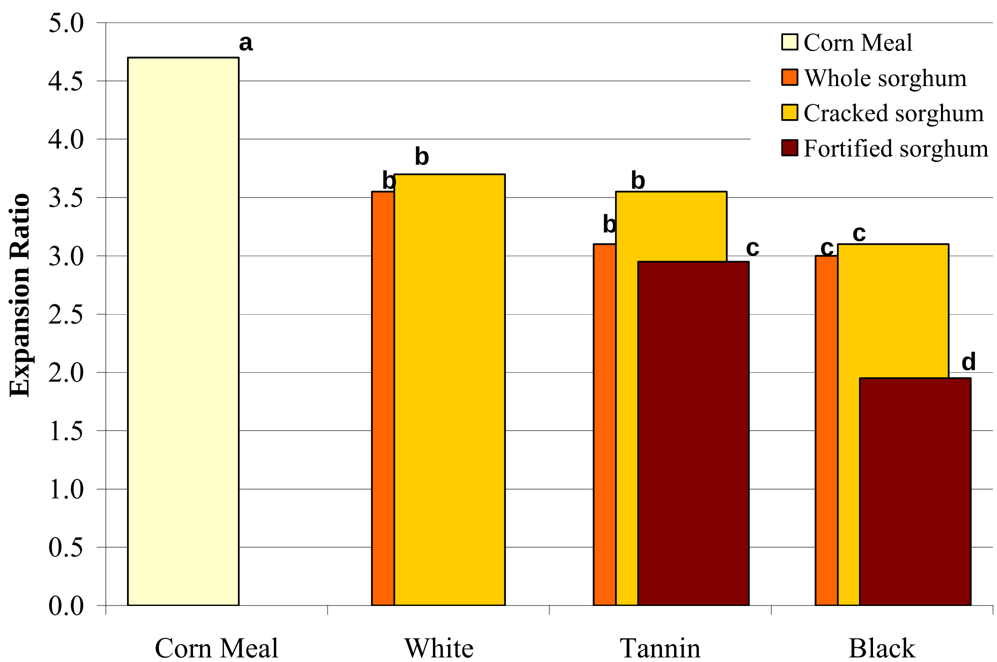


Fig. 27. Expansion ratio of various whole, cracked, and bran fortified sorghum and corn meal extrudates. Note: LSD ($\alpha = 0.05$) = 0.2; means with similar letters were not significantly different.

as easily detected, and thus separated, from the cracked black sorghum and bran, as with the other sorghum grains.

The expansion of tannin and black sorghum extrudates decreased with bran fortification, with black bran fortified extrudates expanding much less than tannin bran fortified extrudates. Lue et al. (1990) also reported that inert components, such as fiber, rupture air cell walls and extrudate external surfaces, thus hindering the full expansion of the gas bubbles, when all other extrusion factors are controlled. These factors may affect the expansion of the black sorghum bran fortified extrudates, due to the sharp glumes particles in the bran. However, these components in black sorghum extrudates need further determination. Gordon states, however, that a preliminary milling step to remove glumes and separate them from the kernel before bran milling (decortication), greatly reduced the content of sharp particles. In fact, de Kock (1999) reports that certain milling processes – like roller-milling – have been observed to separate the epicarp hairs into a different stream from the bran. It is possible that fortification of bread doughs or extrusion materials with roller-milled black sorghum bran may increase expansion, due to decreased glume and epicarp "hair" fragments in the bran. However, experimentation would be needed.

The breaking force needed to rupture and break through whole and cracked sorghum extrudates (Fig. 28) was greater than the force needed to break cornmeal extrudates; however, break forces for cracked sorghum and cornmeal extrudates were not statistically different. Cracked sorghum extrudates tended to take less force to

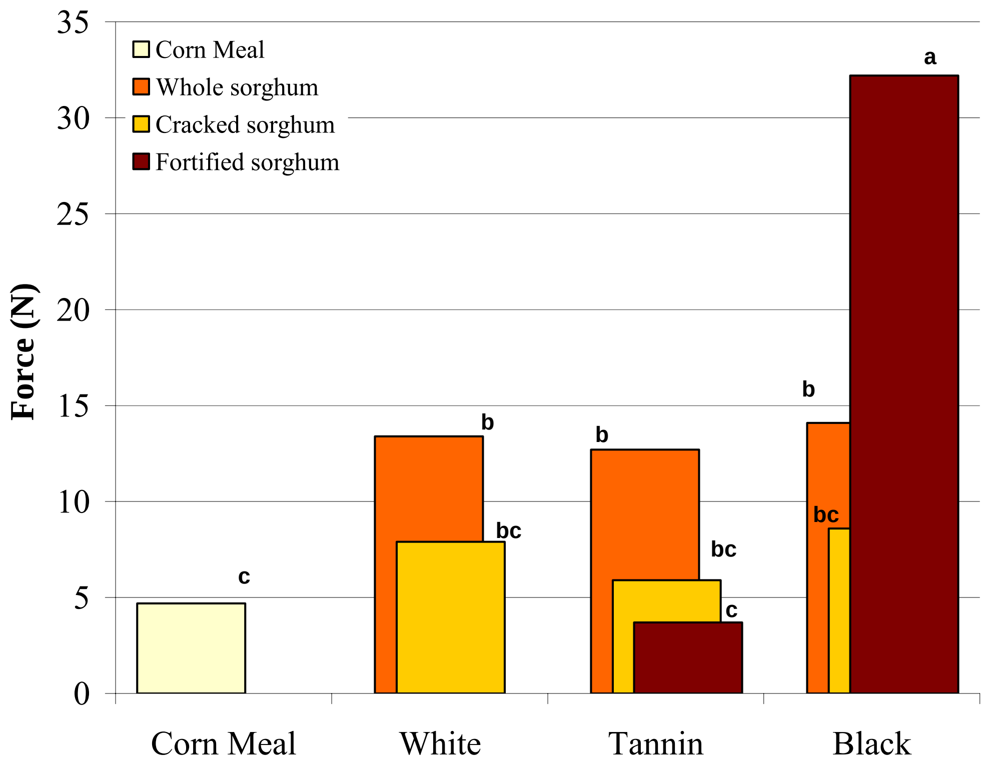


Fig.28. Break force of various whole, cracked, and bran fortified sorghum and corn meal extrudates. Note: LSD ($\alpha = 0.05$) = 6.2 N; means with similar letters were not significantly different.

rupture and break than whole sorghum extrudates, which flowed trends simular to those in experiment I. The black bran fortified extrudates were much harder to break than the whole and cracked extrudates, following the trend of the bran substituted extrudates seen in experiment 1. Yet surprisingly, tannin bran fortified extrudates were softer than cracked and whole unground sorghum extrudates, and even corn meal extrudates. Again, the larger particle size of the decorticated tannin bran used may have been a contributing factor.

L, a, b, Values of White, Tannin, and Black Sorghum Feed Stocks and Extrudates

The L, a, and b values for sorghum materials and corn meal and their extrudates are shown in Table XIV. The black whole, cracked, and both bran fortified tannin and black sorghums are shown in Fig. 29. As expected, ground white sorghum materials and corn meal were naturally lighter in color, less red (– a), and more yellow (+ b), than ground tannin and black sorghum materials. Ground raw materials fortified with black or tannin brans were darker than ground whole and cracked tannin and black sorghum materials. The ground extrudate materials were darker in color than their raw materials, which was probably due to the natural mallard browning affect that occurs during thermal processing.

Dietary Fiber Content (%) of Tannin and Black Sorghum Extrudates Fortified With 0 and 28.5% Bran

The dietary fiber content of tannin and black sorghum extrudates fortified with 0 and 28.5% of their respective bran (Fig. 30) show an average increase of about 50% with the fortification of bran in the cracked sorghum feed stock. The percentage of dietary

TABLE XIV[a]
L, a, b, Values of Extrusion Materials and Extrudates[a]

Sample and Treatment	L-Value	a-Value	b-Value
Cornmeal, Raw	83.6a	-1.7q	35.3a
Cornmeal, Extrudate	78.7b	-2.2r	18.3b
White Whole Sorg, Raw	78.9d	0.09n	12.8d
White Whole Sorg, Extrudate	78.5d	-0.5p	12.9c
White Cracked Sorg, Raw	80.2b	-0.01o	12.5f
White Cracked Sorg, Extrudate	79.6c	-0.5p	12.7e
Tannin Whole Sorg, Raw	66.6g	5.4l	9.3l
Tannin Whole Sorg, Extrudate	60.8h	7.1h	9.2m
Tannin Cracked Sorg, Raw	66.1f	5.6k	9.5k
Tannin Cracked Sorg, Extrudate	58.6i	7.5f	9.9j
Black Whole Sorg, Raw	60.1h	5.4m	6.7q
BlackWhole Sorg, Extrudate	51.6l	7.8d	6.9p
Black Cracked Sorg, Raw	62.8g	5.4l	7.0o
Black Cracked Sorg, Extrudate	56.1j	7.6e	7.2n
Tannin Bran Fortified Sorg, Raw	60.7h	7.4g	10.6h
Tannin Bran Fortified Sorg, Extrudate	53.0l	9.5a	10.3i
Black Bran Fortified Sorg, Raw	53.6k	6.7j	6.1r
Black Bran Fortified Sorg, Extrudate	46.4m	8.9b	6.0s
Tannin Bran (Decorticated)	54.0k	8.5c	11.0g
Black Bran (Decorticated)	42.4n	6.8i	4.5t
LSD (a <0.05)	0.5	0.04	0.04

[a]All samples were ground through a 1mm sieve for comparison. Values with similar letters are not significantly different.

Whole Black Sorghum Extrudate

Cracked Black Sorghum Extrudate

Fortified Black Bran (28.5%) Extrudate

Whole Tannin Sorghum Extrudate

Cracked Tannin Sorghum Extrudate

Fortified Tannin Bran (28.5%) Extrudate

Fig. 29. Extrudates produced from black or tannin, whole or cracked sorghums with 0-28.5% added bran.

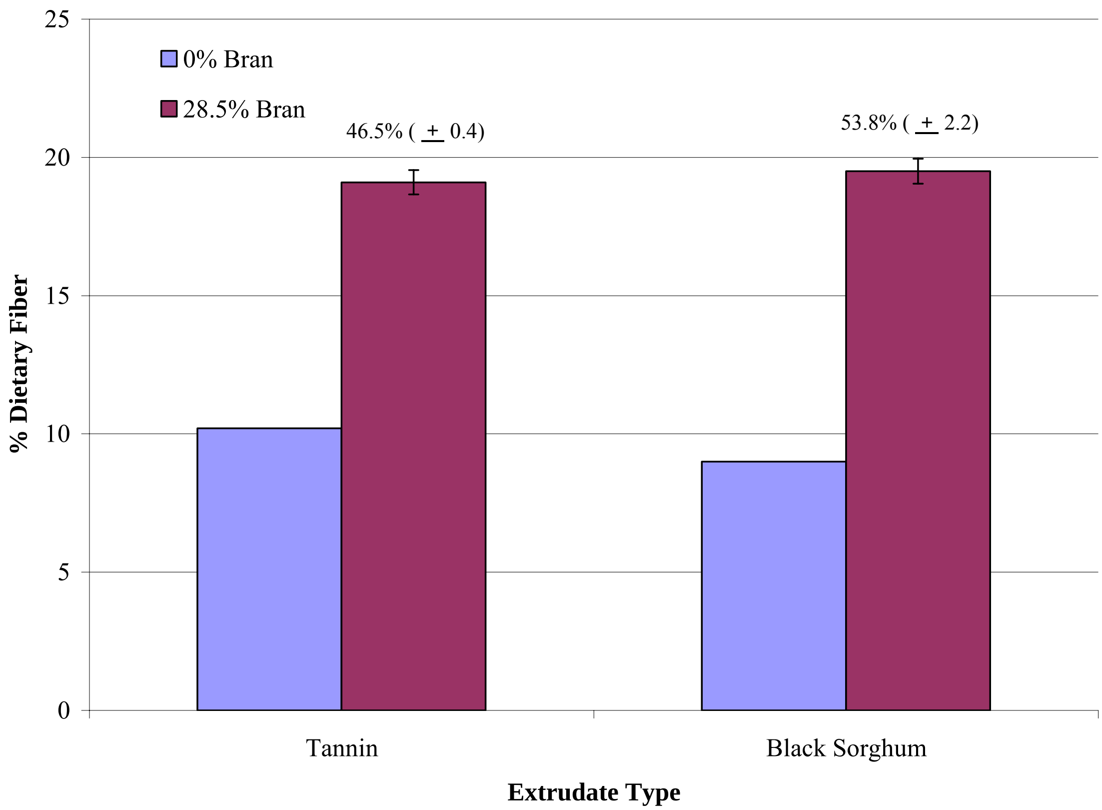


Fig. 30. Dietary fiber content of tannin and black sorghum extrudates fortified with 0 or 28.5% of their respective brans. Note: dietary fiber content was calculated based on dietary fiber values for grains and brans shown in Table (X). Super script values show the percent increase in extrudate dietary fiber with increased bran fortification.

fiber in the extrudates produced from tannin and black sorghum cracked feedstock was estimated (obtained from values in Table X) to be around 10.2 and 9.0%, respectively.

Tannin and black sorghum extrudates produced from decorticated bran fortified feedstock had dietary fiber percentages of 19.1 and 19.5%, respectively. These values were similar to the tannin extrudates containing 30% decorticated bran (20.3% dietary fiber), produced in extrusion experiment I and black sorghum bran fortified materials increased crude fiber content. Several sources have reported that extrusion increases soluble fiber content compared to starting materials (Ralet et al. 1993; Rinaldi et al. 2000; Nelson 2001 b). Whole, cracked, and bran fortified extrudates had increased crude fiber content compared to their raw materials. Fiber content in the grains and bran became partially solubilized, redistributing a percentage of dietary fiber from insoluble to soluble (mainly in the form of pectic substances and hemicelluloses), without extensive degradation of the polymeric structure during extrusion processing (Ralet et al. 1993).

Phenols, Tannins, and Antioxidant Activity of Tannin and Black Sorghum Extrudates and Feed Stocks Containing 0 and 28.5% Bran

The phenols and tannin contents, and antioxidant activity of cracked (0% bran) and bran fortified extrudates (28.5% bran) are shown in (Figs. 31-33). Phenolic content (including tannins) and antioxidant activity increased with bran fortification. Tannin grains, naturally higher in polyphenolic compounds and antioxidant activity than black sorghums (Awika 2000), had higher phenols and antioxidant activity than black sorghums, in both raw material and extrudate treatments. The average recovery (both 0%

and 28.5% bran) of phenols and was 51.3 and 60.4%, respectively, and for black sorghum extrudates, 55.5 and 61.6%, respectively. Average recovery of tannins in tannin extrudates was 27.8%.

Tannin cracked sorghum extrudate phenolic/antioxidant retention percentages from both experiments were similar, however, tannin bran fortified extrudates (experiment II) had lower had lower phenolic and tannin content recovery than expected from experiment I. Tannin cracked sorghum substituted with 15 and 30% bran (experiment I) phenols of 26.7 and 37.2 mg GAE/g respectively, for raw materials and 17.9 and 23.4 mg GAE/g for extrudates. Experiment II tannin cracked sorghum fortified with 28.5% bran phenols values of 37.5 and 18.0 mg GAE/g, for raw materials and extrudates, respectively. Tannin values for sorghum substituted at 15 and 30% bran were 54.0 and 77.3 mg CE/g respectively, for raw materials, and for extrudates, 26.1 and 36.9 mg CE/g, respectively. Values for experiment II tannin bran fortified (28.5%) raw and extrudate materials were 73.3 and 23.6 mg CE/g, respectively. However, antioxidant activities of the 15, 28.5, and 30% bran fortified extrudates was 126.2, 133.1, and 149.6 mg TE/g, respectively. This follows an expected trend for percent bran substitution (true percentage).

This information indicates that experiment II tannin bran fortified extrudates were thoroughly processed (also indications from the extrudate's low bulk density and breaking force), greatly enhancing formation of proanthocyanidin complexes with protein and carbohydrates, rendering them less extractable and detectable to analysis. The causes of decreased anthocyanin content in black sorghum extrudates are

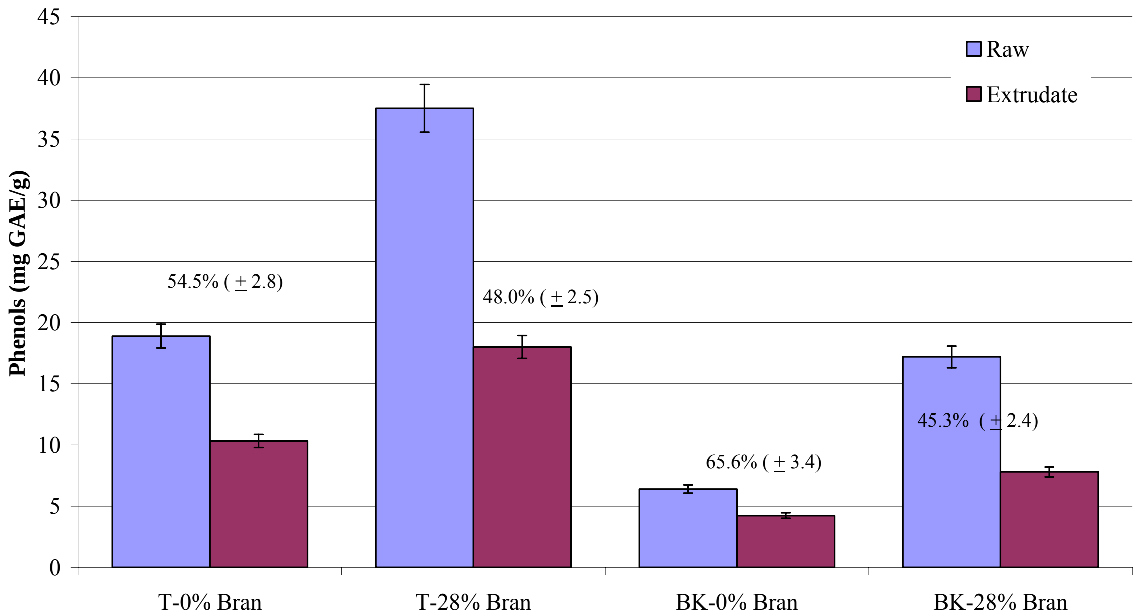


Fig . 31. Phenol content of tannin and black sorghum bran (0 and 28.5%) fortified raw material and extrudates. Note: Values above columns show percent of phenol retention in extrudates; coefficient of variation (a = 0.05) = 5.2%.

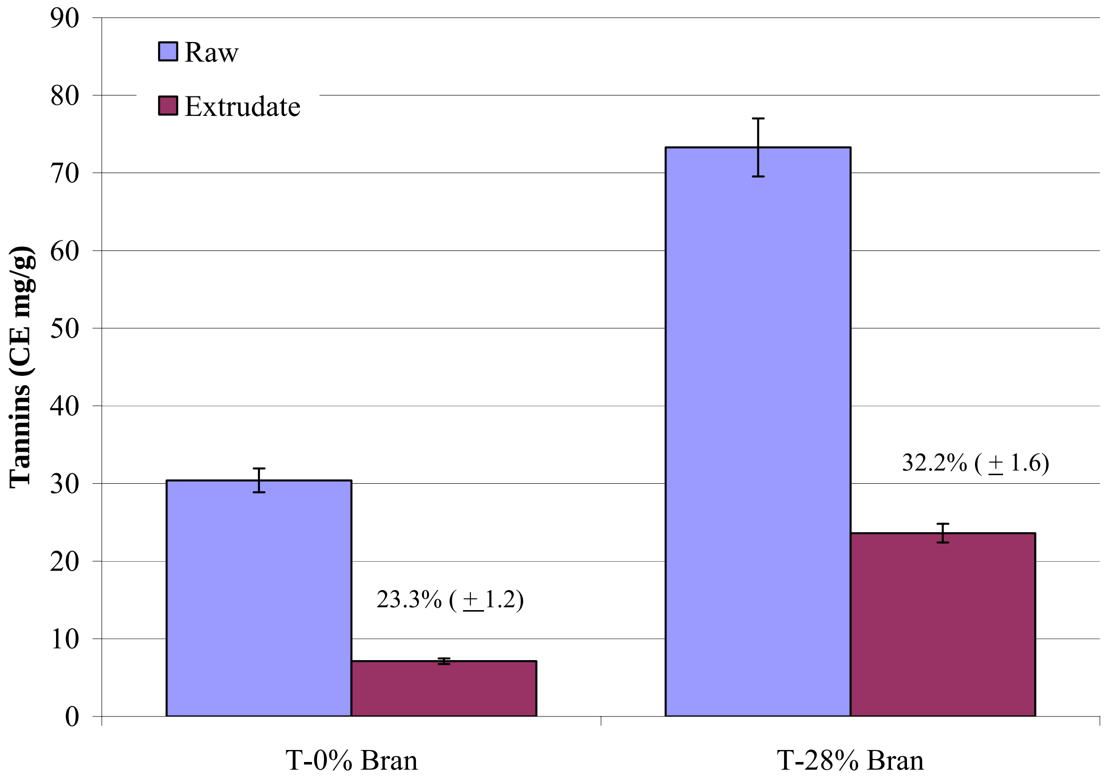


Fig. 32. Tannin content of tannin bran (0 and 28.5%) fortified raw materials and extrudates. Note: Values above columns show percent of tannin retention in extrudates; coefficient of variation (a = 0.05) = 5.1%.

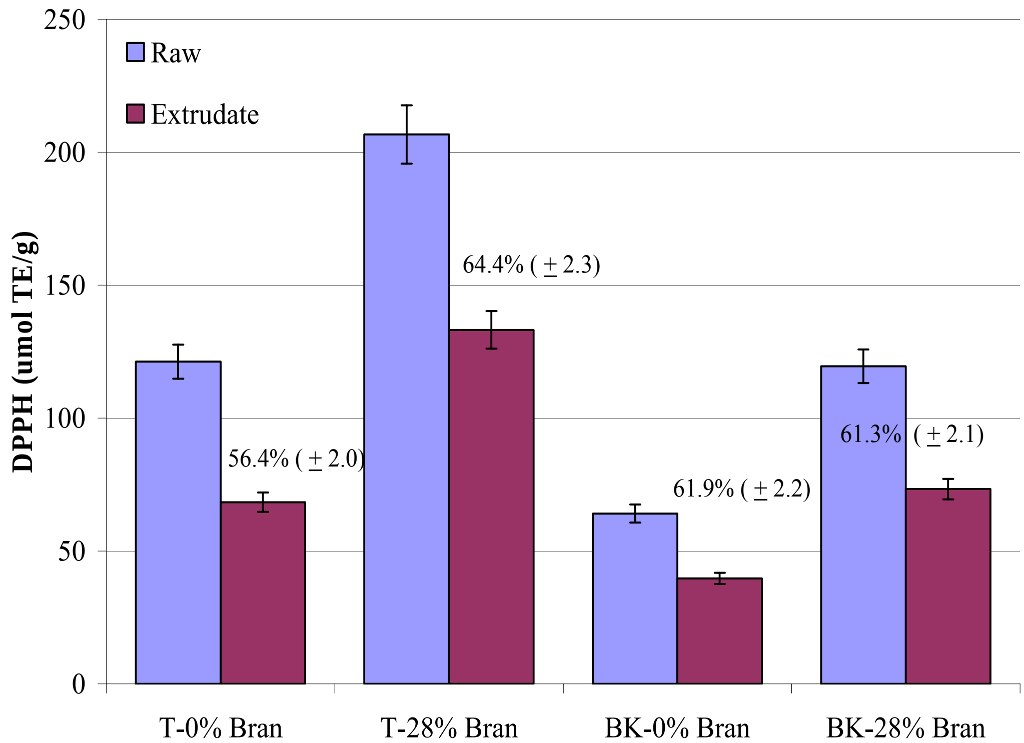


Fig. 33. Antioxidant activity of tannin and black sorghum bran (0 and 28.5%) fortified raw materials and extrudates. Note: values above columns show percent of antioxidant activity retention in extrudates; coefficient of variation (a = 0.05) = 5.3%.

unclear. Anthocyanins are susceptible to oxidation (Kaack and Austed 1998) and/or the formation of complexes with other phenolic compounds (Garcia-Viguera et al. 1999), but more research is needed to understand reasons for detectable loses in extrudates.

CHAPTER VII

ESTIMATION OF SPECIALTY SORGHUM EXTRUDATE (%) DAILY RECOMMENDED VALUES (DRV) FOR DIETARY FIBER AND ANTIOXIDANT ACTIVITY

Many foods, including whole-grain products (breads and cereals) and fruits (raisins and prunes) are high fiber sources, and meet dietary fiber claims set by the Food and Drug Administration (Miraglio 2003). Several grain, fruit, and vegetables and products made there from, have high antioxidant activity, however, there is no set standard method or specific daily reference value (DRV) used to compare antioxidant activity across various food sources. Vitamin E derivatives, (alpha-tocopherols and tocotrienols) have been recognized by the FDA as a natural antioxidants (Farrell and Roberts 1994; Traber and Parker 1995) and the established DRV for vitamin E listed on many food and supplement labels is 30 international units (IU) or 20 mg. Many phytochemical assays, such as ORAC (oxygen radical absorbance capacity), as well as DPPH, use trolox (6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid), a water-soluble synthetic version of vitamin E, to determine the antioxidant potential (ability to quench free radicals) of a food, (Wang and Lin 2000; Zheng and Wang 2003; Awika et al 2003). This chapter attempts to quantify fiber and antioxidant activity of the tannin and black specialty sorghum extrudates and compare them to other foods.

Estimated DRV (%) of Dietary Fiber in Tannin and Black Sorghum Extrudates

RDV dietary fiber (Table XV) values were calculated for specialty sorghum extrudates and compared to other food to other food commodities at the serving

TABLE XV

Comparisons of % RDV Dietary Fiber Values of Specialty Sorghum Extrudates and Other Fiber Sources at 32.1 Grams/Serving (1and 1/8 oz)

Food Commodity	Dietary Fiber (g/serving)	% RDV[a]
White sorghum extrudates (0% bran)	1.9	7.6
Tannin extrudates (0% bran)	3.3	13.2
Tannin extrudates (15% bran)	4.7 – 4.9	18.8 -19.6
Tannin extrudates (28.5% bran)	6.0 – 6.5	24.0 - 26.0
Tannin extrudates (30.0% bran)	6.2 – 6.6	24.8 - 26.4
Tannin extrudates (50.0% bran)	8.1 – 8.9	32.4 - 35.6
Black sorghum extrudates (0% bran)	3.1	12.4
Black sorghum extrudates (28.5% bran)	6.0 – 6.2	24.0 - 24.8
Bread (10%barley/15% wheat bran)[b]	2.3	16.0
Bread (10%barley/15% tannin sorghum bran)[b]	2.2	16.0
Bread (10%barley/15% black sorghum bran)[b]	2.2	16.0
Whole-grain cereals (bran flakes, oatmeal)[c]	2.0 – 8.0	8.0 - 32.0
Bran muffins[c]	2.0 – 2.5	8.0 - 10.0
Fruits (prunes, dates & figs, raisins)[d]	1.6 – 2.6	6.4 - 10.4

[a] Recommended Daily Values (RDV) for dietary fiber = 25g /day

[b] Original dietary values obtained from Gordon (2000). Serving size for bread - 56g (approx. 2 slices)

[c] Original dietary values obtained from Miraglio (2003). One average serving is 28.3g (1ounce) of cereal, 1 small muffin, and 1/4 cup of dried fruit (USDA 1998).

[d] Original dietary values obtained from Nelson (2001 a). Serving size for dried fruits - 1/4 cup (USDA 1998).

size of 32.1 g (1 and 1/8 oz), the average serving size for a single, small bag of extruded snacks used by some companies. For the given serving size, specialty sorghum extrudates have calculated dietary fiber values that are comparable or greater than other fiber rich foods; and values were high enough to make dietary fiber health claims according to FDA guidelines. While a serving of white cracked sorghum extrudates (0% bran) contained only about 8% of the DRV for fiber, respectively, a serving of tannin black cracked sorghum extrudates had enough dietary fiber alone to be valued as a good source of dietary fiber (10-19% DRV/serving or 2.5 to 4.74g). Tannin and black sorghum extrudates fortified with 28.5% bran contained more than 20% of the DRV (5 grams) for dietary fiber and would qualify as a high-fiber source.

However, actual Prosky (1998) dietary fiber analysis of the extrudates' fiber content may provide more conclusive values. Gravimetric determination of dietary fiber in the extrudates would be needed in order to determine the actual total dietary fiber content in the samples and their ratio of soluble to insoluble fiber. The FDA currently allows foods containing at least 0.6g of soluble fiber/serving to be able to make cardiovascular health claims (Miraglio 2003), and reports indicate that extrusion processing causes fiber content in the grains and bran to became partially solubilized, redistributing a percentage of dietary fiber from insoluble to soluble (mainly in the form of pectic substances and hemicelluloses), without extensive degradation of the polymeric structure during extrusion processing (Ralet et al. 1993). Extrudate soluble fiber determination would help determine the actual percentage of insoluble fiber that becomes soluble during the extrusion process. Trends and values, would be expected to be close to those shown in Fig.13, 14, 15, and 20.

Estimated DRV (% - Based on Vitamin E) Antioxidant Activity in Tannin and Black Sorghum Extrudates

Extrudate DPPH trolox (TE umol/g) values were converted to ORAC trolox (TE umol/g) values to make comparisons with other food sources, using the linear equation for the correlation of DPPH to ORAC umol TE/g in sorghum brans, determined by Awika (2003). Specialty sorghum extrudates contained greater calculated ORAC antioxidant potential (Table XVI) than other food commodities (cookies and breads containing sorghum bran, fruits, and vegetables) at the given serving size, presumably due to their high phenolic and/or tannin concentrations.

All food commodities were compared based on a 32.1 g serving-size, used also for the dietary fiber RDV comparison. Calculated RDV values for specialty sorghum extrudates were several times greater than the RDV for vitamin E, indicating that extrudates have radical scavenging ability comparable to high levels of vitamin E equivalents (TE). Calculated ORAC values (linear equation for the correlation of DPPH to ORAC umol TE/g determined by Awika 2003) of tannin extrudates were nearly twice as potent as black sorghum extrudates at 0% (9,370 and 5,450 umol TE/serving) and 28.5% (18,268 and 9,976 umol TE/serving), respectively.

Both ORAC levels (mg TE) and % RDV increased in extrudates per serving with increased bran addition (1,363 – 7,281 mg TE/serving and 6,815 – 36,405 % RDA for

TABLE XVI
Comparisons of ORAC; %RDV Antioxidant Activity of Specialty Sorghum Extrudates and Other Food Sources Based on 32.1 Grams/Serving (1 and 1/8 oz)

Food Commodity	Calculated ORAC (umol TE/serving)	Calculated mg TE/serving (Based on Orac)	% RDV[a] (Based on Vitamin E)
Sorghum Extrudates:			
Tannin[b]	9,370	2,342	11,710
Tannin (15% bran)	15,325	3,831	19,155
Tannin (28.5% bran)	18,268	4,567	22,835
Tannin (30% bran)	20,529	5,132	25,660
Tannin (50% bran)	29,124	7,281	36,405
Black sorghum[c]	5,450	1,363	6,815
Black sorghum (28.5% bran)	9,964	2,494	12,470
Bread:			
Tannin bread (30% bran) [d]	4,895	1,224	6,120
Black sorghum bread[d] (30% bran)	1,772	443	2,215
Cookies:			
Tannin cookies (50% bran) [d]	9,388	2,347	11,735
Black sorghum cookies[d] (50% bran)	4,831	1,208	6,040
Fruits:			
Black raspberries[e]	4,112 - 4,622	1,028 - 1,115	5,140 - 5,775
Red raspberries[e]	3,489 - 3,887	872 - 979	4,360 - 4,895
Vegetables:			
Spinach[f]	213 - 258	53 - 65	265 - 325
Broccoli[f]	98 - 118	25 - 30	125 - 150
Celery[f]	53 - 64	13 - 16	65 - 80

[a]% RDV of vitamin E = 30 IU or 20mg / day

[b]Extrudates produces from cracked (broken) tannin sorghum kernels; initial extrudate without bran fortification (based on percentage of weight).

[c]Extrudates produces from cracked (broken) black sorghum kernels; initial extrudate without bran fortification (based on percentage of weight).

[d]Original ORAC values obtained from Awika (2003). Serving size for bread - 56g (approx. 2 slices) (Gordon 2000).

[e]Orginal ORAC values obtained from Wang and Lin (2000). One average serving is 28.3 g (1ounce) of cereal, 1 small muffin, and 1/4 cup of dried fruit (USDA 1998).

[f]Original ORAC values obtained from Ninafali and Bacchiocca (2003). Serving size for dried fruits - 1/4 cup (USDA 1998); values are expressed on a fresh weight basis.

vitamin E, respectively). Toxicity for high intake of vitamin E in the diet is low, yet, an upper tolerable intake level for vitamin E has been set at 1,000 mg (1,500 IU) (Institute of Medicine, Food, and Nutrition Board 2000). However, toxicity levels for flavonoid antioxidants, such as proanthcyanidins, need further determination in order to determine levels that are effective, yet safe for consumers in extrudate products. Prior and Cao (2000) approximated that a daily antioxidant intake of 3,000 to 3,600 umol TE/day (ORAC) was needed to bring about biological benefits in humans. Yet, Awika (2003) reported ORAC values up to 2 to 3 times greater than the antioxidant threshold prescribed by Prior and Cao, in just one serving of breads and cookies fortified with various percentages of tannin and black sorghum bran.

This information may indicate that even small amounts of specialty sorghum bran or the whole grain itself may be sufficient enough to produce antioxidant rich products, which would be an economic benefit to food producers. However, as mentioned with the dietary fiber content of specialty sorghum extrudates, actual ORAC determination is needed in order to determine conclusive results.

CHAPTER VIII

SUMMARY

Experiment I showed that white and tannin sorghum can produce very similar products during extrusion. White and tannin extrudates had similarities in bulk density, but had slight differences in expansion ratio and breaking (compression force). Cracked sorghums decreased feed rate and increased SME, resulting in extrudates with increased expansion, and decreased bulk density and breaking force.

Substituting cracked tannin and white sorghum materials with increasing percentages of bran showed decreased feed rate, SME, and expansion, and increased bulk density and breaking force. These effects were more pronounced in extrudates containing bran prepared from decortication vs. roller-milling. The decorticated brans had higher fiber content, bulk density, and a higher distribution of finer bran particles. The higher dietary fiber and lower starch content of sorghum decorticated bran contributed to decreased expansion, increased bulk density, and breaking force when incorporated in the extrudates in comparison to roller-milled bran. However, increased dietary fiber correlated strongly with increased bran content in the extrudate material.

Extrudates containing increasing amounts of decorticated bran became darker and more increasingly colored compared to extrudates prepared from roller-milled bran. Phenols, tannins, and antioxidant activity in the decorticated bran fortified extrudates increased with increasing bran substitution, with the average recovery of phenols, tannins, and antioxidant activity from raw materials being 61.5, 42.1, and 66.8%, respectively. The majority of tannins in extrudates are complexed with extrudate components or break down to monomer and oligomer compounds, rendering them less extractable and detectable through vanillin/HCL assayable analysis. Phenol and tannin content, and antioxidant activity increased as much as 68, 87, and 67 %, respectively, in extrudates with bran added as high as 50% of weight. This indicates that bran fortification can greatly improve extrudate phenolic content and antioxidant potential.

In experiment II, black Tx430 specialty sorghum was also extruded along with white and tannin sorghums. Tannin and black bran fortified (28.5%) cracked sorghum, were extruded along with whole and cracked sorghum, and corn meal. The feed rates for whole and cracked sorghums and corn meal were similar and feed rates of and black cracked and whole sorghum materials were lower. Bran fortified extrudates (28%) had reduced feed rates, with black bran fortified extrudates showing the lowest feed rate of all the feed stocks. Corn meal generated higher SME in the extrusion process than the sorghums, although white, tannin, and black, whole and cracked sorghum materials generated similar SME values. Tannin fortified bran extrudates had SME values similar to whole and cracked sorghums, however, black bran fortified extrudates had lower SME. The thick fibrous, pericarp of the black sorghum may lower viscosity in the extruder and decrease expansion.

Corn meal extrudates were less dense, more expanded, and softer than sorghum extrudates. Cracking the sorghums produced extrudates that were lighter, more expanded, and less dense than the whole sorghum, though values were not statistically different. Black sorghum whole and cracked sorghum extrudates were less expanded than white and tannin extrudates, due the black sorghum's thick fibrous paricarp (which contained tightly adhered glume fractions) and inherent abundance of soft endosperm.

Bran fortified materials were generally less expanded, more dense and harder than whole and cracked extrudates. However, tannin bran fortified extrudates were less dense and softer than whole and cracked extrudates, and nearly similar to that of corn meal. The decorticated tannin bran contained larger particles than both the roller-milled and decorticated brans used in the first experiment, and may have been better distributed throughout the cracked sorghum feed stock during mixing. This may have allowed the bran to incorporate into the cracked sorghum better, producing more uniform gelatinization in the feed stock, resulting in a lighter, softer product. The decreased feed rate of the material allowed for more complete cooling than the whole and cracked sorghums, producing better air cell formation. The black bran fortified extrudates, however, were very dense and hard to break, due to high fiber and pericarp glume fractions in the bran, and soft endosperm of the kernel. Using roller-milled bran may aid in increasing expansion, and reducing bulk density and break force.

Fortified tannin and black sorghum extrudates had an estimated 50% increase in dietary fiber with bran fortification at 28.5%. Phenolic content, tannins (tannin sorghum only), and antioxidant activity also increased with bran fortification. Tannin sorghum extrudates were higher in polyphenolic compounds and antioxidant activity than the black sorghum extrudates. Estimated daily recommended values for fiber and antioxidant activity (based on vitamin E) in tannin and black sorghum extrudates indicated that both cracked - whole grain (0% bran) and bran fortified specialty sorghum extrudates are potent sources of dietary fiber and antioxidants even in small servings.

Further Research

More research is needed to find optimum conditions to produce quality specialty whole kernel and bran fortified extrudates. Acosta-Sanchez (2003) indicated that 14% moisture produced the highest quality of white sorghums in a controlled study. In these two studies, tannin and black sorghum materials were tempered to 13.5 or 14% moisture, however, because of their inherent grain composition, it is uncertain whether these are optimal moisture levels for these specific grains.

Fortification increases dietary fiber and antioxidant content in the extrudates and adversely affect extrudate characteristics. More research is needed to determine the optimum extrudate characteristics of bran fortified extrudates. Increasing extrusion screw speed, optimizing moisture/temperature, and the addition of starch are all options that could be used to enhance product quality. Also, the determination of desirable bran particle size should be considered.

Lastly, organoleptic and nutritional studies should be conducted for consumer taste approval and actual health benefits. It is known that food substances highly concentrated with tannins can produce an astringent taste from the concentrated compounds. Determining or developing flavorings, additives, etc. that would compliment the sorghum extrudates natural flavor is required. Also, establishing the optimum level of bran (antioxidants) in extrudates that would meet consumer acceptability, safety, and biological health needs, should be researched.

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APPENDIX A

BULK DENSITY, EXPANSION RATIO, AND BREAK FORCE OF WHOLE AND CRACKED SORGHUM EXTRUDATES

TABLE IA
Bulk Density (g/L) of Tannin and White Sorghum Extrudates Produced From Whole and Cracked Kernels; Corn Meal Extrudates (Experiment I)[a]

Process/Type	Tannin (CSC3xR8)	White (ATx631xTx436)
Whole Sorghum	3.1e	3.3d
Cracked Sorghum	3.6c	3.8b

Corn meal extrudate = 4.9d; LSD = 0.2

[a] Means with the same letter values are not significantly different.

TABLE IIA
Expansion Ratio of Tannin and White Sorghum Extrudates Produced From Whole and Cracked Kernels; Corn Meal Extrudates (Experiment I)[a]

Process/Type	Tannin (CSC3xR8)	White (ATx631xTx436)
Whole Sorghum	121a	122.9a
Cracked Sorghum	86.7c	89.7b

Corn meal extrudate = 66.7d; LSD = 2.0 g/L

[a]Means with the same letter values are not significantly different.

TABLE IIIA
Break Force (N) Tannin and White Sorghum Extrudates Produced From Whole and Cracked Kernels; Corn Meal Extrudates(Experiment I) [a]

Process/Type	Tannin (CSC3xR8)	White (ATx631xTx436)
Whole Sorghum	13.2a	15.9a
Cracked Sorghum	4.6b	8.4b

aCorn meal extrudate = 5.0d; LSD = 4.0 g/L

[a]Means with the same letter values are not significantly different.

APPENDIX B

BULK DENSITY, EXPANSION RATIO, AND BREAK FORCE OF TANNIN AND WHITE CRACKED EXTRUDATES CONTAINING BLENDS OF ROLLER-MILLED AND DECORTICATED BRANS

TABLE IB
Bulk Density (g/L) of Tannin and White Sorghum Extrudates Containing Roller-Milled and Decorticated Brans(Experiment I)[a]

	Tannin (CSC3xR8)		White (ATx631xTx436)	
Bran	**Roller-milled Bran**	**Decorticated Bran**	**Roller-milled Bran**	**Decorticated Bran**
0% Bran	86.7c	86.7c	89.7b	89.7b
15% Bran	102.5i	113.0h	104.8i	171.2d
30% Bran	118.9g	170.5d	128.0f	324.1b
50% Bran	151.7e	252.7c	170.0d	414.3a
Overall LSD (α = 0.05) = 4.2 g/L				

[a]Means with the same letter values are not significantly different.

TABLE IIB
Expansion Ratio of Tannin and White Sorghum Extrudates Containing Roller-Milled and Decorticated Brans(Experiment I) [a]

	Tannin (CSC3xR8)		White (ATx631xTx436)	
Bran	**Roller-milled Bran**	**Decorticated Bran**	**Roller-milled Bran**	**Decorticated Bran**
0% Bran	3.6b	3.6b	3.8a	3.8a
15% Bran	3.2e	3.1e	3.4c	2.8d
30% Bran	2.9f	2.6g	3.0e	2.0h
50% Bran	2.5g	2.0h	2.9f	1.6j
Overall LSD (α = 0.05) = 0.1				

[a]Means with the same letter values are not significantly different.

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TABLE IIB

Break Force (N) of Tannin and White Sorghum Extrudates Containing Roller-Milled and Decorticated Brans (Experiment I)[a]

	Tannin (CSC3xR8)		White (ATx631xTx436)	
Bran	**Roller-milled Bran**	**Decorticated Bran**	**Roller-milled Bran**	**Decorticated Bran**
0% Bran	4.6f	4.6f	8.4fe	8.4fe
15% Bran	7.7e	8.8fe	10.7e	22.2b
30% Bran	11.6de	16.7dc	12.2cde	31.4a
50% Bran	12.7cde	25.0b	16.9c	36.0a
Overall LSD (α = 0.05) = 5.2N				

[a]Means with the same letter values are not significantly different.

APPENDIX C

L, A, B, VALUES OF TANNIN EXTURDATES CONTAINING BLENDS OF ROLLERMILLED AND DECORTICATED BRAN

TABLE IC
L Values of Tannin of Extrudates Containing Roller-milled and Decorticated Brans (Experiment I)

	Tannin Extrudates Fortified With Bran	
Bran/material	**Roller-milled Bran**	**Decorticated Bran**
0% Bran	61.8	61.8
15% Bran	59.7	59.1
30% Bran	57.3	53.4
50% Bran	55.6	50.0
CV (a = 0.05) = 0.01%		

TABLE IIC
A Values of Tannin of Extrudates Containing Roller-milled and Decorticated Brans (Experiment I)

	Tannin Extrudates Fortified With Bran	
Bran/material	**Roller-milled Bran**	**Decorticated Bran**
0% Bran	7.1	7.1
15% Bran	7.2	7.7
30% Bran	8.1	8.5
50% Bran	8.7	9.8
CV (a = 0.05) = 0.2%		

TABLE IIIC
B Values of Tannin of Extrudates Containing Roller-milled and Decorticated Brans (Experiment I)

	Tannin Extrudates Fortified With Bran	
Bran/material	**Roller-milled Bran**	**Decorticated Bran**
0% Bran	10.5	10.5
15% Bran	10.6	11.0
30% Bran	11.1	10.8
50% Bran	10.6	11.1
CV (a = 0.05) = 0.2%		

APPENDIX D

PHENOL AND TANNIN CONTENT; ANTIOXIDANT ACTIVITY OF TANNIN EXTRUDATES CONTAINING BLENDS OF DECORTICATED BRAN

TABLE ID
Phenol (mg GAE/g) Content of Tannin Extrudates Containing Decorticated Brans (Experiment I)

Tannin Extrudates Fortified With Bran		
Bran/material	**Raw Material**	**Extrudate**
0% Bran	18.9	10.3
15% Bran	26.7	17.9
30% Bran	37.2	23.9
50% Bran	50.3	30.9
Overall CV (a = 0.05) = 5.3%		

TABLE IID
Tannin (mg CE/g) Content of Tannin Extrudates Containing Decorticated Brans (Experiment I)

Tannin Extrudates Fortified With Bran		
Bran/material	**Raw Material**	**Extrudate**
0% Bran	30.3	7.1
15% Bran	54.0	26.1
30% Bran	74.4	36.9
50% Bran	112.2	54.0
Overall CV (a = 0.05) = 5.1%		

TABLE IIID
Antioxidant Activity (mg TE/g) Content of Tannin Extrudates Containing Decorticated Brans (Experiment I)

Tannin Extrudates Fortified With Bran		
Bran/material	**Raw Material**	**Extrudate**
0% Bran	121.2	64.1
15% Bran	166.9	114.4
30% Bran	209.8	143.7
50% Bran	251.4	196.4
Overall CV (a = 0.05) = 5.1%		

APPENDIX E

FEED RATE, SME, BULK DENSITY, EXPANSION RATIO, AND BREAK FORCE OF WHITE, TANNIN, AND BLACK , WHOLE AND CRACKED EXTRUDATES; EXTRUDATES CONTAINING BLENDS OF DECORTICATED BRANS; CORN MEAL EXTRUDATES

TABLE IE
Feed Rate (Kg/hr) of Various Whole, Cracked, and Bran Fortified Sorghum Materials and Corn Meal (Experiment II)[a]

Process/Type	White (ATx631xTx436)	Tannin (CSC3xR8)	Black TX430
Whole Sorghum	145.8a	145.6a	134.8b
Cracked Sorghum	145.0a	143.4a	137.0b
Bran Fortified Sorghum	----	89.7b	124.9c

Corn meal extrudate = 145.3a; LSD ($\alpha = 0.05$) = 6.7 kg/hr
[a]Means with the same letter values are not significantly different.

TABLE IIE
Specific Mechanical Energy (J/g) of Various Whole, Cracked, and Bran Fortified Sorghum Materials and Corn Meal (Experiment II) [a]

Process/Type	White (ATx631xTx436)	Tannin (CSC3xR8)	Black TX430
Whole Sorghum	224.8bc	216.1c	221.2c
Cracked Sorghum	232.9bc	224.0bc	220.1c
Bran Fortified Sorghum	----	220.5c	116.8d

Corn meal extrudate = 250.7a; LSD ($\alpha = 0.05$) = 9.6 j/g
[a]Means with the same letter values are not significantly different.

TABLE IIIE
Bulk Density (g/Kg) of Extrudates Produces From Various Whole, Cracked, and Bran Fortified Sorghum Materials and Corn Meal (Experiment II)[a]

Process/Type	White (ATx631xTx436)	Tannin (CSC3xR8)	Black TX430
Whole Sorghum	102.9bc	131.5b	125.9b
Cracked Sorghum	92.6bc	113.2b	122.8b
Bran Fortified Sorghum	----	70.0c	296.5a

Corn meal extrudate = 66.7d; LSD (α = 0.05) = 41.6 g/kg
[a]Means with the same letter values are not significantly different.

TABLE IVE
Expansion Ratio of Extrudates Produces From Various Whole, Cracked, and Bran Fortified Sorghum Feed Stocks and Corn Meal (Experiment II)[a]

Process/Type	White (ATx631xTx436)	Tannin (CSC3xR8)	Black TX430
Whole Sorghum	3.6b	3.1b	3.0c
Cracked Sorghum	3.7b	3.6b	3.1c
Bran Fortified Sorghum	----	3.0c	2.0d

Corn meal extrudate = 4.7a; LSD (α = 0.05) = 0.4
[a]Means with the same letter values are not significantly different.

TABLE VE
Break Force (N) of Extrudates Produces From Various Whole, Cracked, and Bran Fortified Sorghum Feed Stocks and Corn Meal (Experiment II)[a]

Process/Type	White (ATx631xTx436)	Tannin (CSC3xR8)	Black TX430
Whole Sorghum	7.9bc	12.7b	14.1b
Cracked Sorghum	13.4b	5.9bc	8.6bc
Bran Fortified Sorghum	----	3.7c	32.2a

Corn meal extrudate = 4.70c; LSD (α = 0.05) = 6.4 N

[a]Means with the same letter values are not significantly different.

APPENDIX F

PHENOL AND TANNIN CONTENT; ANTIOXIDANT ACTIVITY OF TANNIN AND BLACK CRACKED SORGHUM EXTRUDATES; EXTRUDATES CONTAINING 28.5% DECORTICATED BRAN

TABLE IF
Phenol (mg GAE/g) Content of Tannin and Black Sorghum Raw Feedstock and Extrudates Fortified With 0% and 28.5% Decorticated Bran
(Experiment II)

	Extrudates Fortified With Bran			
	Tannin		Black	
Type/Process	**Raw Material**	**Extrudate**	**Raw Material**	**Extrudate**
0% Bran	18.9	10.3	6.4	4.2
28.5% Bran	37.5	18.0	17.2	7.8

Overall CV (a = 0.05) = 5.1%

TABLE IIF
Tannin (mg CE/g) Content of Tannin Sorghum Raw Feedstock and Extrudates Fortified With 0% and 28.5% Decorticated Bran
(Experiment II)

	Tannin Extrudates Fortified With Bran	
Bran	**Raw Material**	**Extrudate**
0% Bran	30.4	7.1
28.5% Bran	73.3	23.6

Overall CV (a = 0.05) = 5.1%

TABLE IIIF
Antioxidant Activity (mg TE/g) of Tannin and Black Sorghum Raw Feedstock and Extrudates Fortified With 0% and 28.5% Decorticated Bran (Experiment II)

	Extrudates Fortified With Bran			
	Tannin		Black	
Type/Process	**Raw Material**	**Extrudate**	**Raw Material**	**Extrudate**
0% Bran	121.2	64.1	54.0	39.7
28.5% Bran	206.6	119.5	88.4	73.3
Overall CV (a = 0.05) = 5.1%				

VITA

Duane Lawrence Turner was born in Houston, Texas in February 1978. He initiated his studies at Texas A&M University in the fall of 1996, and received a B.S. in nutritional science in May of 2001. He began his graduate career in Texas A&M's Food Science and Technology program (emphasis in cereal chemistry) in the fall of 2001. His research there was mainly focused on the use of tannin sorghums in extrusion processing and examining the physical and antioxidant characteristics of their extruded products.

While in graduate school, he also worked in Texas A&M 's Residence Life department as a graduate hall director in Moore Hall for two years. Previous to that, he was a resident advisor in Crocker Hall for three years as an undergraduate. Also, Duane has been involved in ReJOYce in Jesus Campus Fellowship since his freshman year and continued to be active in the organization throughout graduate school.

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