WHITE FOOD-TYPE SORGHUM IN DIRECT-EXPANSION EXTRUSION APPLICATIONS

A Thesis

by

DAVID ACOSTA SANCHEZ

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

December 2003

Major Subject: Food Science and Technology

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ABSTRACT

White Food-Type Sorghum Performance in Direct-Expansion Extrusion Applications.

(December 2003)

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Whole sorghum kernels were directly processed into whole grain snacks with acceptable texture. Extrudates made from whole sorghum had a harder gritty texture than those made from decorticated materials. Extrusion of whole sorghum provides significant savings in processing: there are no dry matter losses; no equipment or energy is required for decortication or milling; the extruder consumes less power and processes more material per time unit. In addition, the extruder utilized is a simple adiabiatic, friction extruder of relatively low cost.

Grinding whole sorghum and removing fines did not improve product expansion during extrusion but altered the gritty pieces in the extrudates. The best products were obtained when whole sorghum (ground or un-ground) was extruded at 14% moisture. The whole sorghum extrudates had larger bubbles with thick cell walls, which made extrudates more crunchy.

Decortication of sorghum improved extrusion performance and products by allowing adequate formation and retention of air cells. Decortication to remove 20% of the original sorghum weight was enough to produce extrudates with characteristics comparable to those made from commercial yellow corn meal.

Sorghum milled fractions with composition and particle size distribution similar to corn meal produced extrudates with higher expansion, lower bulk density and similar texture. In addition, sorghum extrudates were rated equal to corn meal extrudates by a taste panel for appearance, flavor, texture and overall characteristics. Extrudates made from polished rice were less expanded and whiter than extrudates made from sorghum. When processed under similar conditions, sorghum extrusion required more energy than corn meal extrusion. However, whole sorghum extrusion required less energy than corn meal extrusion.

Unground sorghum samples (decorticated or non-decorticated) produced harder extrudates compared to those made from ground raw material. White sorghum is a feasible option for snack extrusion because of its versatility, product characteristics, cost and processing properties.

DEDICATION

I dedicate this work to my father, Regino Acosta, for his continuous and unconditional support, and for being my father. All I can feel is simply eternal gratitude. I dedicate it also to my mother, Irma Sanchez, and sister, Regina Acosta, who also supported me greatly and were strong, especially through all the difficult times. I owe all I am and will ever be to them. Thank you.

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I thank Dr. Waniska for always being available and his attempts to make me think. I hope they worked. I thank Cassandra McDonough for all her help and sense of humor, in addition to her help with all the images you will see in this thesis. I thank Dr. Riaz for his guidance and for allowing me to use all the equipment in the Food Protein R&D Center. I thank Pam for always helping me to solve problems at lightning speed. I also thank my fellow graduate students, Ana Leal and Arturo Gutierrez, for their help, comments and friendship.

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CHAPTER I

INTRODUCTION

Extrusion cooking is used to produce a wide variety of food products with unique sensory attributes (Desrumaux et al 1999). It has been used in the cereal grain industry for decades (Zhang and Hoseney 1998) to manufacture breakfast cereals and snacks (Yeh and Jaw 1999) because it provides versatility and economic benefits.

An extruder conveys, mixes, kneads, cooks and forms in one continuous process. The energy input comes mainly from the conversion of mechanical to thermal energy. Extruded food materials undergo various transformations, including starch gelatinization, fragmentation and protein denaturation, which affect the properties of the extrudates.

The engineering involved in this technology is relatively advanced; however, information about the effect of raw material properties on extrusion performance is limited (Zhang and Hoseney 1998). Starch provides the structure and texture of many extruded foods.

The most common cereals used in the extrusion of snacks and breakfast cereals are corn, wheat, rice and oats, while other cereals such as barley, rye, sorghum and triticale could be used but so far have not been used extensively (Moore 1994).

Rice is used in multigrain snacks to increase the crispiness, reduce hardness, and as a carrier for mild flavors (Riaz 1997). Rice extrudates have white color and bland flavor, which makes them useful for providing the starch matrix for expansion while allowing alternative flavors to be added (Moore 1994). The main disadvantage of rice is

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This thesis follows the style and format of Cereal Chemistry.

Sorghum is better suited for hot, dry climates and may be less expensive than other cereals. However, it is not a major ingredient in extruded snacks (Riaz 1997; Falcone and Philips 1988) or breakfast cereals. Because of its lower cost, sorghum is an attractive ingredient for the production of extruded snacks or breakfast cereals. The extrusion performance and product characteristics of white food sorghums have not been thoroughly documented.

The objectives of this study are: 1) to evaluate the effects of decortication level and particle size on extrudate characteristics, 2) compare the characteristics of extrudates made from corn meal, rice and sorghum, 3) determine optimal conditions for the extrusion of whole white sorghum, 4) determine the effects of grinding on whole sorghum extrusion.

CHAPTER II

LITERATURE REVIEW

Expanded snacks

The increasing amount of time spent away from home has led to an increase in snacking (Euromonitor 2001). Consumers now see eating as something to be done while you do something else (Calder 2000). The percentage of US adults incorporating snacks as part of their daily eating habits reached 63% in 1999, an increase of five percentage points from 1995. In 2000 the US market of savory snacks grew 5.2% over 1999, to reach US$17.6 billion. The market is forecast to total US$20.49 billion by 2005, a gain of 11.1%.

There are two types of expanded snacks: second and third generation. Second generation snacks are those that expand when they come out of the extruder. This is the most popular type of expanded snack. Third generation snacks or pellets do not expand when they come out of the extruder. After storage, the pellets are puffed by frying, microwave heating or hot air puffing.

Expanded products like snacks and breakfast cereals are very popular today because of their crunchy texture, which arises from the honeycomb structure imparted to the material during extrusion (Barrett and Peleg 1992). In the US, snacks and breakfast cereals are normally made from corn, although rice, wheat and oats are also used. Because they have not been available until recently, new white food sorghums have not been utilized in extrusion in the US in spite of its lower cost, white endosperm and bland flavor. If the processing characteristics of white food sorghums resemble those of corn or rice, they could represent an attractive alternative in extrusion processing of snacks.

Extrusion

Extrusion is a process in which starchy raw materials are heated, sheared and pressurized to form a viscous melt. This melt is later forced through a die that forms the product. According to the extrusion conditions used and products obtained Rokey (2000) classified extrusion processes into three categories:

- Low-shear (forming) extruders: used to increase density of material that is generally high in moisture (e.g. pasta) using low screw speeds.
- Medium-shear stress: used to process raw materials with lower moisture content with higher energy inputs (e.g. pet foods, aquatic feeds, texturized vegetable protein).
- High-shear stress: where extrusion speeds and energy inputs are high to process low-moisture raw materials in a short length-to-diameter ratio barrel. Highly expanded products are obtained (e.g. snacks, breakfast cereals).

One type of high-shear stress extruders is the dry friction-type extruder. This extruder does not require an external source of heating since friction produces temperatures above 150 °C. Heating is only required to pre-heat the extruder barrel and die. This type of extrusion is usually performed in single-screw extruders.

Single-screw extruders

Single-screw extruders are the most important type of extruders used in the food industry. They are used to process many different products like pasta, expanded snacks, pet foods, breakfast cereals and snacks. They contain only one screw inside the barrel, compared to the twin-screw extruders, which have two.

Their operation is fairly simple. The raw materials are fed into a bin, which has to be of adequate size to support extruder operation. It ensures a continuous supply of material into the extruder, which is essential for the stability of the process. The raw materials are fed into the barrel or pre-conditioner of the extruder at a uniform rate controlled by a metering device. The pre-conditioner is used to temper the raw material by adding water and heat. Tempering enhances water homogeneity in the product and consequently, allows the production of better products compared to those produced when the water is added directly into the barrel. However, tempering in a mixer (adjust moisture) before extrusion eliminates the need for a pre-conditioner in the extruder.

According to Rokey (2000), the extruder barrel assembly consists of a rotating extruder shaft (screw) and elements (maybe segmented screws and shearlocks), a stationary barrel housing (maybe segment sections), and a die and knife assembly. The screw is responsible for the mechanical energy application and materials conveying.

Screw geometry is very important because of its effects on mixing, conveying, heat and pressure development. The geometry can vary in pitch distance, depth and angle, root diameter, number of flights, shearlocks and total screw diameter. The most common extruders normally include varying pitch, constant depth, increasing root diameter, increasing number of flights, and decreasing diameter (Rokey 2000).

Effect of main extrusion parameters

Particle size

Particle size greatly affects both processing and extrudate characteristics. It basically alters the extent at which starch is modified inside the extruder. Finer raw materials tend to give products with softer textures and smaller cell structures, while coarse particle size materials produce extrudates with crunchier texture and larger cell structure.

However, small particles cause problems during extrusion. Small particles tend to segregate in the feeding system and in the inlet portion of the extruder barrel. Small particles absorb water much faster than coarse particles, causing a non-homogeneous moisture distribution. This alters product flow and cooking uniformity inside the extruder, producing surging and fluctuation in product quality. This surging can cause the extruder to plug, stopping the production. However, this problem can be diminished with tempering, equilibration and proper granulation of the raw materials. Single-screw extruders are more susceptible to problems with fines (small particles) compared to twin-screw extruders.

Moisture

Moisture in the raw materials allows the extrudates to expand. In high friction extrusion, the raw material becomes liquid inside the extruder. The temperature is well above the boiling temperature of water but under pressure. When the product exits through the die the pressure decreases suddenly and the super-heated water evaporates, expanding the product.

Water also reduces interactions between the raw materials by plasticising the polymer, transforming them from solids to deformable plastic fluids (Guy 2000). Plasticization reduces friction inside the extruder by reducing the dissipation of mechanical energy and heat input. The viscosity of the melt decreases with increasing moisture content.

Screw speed

The screw conveys the materials inside the extruder. Thus, it controls the residence time in the extruder and how much mechanical energy is transferred to the raw material. The higher the screw speed, the higher the specific mechanical energy applied to the product in the form of friction. It is expected to have a higher expansion ratio with increasing screw speed.

Sorghum

Sorghum originated in equatorial Africa and is distributed throughout the tropical, semitropical, and arid regions of the world (Waniska and Rooney 2000). It was domesticated as human foodstuff and animal feed 3000 to 5000 years ago in Africa and spread subsequently into India and China (Hancock 2000). It is well suited for hot and dry climates. It is less expensive than other cereals and the new food-type white hybrids have excellent potential for processing into foods.

Sorghum (*Sorghum bicolor* L. Moench) is a staple food for millions of people around the world, mainly in Africa and Asia, where it is utilized to make, porridges, beers, other alcoholic and non-alcoholic beverages, and leavened or unleavened breads. However, it is normally used as animal feed in western countries like the US. Tannins are polymeric phenols produced mainly in the testa as a defense mechanism against molds and birds. However, they lower digestibility of foods by binding proteins and carbohydrates, which, in turn decreases weight gain. Nevertheless, white food-type sorghums with a white pericarp and without a pigmented testa have been developed recently and are grown under identity preserved conditions.

The endosperm forms from the fusion of a male gamete with two female polar cells and has a starch content of about 80%. The pericarp is the outermost layer of the sorghum kernel. It originates from the ovary cell wall and is rich in fiber and ash. The testa or seed coat derives from the ovule integuments and can contain tannins and other anthocyanin pigments. The aleurone layer is actually part of the endosperm and is rich in protein and ash. The germ is diploid and is formed by the fusion of a male and female gametes. It is rich in oil and proteins.

Sorghum is normally decorticated before being processed into food products to separate the outer layers from the starch-rich endosperm. The layers normally removed are the pericarp, testa, aleurone layer and germ. Decortication results on reduction of the protein, fat, crude fiber and ash content of the decorticated grain compared to the whole grain (Rooney et al 1972). The chemical composition of sorghum is shown in Table I.

Table I
Chemical composition (%) of sorghum and its anatomical tissues (Waniska and Rooney 2000)

	Caryopsis	Endosperm	Germ	Pericarp
Caryopsis	100	84.2	9.4	6.5
Range	------------	81.7-86.5	8.0-10.9	4.3-8.7
Protein	11.3	10.5	18.4	6.0
Range	7.3-15.6	8.7-13.0	17.8-19.2	5.2-7.6
Distribution	100	80.9	14.9	4.0
Fiber	2.7	------------	------------	------------
Range	1.2-6.6	------------	------------	------------
Distribution	100	------------	------------	------------
Lipid	3.4	0.6	28.1	4.9
Range	0.5-5.2	0.4-0.8	26.9-30.6	3.7-6.0
Distribution	100	13.2	76.2	10.6
Ash	1.7	0.4	10.4	2.0
Range	1.1-2.5	0.3-0.4	------------	------------
Distribution	100	20.6	68.6	10.8
Starch	71.8	82.5	13.4	34.6
Range	55.6-75.2	81.3-83.0	------------	------------
Distribution	100	94.4	1.8	3.8

Sorghum processing

White sorghums have good processing characteristics and have been used satisfactorily to process a wide variety of products normally made from other cereals like cookies (Leon-Chapa 1999), tortillas (Quintero-Fuentes 1999; Choto et al 1985; Almeida-Dominguez et al 1991), noodles and related products (Murty and Kumar 1995), among others. Products made from white sorghum normally have a desirable bland flavor and white color.

Almeida–Dominguez et al (1996) processed tempered sorghum meal in a single screw extruder to manufacture expanded snacks. They found that sorghum meal extruded at low feed moisture and high screw speeds developed high expansion and resulted in sorghum extrudates with low bulk densities. They concluded that sorghum could be used in blends with other cereals and/or legumes to produce snacks or precooked flours.

Maranphal et al (2002) extruded sorghum meals of varying particle sizes and decortication levels. They concluded that sorghum extrudates have a bland flavor and white color that can be used as carriers for other flavors. In Japan, there are different types of extruded snacks made from white sorghum that are already being produced and merchandised. Those snacks are highly expanded, light, have soft texture, and very bland flavors.

Starch in sorghum

Starch is found in the endosperm of cereals in the form of water-insoluble semi-crystalline granules embedded in a continuous protein matrix. The semi-crystallinity is due to the presence of both crystalline and amorphous areas in the granule. The crystalline areas are formed by hydrogen bonds in aligned neighboring branches of amylopectin molecules.

Sorghum starch granules are normally polygonal and are very similar to corn starch granules. A normal sorghum starch granule contains 23-30% amylose (Waniska and Rooney 2000), the rest being amylopectin. However, there are waxy and heterowaxy sorghum varieties which have less and/or no amylose content.

There are three characteristic areas in the endosperm, peripheral, corneous or hard and soft or floury. In the peripheral there is a high protein content in the form of a strong protein matrix and protein bodies. The hard endosperm is tightly packed (due to a strong protein matrix) with no air voids, which makes it look translucent. Protein-starch interactions are very strong in this area of the endosperm. If endosperm is fractured, the break often occurs through starch granules instead of at the starch-protein interface (Floyd 1996).

In the soft endosperm, the protein matrix is much weaker and there are air cells that make it look opaque. The processing characteristics of the different types of endosperm are very different, especially in extrusion.

Decortication is normally done without tempering in an abrasive pearler containing stones or resinoid disks (Rooney and Waniska 2000). From 5 to 20% of the original kernel weight is normally removed using this method. According to Rooney and Waniska (2000), kernels with a thick pericarp, hard endosperm and round shape are preferred because they are faster and more easily decorticated and they produce higher yields. Kernels with soft endosperm are not normally decorticated.

Structure formation

At elevated temperatures, biopolymers in food (starch and protein) start losing their orderly molecular structure. Proteins begin denaturing and starch begins gelatinizing (Akdogan et al 1997). Starch gelatinization causes an initial rise in the viscosity of the melt in the extruder. However, fragmentation and formation of complexes may follow gelatinization of starch in the extruder, depending on the degree of severity of the process, which may decrease the melt viscosity.

Amylopectin is more susceptible to breakage during extrusion because its size and highly branched shape generates more friction. Fragmentation occurs mainly through the breakage of the α–1,6 bonds in the amylopectin chains (Gropper et al 2002), although some α–1,4 linkages cleavage occurs at temperatures above 180 °C through a pyroconversion process (Brummer et al 2002[a]).

The process variables such as mass flow, water injection, barrel temperature, screw configuration, screw speed, feed rate, and feed material affect physical properties of extrudates (Ryu and Ng 2001). In addition, physical features of raw materials, such as the particle size, hardness and frictional characteristics of powders and the lubricity and plasticising power of fluids are very important in this process (Guy 2001).

The structure of an extruded product is created by forming a melt fluid from biopolymers at high pressure. When the melt exits through the die, the sudden decrease in pressure vaporizes the water (which is heated above 100 °C), and causes the product to expand, forming foam-like extrudates. Extrudate temperature decreases rapidly during expansion due to water evaporation, while melt viscosity increases because of the decrease in temperature and moisture loss, which rigidifies the cellular structure (Guy 2001).

Because of the elastic properties of the pore wall of the expanded melt, the pores contract when the water vapor inside the pores falls below the counter pressure exerted by the elasticity of the pore wall (Brummer et al 2002[b]). This contraction continues until the melt attains the glassy state. Pore wall-forming polymers must have a minimum molecular weight sufficient to give enough fluid viscosity to prevent or control the shrinkage of an extrudate after it has reached its maximum expansion and ruptured the gas cells. On the other hand, a highly viscous melt would produce rapid shrinkage of the structure of the extrudate.

The extrudates harden upon further loss of water (drying phase) and cooling (cooling phase), after attaining the glassy-state (Brummer et al 2002[b]). Since the glassy state appears after the product temperature falls below the Tg, the solidification of the extrudates depends on molecular size, moisture and product temperature when it exits through the die.

To increase the volume of the product, the film of biopolymers must flow easily in the bubble walls to allow the bubbles to expand (Guy 2001). Since the average polymer size found in most natural starches is too large to achieve the necessary polymer flow, the use of high mechanical shear during extrusion cooking is necessary to reduce the average molecular weight of the starch. The smaller molecules allow more flow in bubble cells walls and cause an increase in expansion from 1 to 25 ml/g (Guy 2001).

Expansion is a very important parameter because it is related to product quality. Expansion volume is the primary quality parameter associated with product crispiness, water absorption, water solubility and crunchiness (Ali et al 1996). Expansion depends upon feed composition, extent of cooking and melt flow in the die (Desrumaux et al 1998).

Starch amylose and amylopectin contents have a marked impact on extrusion expansion (Zhang and Hoseney 1998). A higher proportion of amylose tends to reduce expansion, while the opposite happens with amylopectin. Under normal conditions, the high molecular weight amylopectin (AMP) is fragmented. This decrease in AMP size ranges from 17 to 60%, depending on the moisture content of dough and the screw speed of the extruder (Zhang and Hoseney 1998).

After extrusion, the product usually has moisture content between 8 and 10%. So, the product is baked at high temperatures to increase crispness by reducing moisture to the desired range of 1-3% moisture.

CHAPTER III

DECORTICATION LEVEL AND PARTICLE SIZE EFFECTS ON EXTRUDATES MADE FROM A FOOD-TYPE WHITE SORGHUM

Justification

Decortication and particle size are variables that have a profound effect on extrusion performance. Several studies have analyzed the effects of particle size (Desrumaux et al 1998; Chauhan and Bains 1985; etc.) and the composition (altered by decortication) (Grenus et al 1993; Andersson et al 1981; etc) on extrusion of corn and rice raw materials. However, their effects on sorghum extrusion have not been sufficiently studied. Thus, the objective of this experiment was to evaluate the effects of decortication level and particle size on extrudates made from white sorghum, and compare sorghum extrudates to those made from corn meal and rice.

Materials and methods

Raw materials preparation

White sorghum hybrid, ATX631xRTX436, grown in College Station, Texas in 2001 was used for extrusion. Yellow cornmeal (Archer Daniels Midland Company, February 2001), long grain and polished long grain rice acquired in a local Kroger store (College Station, TX., 2002) were used as controls.

Sorghum was decorticated in 4 kg batches in a PRL mini-dehuller (Nutama Machine Co., Saskatoon, Canada) to remove 10, 20 and 30% of the original grain weight (Fig. 1, Table II). The decorticated grain was cleaned through a KICE grain cleaner (Model 6DT4-1, KICE Industries Inc., Wichita, KS). After cleaning, whole grain and samples of the three different decortication levels were milled in a hammer mill (Fitzpatrick Hammer Mill D, Fitzpatrick Co., Chicago, IL) through a mesh with 2360 μm holes. The ground samples were sieved using No. 20 and 50 US Standard sieves (850 and 300 µm, respectively). The overs of No. 20 (coarse) and 50 US Standard sieves (meal) were retained and the fines discarded (Fig. 2). Whole and decorticated kernels (not milled) were also processed. Protein, residual fat and ash was determined for all raw materials using standard analytical procedures (AACC 2000).

Sorghum characterization

Density was evaluated using a gas comparison pycnometer (Multipycnometer, Quantachrome, Syosset, NY). Test weight was determined with a Winchester Bushel Meter. Hardness index was evaluated with a Tangential Abrasive De-Hulling Device (TADD) with 20 g sample and 3.5 min abrasion time. Thousand kernel weight (TKW) was determined by weighing 100 kernels and multiplying by 10. The diameter of 20 sorghum kernels were determined with an electronic caliper and averaged. Hardness was also determined with a single kernel hardness tester (SKHT, model SKCS 4100, Perten Instruments, Reno, NV). Particle size distribution was calculated in triplicate using #10, 20, 30, 40, 60, 80 and 100 US standard sieves and 50 g sample size.

Extrusion

Raw materials were tempered at 14% moisture content 24 h prior to processing. Extrusion was performed in a single-screw friction-type extruder (model MX- 300I, Maddox Inc, Dallas, TX). The extruder had a length/diameter ratio of 4, two flow plates and a die with 6, 1/8 inch (3.175 mm) holes. The energy consumed by the extruder was monitored during processing on the extruder display. The nominal mechanical power applied by the extruder was calculated using the power formula for three-phase motors.

$$Power(kW) = \sqrt{3} * Current(Amp) * Voltage(KV) * PF * Eff$$

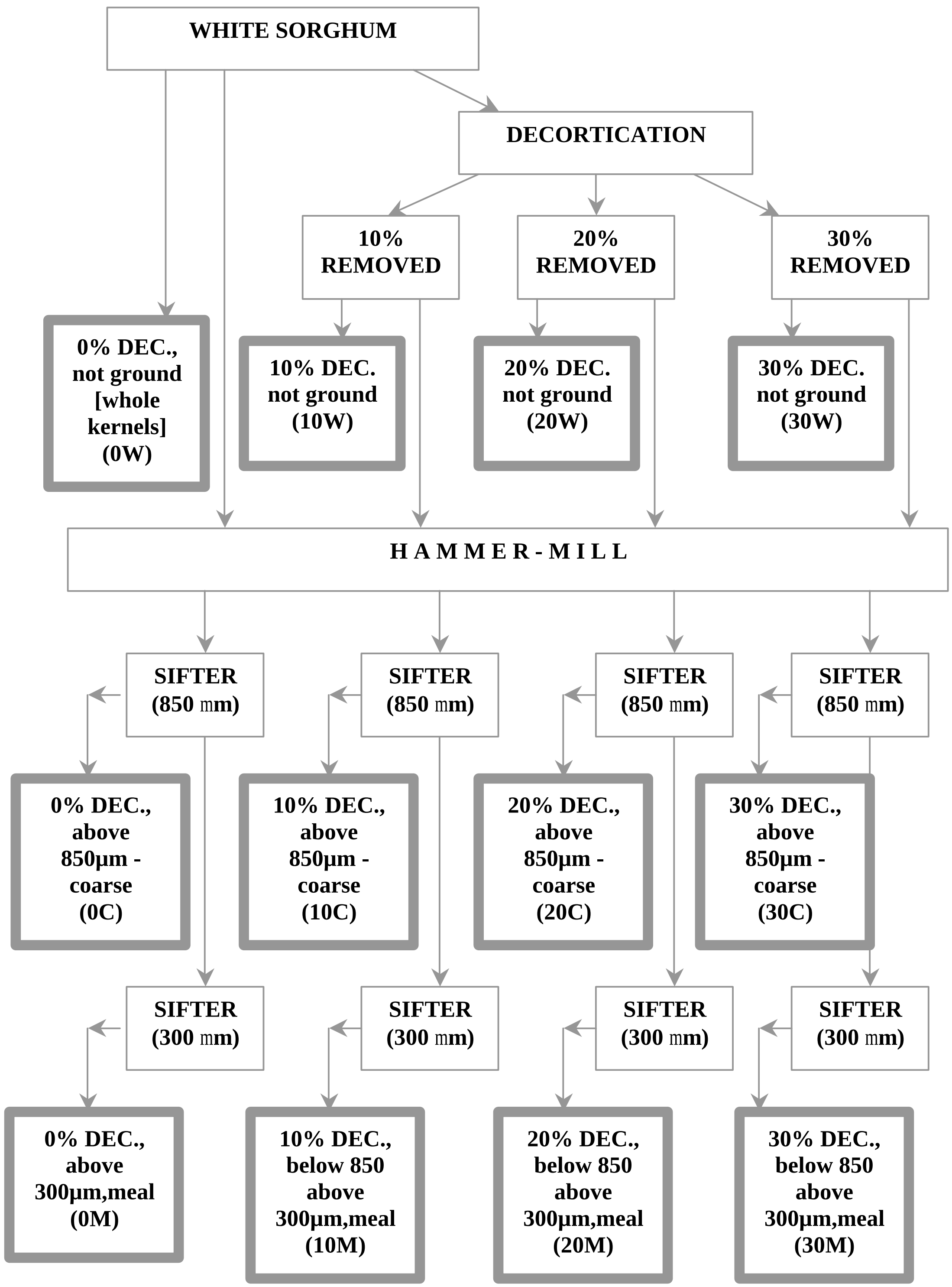

Fig. 1. Flow chart of raw materials preparation procedure from white sorghum (thick line square=treatment).

Table II

White sorghum raw materials used for extrusion and abbreviations

Decortication / particle	**Whole** (not ground)	**Coarse** (ground, above #20 US Sieve)	**Meal** (ground, between #20 and 50 US Sieves)
0%	0W[a]	0C	0M
10%	10W	10C	10M
20%	20W	20C	20M
30%	30W	30C	30M

a The number in abbreviation refers to the % removed during decortication. Letter in refers to the particle size.

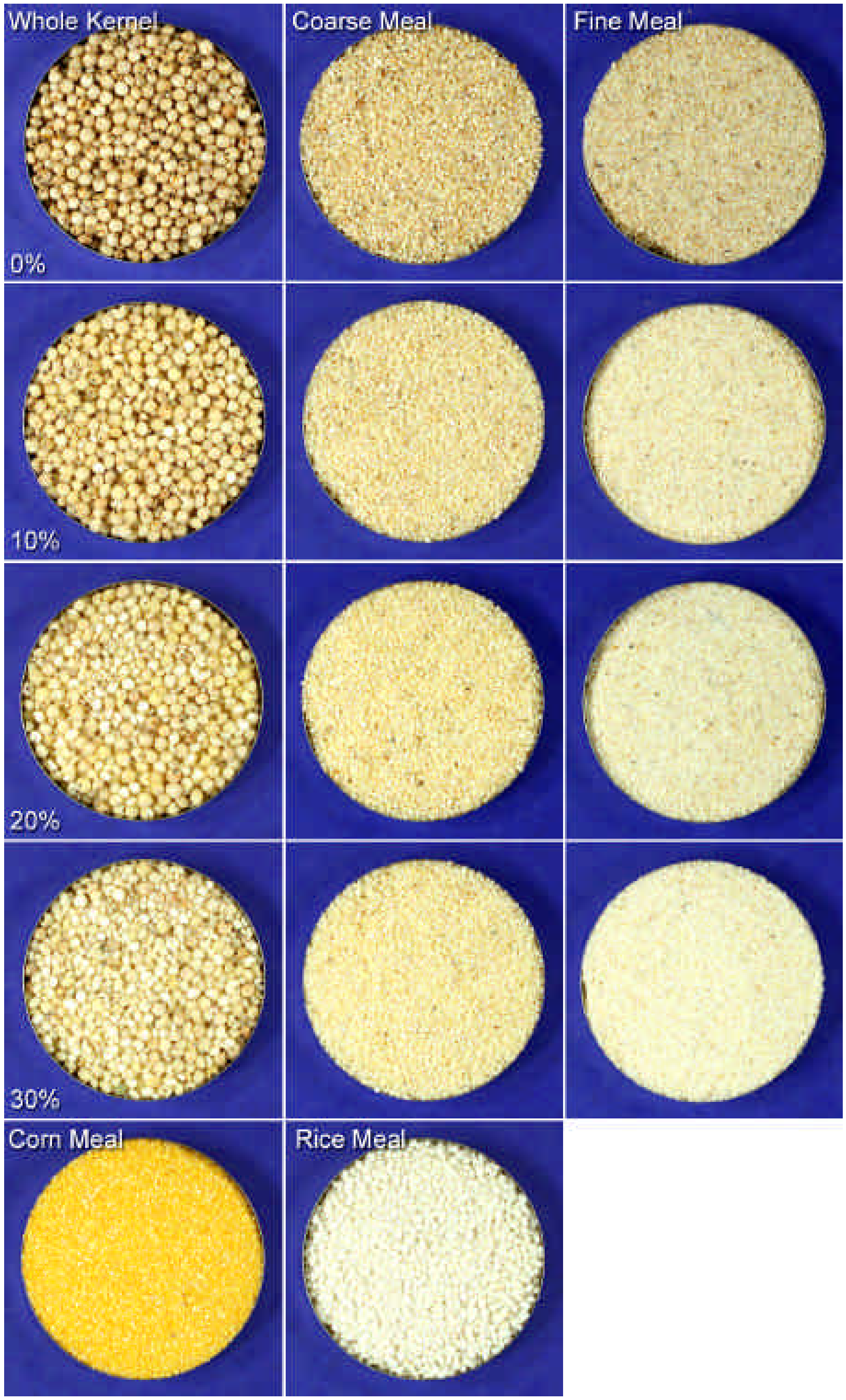

Fig. 2. Physical appearance of sorghum, corn and rice raw materials.

where PF is the power factor of the motor, and Eff is the motor efficiency. The voltage was 460 V, the power factor of motor was 80%, and the efficiency 93%.

After extrusion, the samples were baked at 100°C for 30 min in a tray convection oven and stored in metallic plastic bags. The baked extrudates (between 1.5 and 3% moisture) were used for analysis.

Expansion and bulk density

The expansion ratio was determined according to method of Gomez et al (1988). Radial expansion ratio was calculated by the ratio of average extrudate diameter to die diameter. Ten extrudates were measured and averaged. A container of extrudates with a 15 L volume was weighed. The weight of the extrudates measured in triplicate divided by the container volume was the bulk density.

Color

The color of extrudates was determined with a colorimeter (model CR-310, Minolta, Osaka, Japan), using CIE L*a*b* color scale. The parameters reported were L*, a*, b*, and chroma. The test was performed on ground extrudates passing through US standard sieve no. 40 (Hsieh et al 1993).

Water solubility index

Water solubility index (WSI) was evaluated on ground extrudates passing through US Standard sieve no. 40 (425 µm) using the method of Anderson et al (1969). Sample (2 g on dry basis) was mixed with 40 g of water in a tared centrifuge tube. The suspension was allowed to stand for 30 min, mixing by agitation at 15 min of resting time, and centrifuged at 3900 g for 15 min in a centrifuge (model TJ-6, Beckman, Palo Alto, CA). The supernatant was transferred to another tube and the sediment weighed.

The supernatant was dried for 24 h and weighed. The WSI was calculated using the formula (Lo et al 1998):

$$WSI = \frac{(a-b)}{(100-M)\times c}\times 100$$

where a, b, c and M represent the weight of the dried tin for supernatant plus sample, weigh of the empty tin, initial sample, and sample moisture content, respectively.

Mechanical properties

The mechanical properties of the extrudates were tested using a texture analyzer (model TA.XT2i, Texture Technologies Corp., Scarsdale, NY) using a needle to puncture the extrudates on a flat platform. The needle utilized had a flat tip and a 2 mm diameter.

The mean force, elastic (Young's) modulus, work required to puncture the extrudates and the number of force peaks were recorded. Forty measurements per treatment were conducted and averaged. Elastic modulus was calculated as the slope of the linear region of the curve of force vs. distance, before the extrudate is ruptured.

Statistics

The effect of decortication level and particle size on the extrusion properties of sorghum was evaluated in a factorial experiment with a completely randomized design. Treatments were separated with Fisher's LSD with an α=0.05. Statistics were performed with SAS statistical software package (SAS 2000).

Results and discussion

Sorghum characterization

The time required to decorticate sorghum is shown (Table III). ATx631xRTx436 sorghum hybrid showed typical values when characterized (Table IV). Sorghum characterization showed that it had a high proportion of hard endosperm because of its high density, test weight, and TKW; its relatively low % weight removed in the TADD and the hard classification given by the SKHT.

Sorghum had a characteristic pericarp color with negligible weathering. Excellent extrusion performance was obtained because of the endosperm hardness and clean, bright, shiny sorghum kernels.

Particle size and composition

The corn meal had typical particle size distribution for extrusion of expanded corn puffs (Table V), in which the majority of the particles are retained above #40 US Standard sieve (Burtea 2001). None of the sorghum raw materials had a particle size distribution similar to that of rice or corn meal. However, coarse sorghum (C) samples had most of the particles above the #40 US Standard sieve (425 μm) like corn meal.

Decortication broke many of the whole particles. Thus, as decortication level increased, more particles passed through the #10 and #20 US Standard sieves (2000 and 850 μm, respectively).

As expected, the protein, oil and ash contents decreased for sorghum raw materials with increasing decortication level (Table VI and VII). Ash is evidence of pericarp presence since its concentration is 30 times higher in the pericarp than the

Table III

Time of decortication required to abrade and remove the desired amount of initial sorghum kernel weight

Decortication %	Time (s)
10	140
20	290
30	510

Table IV

Physical characteristics of ATx631xRTx436 sorghum hybrid

Test	Value
Test weight	62.2 lb/bu
Density	1.371 g/cm^3
Thousand Kernel Weight (TKW)	31.44 g
Kernel average diameter	3.7 mm
Single Kernel Hardness Test (SKHT)	Hard
Weight removed (TADD)	23.2%

Table V

Particle size distribution (% weight) of sorghum, corn and rice materials

Sample/ US Std Sieve	#10 (2000 mm)	#20 (850 mm)	#30 (600 mm)	#40 (425mm)	#60 (250 mm)	#80 (180 mm)	#100 (150 mm)	Plate (<150 mm)
0W	99.9 a[a]	0.04 g	0 f	0 f	0 e	0 c	0 d	0 c
10W	98.9 a	1.0 g	0 f	0 f	0 e	0 c	0 d	0 c
20W	87.3 b	12.6 d	0.03 f	0 f	0 e	0 c	0 d	0 c
30W	71.0 c	28.8 c	0.13 f	0 f	0 e	0 c	0 d	0 c
0C	0 e	95.6 a	4.3 e	0.03 f	0 e	0 c	0 d	0 c
10C	0 e	94.0 a	5.9 d,e	0 f	0 e	0 c	0 d	0 c
20C	0 e	93.5 a	6.4 d	0 f	0 e	0 c	0 d	0 c
30C	0 e	91.1 a	7.6 d	0.9 e,f	0.2 e	0 c	0 d	0 c
0M	0 e	7.1 e,f	37.4 b,c	38.8 a	13.5 c	2.1 b	0.5 c	0.2 b
10M	0 e	8.3 d,e	38.1 c	33.5 b	15.3 b,c	2.8 b	1.3 b	0.4 b
20M	0 e	9.1 d,e	36.6 c	29.8 c	16.9 b,c	3.9 a	2.1 a	1.2 a
30M	0 e	8.5 d,e	38.7 b	27.5 d	20.0 a	2.2 b	1.4 b	1.3 a
Corn meal	0 e	3.5 f,g	51.2 a	40.7 a	4.1 d	0.3 c	0 d	0 c
Rice	8.2 d	81.5 b	6.5 d	3.1 e	0.5 e	0 c	0 d	0 c
LSD(α=0.05)	4.5	4.7	1.9	2.3	2.87	1.0	0.29	0.29

a Treatments with same letter are not significantly different ($p<0.05$)

Table VI

Composition of sorghum, corn and rice materials used for extrusion

Particle size	Decortication %	% Crude Protein[a]		% Ash[b]		% Oil[b]	
Whole (un-ground)	0	9.45	d[c]	1.31	b	3.43	b
	10	9.97	c	1.01	c	2.50	c
	20	8.89	f	0.77	e,f	1.73	e
	30	9.00	f	0.65	g	1.00	h
Coarse	0	10.00	c	0.86	d,e	2.68	c
	10	10.35	b	0.76	e,f,g	1.51	f
	20	9.33	d,e	0.50	h	1.06	h
	30	9.12	e,f	0.41	h	0.91	h
Meal	0	10.67	a	1.74	a	4.04	a
	10	10.82	a	1.35	b	3.27	b
	20	9.32	d,e	0.91	c,d	2.22	d
	30	9.00	f	0.71	f,g	1.32	g
Corn meal		9.03	e,f	0.75	f,g	2.10	e
Rice		8.20	g	0.41	h	0.69	I
LSD (α=0.05)		0.32		0.11		0.19	

a Crude protein was calculated using the Dumas method
b Ash and residual oil were calculated using standard methods (AACC, 2000)
c Treatments with same letter are not significantly different ($p<0.05$)

Table VII

Average composition of sorghum samples from different particle sizes and decortication levels

Groups	% Crude[a] protein		% Ash[b]		% Oil[b]	
Particle size						
Whole (un-ground)	9.33	c[a]	0.85	b	2.17	b
Coarse	9.70	b	0.56	c	1.54	c
Meal	9.95	a	1.04	a	2.71	a
LSD (α=0.05)	0.16		0.05		0.10	
Decortication %						
0	10.04	b	1.17	a	3.38	a
10	10.38	a	0.93	b	2.43	b
20	9.18	c	0.65	c	1.67	c
30	9.04	c	0.53	d	1.08	d
LSD (α=0.05)	0.32		0.11		0.19	

a Crude protein was calculated using the Dumas method
b Ash and residual oil were calculated using standard methods (AACC, 2000)
c Treatments with same letter are not significantly different ($p<0.05$)

endosperm. At the same decortication level, meal particles had higher oil and ash content, followed by whole and coarse particles (Table VII). Thus, fiber and germ pieces were in a higher proportion in the meal particles. This affected their extrusion performance compared to the other particle sizes at the same decortication level.

Power consumed

The power consumption of the extruder increased as the decortication level of sorghum raw materials increased (Fig. 3, Tables VIII and IX). This agrees with previous studies in which there was a decrease in energy consumption when rice flour with increasing bran content was extruded (Grenus et al 1993).

This behavior was due to the lower oil and fiber content (described by lower ash content) of samples with increasing decortication (Table VI and VII). Probably, starch required more energy to be extruded compared to oil or fiber present in sorghum. In addition, germ removal caused by decortication reduced oil content (Table VI), increased friction and thus, increased the power consumed by the extruder (Tables VIII and IX).

Sorghum decorticated to remove 30% of the initial weight had a composition and yield (decorticated material per initial kernel weight) similar to that of rice or corn meal (Rooney and Suhendro 2001). Samples decorticated to 30% consumed more power compared to corn meal, which means that sorghum required more energy to be transformed inside the extruder. Power consumed by rice was similar but still lower than that of sorghum.

Coarse particles consumed more energy inside the extruder compared to whole particle sizes (Table IX). This could be due to the higher proportion of hard endosperm of coarse compared to whole particles, which increased energy consumption.

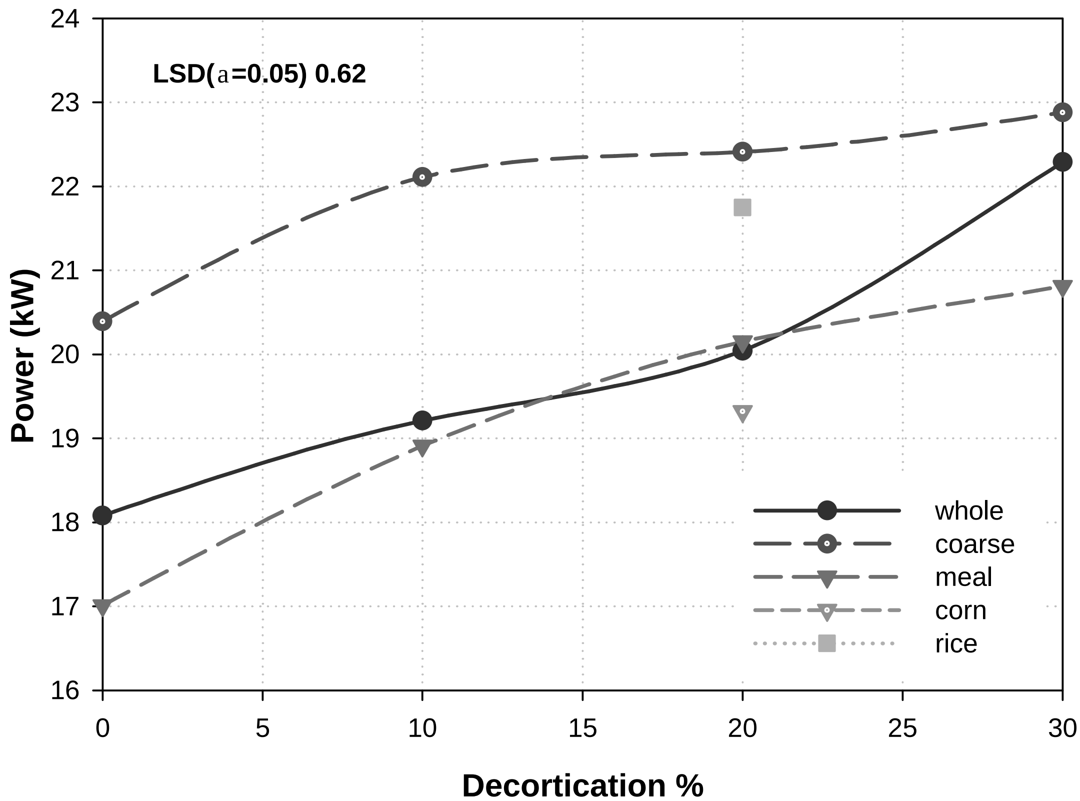

Fig. 3. Power consumed by the extruder when sorghum, corn meal and rice were processed at 14% moisture (Whole=un-ground particles, coarse= ground and above #20 US Std Sieve, meal=ground and between #20 and #50 US Std Sieve).

Table VIII

Power consumed for extrusion[a] of sorghum, rice and corn

Particle size	Decortication %	Power (kW)	
Whole (un-ground)	0	24.30	g[b]
	10	25.81	f
	20	26.93	e
	30	29.96	a,b,c
Coarse	0	27.41	d,e
	10	29.72	b,c
	20	30.12	a,b
	30	30.75	a
Meal	0	22.87	h
	10	25.42	f
	20	27.09	e
	30	27.97	d
Corn meal		25.97	f
Rice		29.24	c
LSD (α=0.05)		0.84	

a All samples extruded at 14% moisture
b Treatments with same letter are not significantly different ($p<0.05$)

Table IX

Average power consumed in extrusion[a] of sorghum with different particle sizes and decortication levels

Groups	Power (kW)	
Particle size		
Whole (un-ground)	26.75	b[b]
Coarse	29.50	a
Meal	25.83	c
LSD (α=0.05)	0.42	
Decortication %		
0	24.86	d
10	26.98	c
20	28.05	b
30	29.56	a
LSD (α=0.05)	0.49	

a All samples extruded at 14% moisture
b Treatments with same letter are not significantly different ($p<0.05$)

Desrumaux et al (1998) suggested that larger particles have less contact area between them, decreasing friction, and thus, power consumption compared to smaller particles. This could explain the higher power consumption for coarse compared to whole particles. However the last statement did not apply for meal particle size, which consumed less energy than coarse particles (Table IX). This could be caused by the higher oil and lower hard endosperm content of meal particles (Table VII).

Extrudates

All raw materials worked well in the extruder. Extrudates from all treatments were highly expanded and had a characteristic expanded snack appearance (Fig. 4). Whiter, more expanded extrudates were obtained from sorghum raw materials with increasing decortication level.

Extrudates made from coarse particles looked more expanded than those made from other particle sizes, even when the sorghum was not decorticated (0C). Some sorghum extrudates were as expanded or more than those made from corn or rice. Extrudates from corn meal were yellow color while extrudates made from polished rice were white (Fig. 4).

Expansion

In general, extrudate expansion ratio increased and bulk density decreased as decortication level increased for all particle sizes (Fig. 5). Lower expansion due to the presence of bran was also described by Faubion and Hoseney (1982) and Grenus et al (1993). Expansion ratio was the highest (including corn meal and rice kernels) for 20C treatment with a value of 5.04 (Table X). The expansion ratio and bulk density are important because they are the primary quality parameters associated with product crispness, water absorption, water solubility and crunchiness (Ali et al 1996).

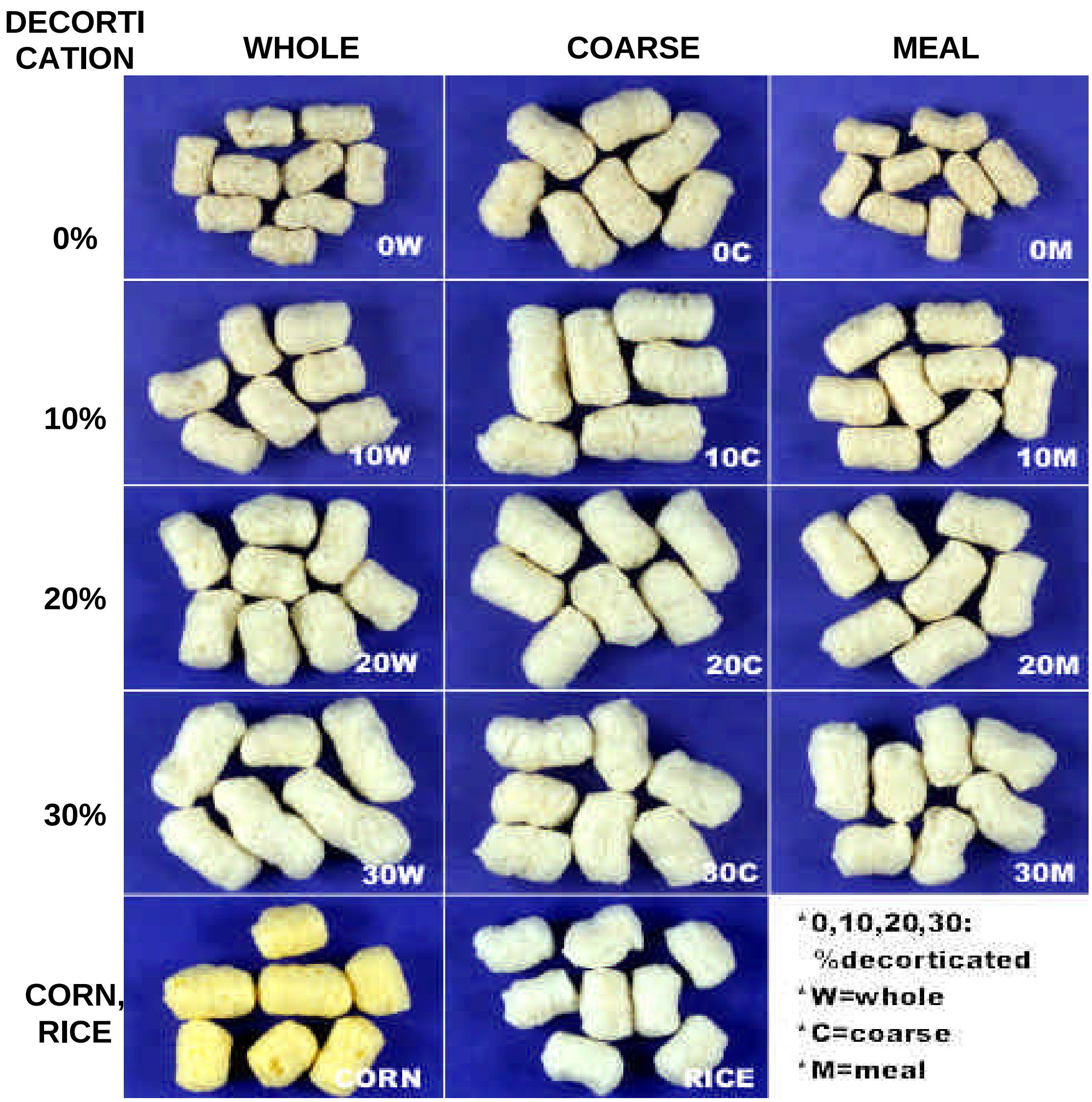

Fig. 4. Physical appearance of sorghum, corn and rice extrudates.

Increasing decortication level allowed the production of sorghum extrudates with more desirable characteristics and compared favorably with corn meal extrudates. Although sorghum particles decorticated to 30% (for all particles sizes) expanded more when extruded (except for coarse particles which was the same as for 20% decortication), decortication to 20% was enough to produce extrudates with an expansion similar to that of corn or rice.

The removal of the pericarp, testa, aleurone layer and germ (and consequently the protein, bran and oil removal) during sorghum decortication allowed the starch to form the extrudate structure more adequately, retaining more and larger bubbles (higher expansion). Thus, higher expansion was obtained with increasing decortication level.

Expansion ratio of extrudates was higher when prepared using coarse particles compared to whole and meal sizes, regardless of the decortication level (Fig. 5, Table XI). However, whole sorghum without decorticating and/or milling was extruded to produce extrudates with good expansion, (Fig. 4). This could be a unique property of sorghum, which could allow whole grain snack extrusion and reduction in processing costs.

As previously mentioned, extrudates made from coarse sorghum particles expanded more and in general had more desirable characteristics than those made from whole and meal particles (Table XI). Apparently, the coarse particles are more adequately transformed into expanded snacks in this type of extruder. The removal of the softer endosperm pieces probably allowed coarse particles to work better in the extruder. This can be inferred from the better products obtained from coarse particles, when compared to those made from meal and whole particles containing fines.

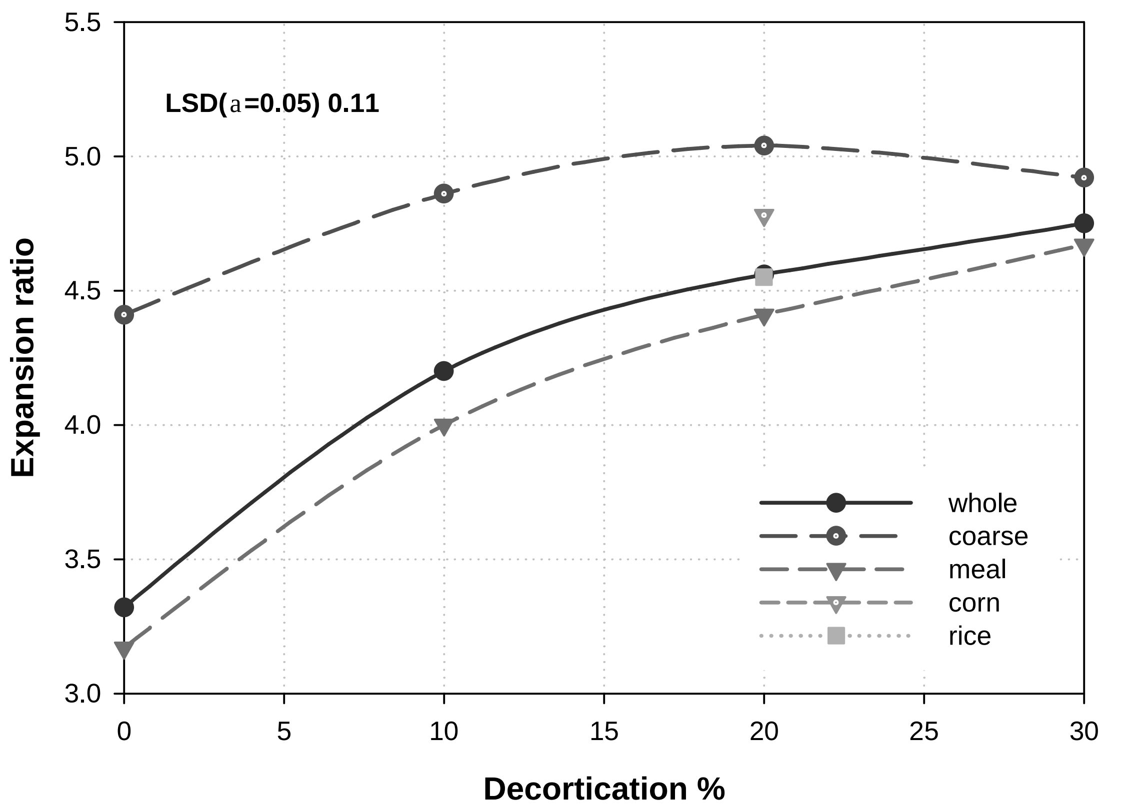

Fig. 5. Effect of decortication and particle size on expansion ratio of extrudates made from sorghum, corn meal and rice (whole=un-ground particles, coarse= ground and above #20 US Std Sieve, meal=ground and between #20 and #50 US Std Sieves).

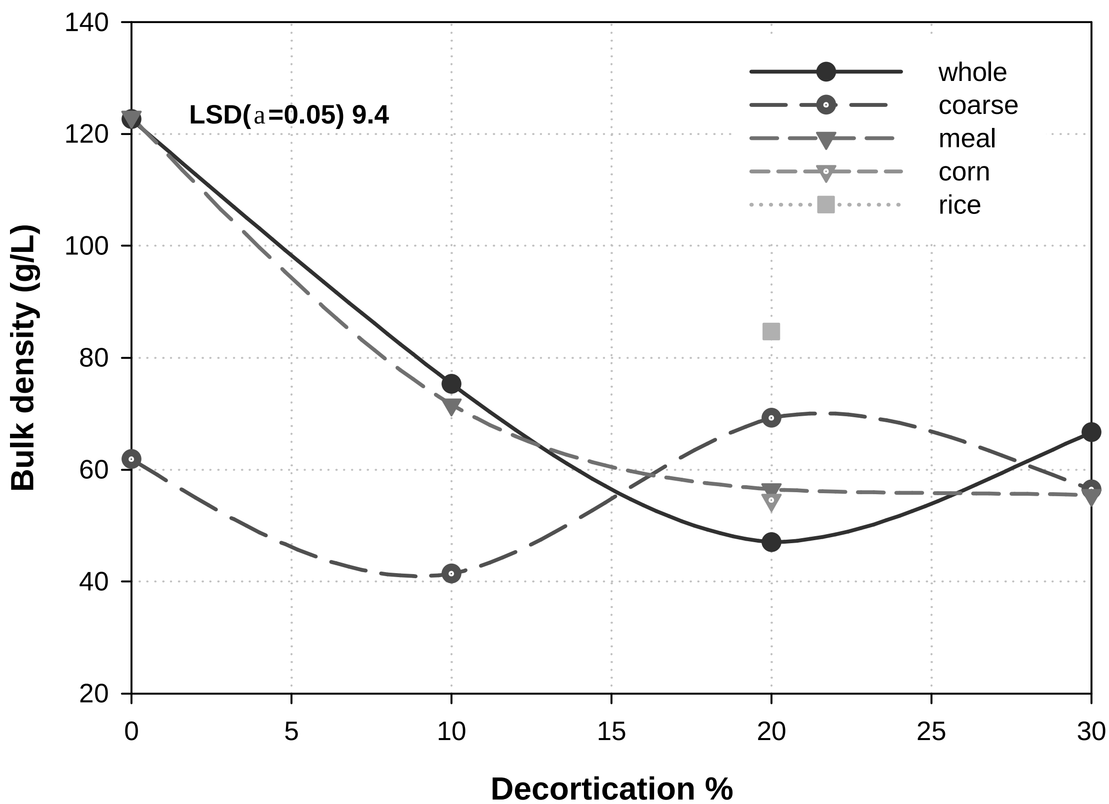

Fig. 6. Effect of decortication and particle size on bulk density of extrudates made from sorghum, corn meal and rice (whole=un-ground particles, coarse= ground and above #20 US Std Sieve, meal=ground and between #20 and #50 US Std Sieves).

Table X

Expansion ratio and bulk density values for extrudates made from sorghum, rice and corn

Particle size	Decortication %	Expansion ratio		Bulk density (g/L)	
Whole (un-ground)	0	3.32	j[a]	122.6	a
	10	4.20	h	75.3	b,c
	20	4.56	e,f	47.0	f,g
	30	4.75	c,d	66.6	c,d
Coarse	0	4.41	g	61.9	d,e
	10	4.86	b,c	41.4	g
	20	5.04	a	69.2	c,d
	30	4.92	a,b	56.4	e,f
Meal	0	3.17	k	123.1	a
	10	4.00	l	71.6	c
	20	4.41	g	56.5	e,f
	30	4.67	d,e	55.4	e,f
Corn meal		4.78	c,d	54.6	e,f
Rice		4.55	f	84.7	b
LSD (α=0.05)		0.12		9.4	

a Treatments with same letter are not significantly different (p<0.05)

Table XI

Average expansion ratio and bulk density values for extrudates made from sorghum with different particle sizes and decortication levels

Groups	Expansion ratio		Bulk density (g/L)	
Particle size				
Whole (un-ground)	4.21	b[a]	78.0	a
Coarse	4.81	a	57.2	b
Meal	4.06	c	76.5	a
LSD (α=0.05)	0.06		1.9	
Decortication %				
0	3.63	d	102.3	a
10	4.36	c	62.8	b
20	4.67	b	57.6	c
30	4.78	a	59.6	c
LSD (α=0.05)	0.07		2.2	

a Treatments with same letter are not significantly different (p<0.05)

For coarse particle size, decortication had no clear effect on extrudate bulk density, opposed to the whole and meal particle sizes in which bulk density tended to decrease as decortication level increased (Fig. 6).

However, the average for all particle sizes showed that increasing decortication to 20% decreased the extrudate bulk density (Table XI). For sorghum samples decorticated to remove 30% of original weight, the bulk density was very similar for all particle sizes.

Gomez et al (1988) extruded different varieties of sorghum in an expander extruder cooker with a maximum expansion ratio of 3.27 for a waxy sorghum. The expansion ratio of extrudates obtained in this experiment were higher than those previously reported by Gomez et al (Fig. 5) and was 5.04 the highest for coarse particles at 20% decortication (20C).

Rice extrudates had acceptable expansion and a white color. On the other hand, extrudates made from yellow corn meal were more expanded than rice extrudates, and had a yellow color. However, some of the sorghum extrudates expanded more than either rice or corn samples, with similar bulk densities and texture characteristics (e.g. 10C, 20C, 30C, 20W, 30W) (Fig. 5).

Color

Particle size and decortication level affected color of sorghum extrudates (Table XII). The extrudates lightness (L*) increased with increasing decortication, while chroma decreased. Chroma was calculated from a* and b* values (Table A.1). This agrees with studies that found that darker extrudates were obtained (lower L*) with increasing bran content (Grenus et al 1993). The L* value was higher for extrudates made from coarse particle size (Table XIII) but the chroma was lower for the meal particle size.

The L* value of the extrudates produced from different particle sizes but same decortication level was directly correlated to the expansion ratio (R^2=0.813) and inversely correlated to the ash content (R^2=0.852). Thus, the L* value was higher for the extrudates made from coarse particles probably as a consequence of their higher expansion and lower ash content.

The color of the extrudates was whiter when the decortication level increased as measured by the increased L* and decreased chroma of the samples. This is a consequence of the removal of the colored compounds present in the pericarp, which give white sorghum a light yellowish color, and the higher expansion that extrudates made from sorghum with increasing decortication had. Rice extrudates were whiter than all the other extrudates as described by the lower chroma and higher L*. As expected, extrudates made from corn were more colored as revealed by the high chroma value.

Texture

Force peaks are produced when the probe breaks air cells in the product. Consumers perceive a sample with higher numbers of air cells as crisper (McDonough 2003). Thus, other variables being constant, the more force peaks produced during puncturing, the crisper a product is. From this it can be concluded crisper and more expanded products were produced when sorghum raw materials with greater decortication were processed as revealed by the number of force peaks during puncture of extrudates (Fig. 7, Tables XIV and XV). This is a consequence of the removal of the non-starch components during decortication, which permits adequate bubble formation.

Sorghum samples that were decorticated but not ground (whole) produced extrudates that gave more force peaks when punctured than coarse or meal particles

Table XII

Color parameters L*, and chroma for sorghum, rice and corn extrudates[a]

Particle size	Decortication %	L*		Chroma[b]	
Whole (un-ground)	0	78.9	g[c]	15.2	b
	10	82.5	e,f	14.7	c
	20	83.5	d,e	14.5	c
	30	84.7	c,d	12.9	g
Coarse	0	81.1	f	15.3	b
	10	84.9	b,c,d	14.0	e,f
	20	85.9	a,b,c	13.8	e,f
	30	86.2	a,b	13.7	f
Meal	0	75.5	h	15.3	b
	10	82.5	e,f	14.4	c,d
	20	83.8	d,e	14.1	d,e
	30	84.5	c,d	13.6	f
Corn meal		84.6	c,d	34.4	a
Rice		87.4	a	10.8	h
LSD (α=0.05)		1.5		0.37	

a Color determined on ground extrudates passing through a US 40 Standard sieve
b Chroma was obtained from a* and b* values using the formula ((a*^2)+(b*^2))^0.5
c Treatments with same letter are not statistically different ($p<0.05$)

Table XIII

Average color parameters L*, and chroma for extrudates[a] made from sorghum with different particle sizes and decortication levels

Groups	Luminosity (L*)		Chroma[b]	
Particle size				
Whole (un-ground)	82.4	b[c]	15.2	a
Coarse	84.5	a	14.2	b
Meal	81.6	c	13.6	c
LSD (α=0.05)	0.8		0.2	
Decortication %				
0	78.5	c	14.4	a,b
10	83.3	b	14.2	b,c
20	84.4	a	14.5	a
30	85.1	a	14.1	c
LSD (α=0.05)	0.9		0.2	

a Color determined on ground extrudates passing through a US 40 Standard sieve
b Chroma is obtained from a* and b* values using the formula ((a*^2)+(b*^2))^0.5
c Treatments with same letter are not significantly different ($p<0.05$)

(Table XV). Extrudates made from corn and rice had a higher number of force peaks when punctured than extrudates from sorghum except for 30W (Table XIV).

Elastic (Young's) modulus is an index of the force necessary to deform a material. Thus, the higher the elastic modulus the stiffer the material is. Extrudates made from sorghum that was not ground (whole particle size) were less stiff as decortication level increased to 20%, but were stiffer when decortication level of raw materials increased from 20 to 30% (Fig. 8). On the other hand, extrudates made from coarse and meal particles were less stiff as decortication level increased to 20%, but were statistically the same for 20% and 30% decorticated samples (Table XIV).

Decortication decreased elastic modulus significantly (0% vs. 10, 20, and 30%). It is hypothesized that the pieces of pericarp present especially in non-decorticated samples, regardless of the particle size, caused extrudates to have stiffer cell walls (Table XV).

Extrudates made from coarse sorghum particles were in general less stiff than extrudates made from whole and meal particles regardless of the decortication level (Table XV). Extrudates made from whole and meal particles were equally stiff (Table XV). Extrudates made from sorghum decorticated to 20% were similar regardless of the particle size.

Extrudates made from whole particles had many force peaks and a high elastic modulus. A high number of force peaks and a higher elastic modulus reveals that extrudates made from whole particles where crunchier than the other sorghum extrudates. This agrees with Rokey (2002) recommendation to extrude raw materials with a larger particle size distribution if an extrudate with a crunchier texture is desired.

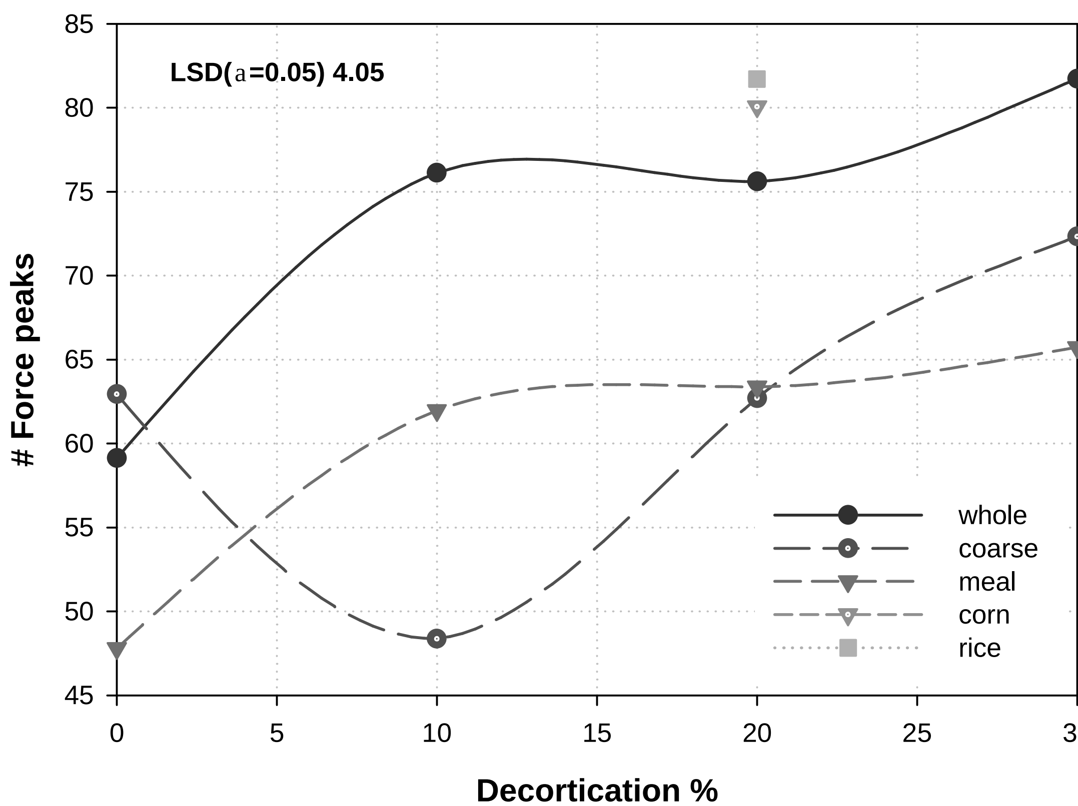

Fig. 7. Effect of decortication and particle size on number of force peaks during puncturing of white sorghum, corn meal and rice extrudates (whole=un-ground particles, coarse= ground and above #20 US Std Sieve, meal=ground and between #20 and #50 US Std Sieve).

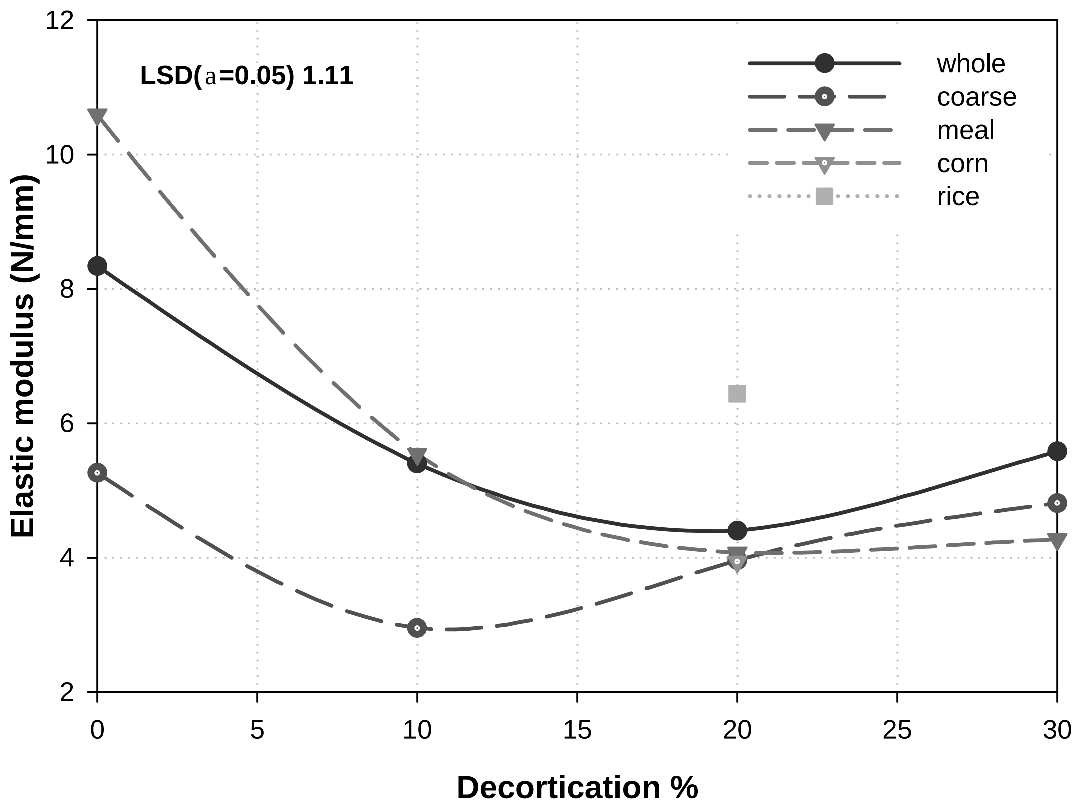

Fig. 8. Effect of decortication and particle size on elastic modulus of white sorghum, corn meal and rice extrudates (whole=un-ground particles, coarse= ground and above #20 US Std Sieve, meal=ground and between #20 and #50 US Std Sieve).

Table XIV

Number of force peaks and elastic modulus[a] of extrudates from sorghum, rice and corn

Particle size	Decortication %	# Force peaks		Elastic modulus (N/mm)	
Whole (un-ground)	0	59.1	e[b]	8.3	b
	10	76.1	b,c	5.4	c,d,e
	20	75.6	c	4.4	e,f,g
	30	81.7	a	5.6	c,d
Coarse	0	62.9	d,e	5.3	d,e,f
	10	48.4	f	2.9	h
	20	62.7	d,e	3.9	g,h
	30	72.3	c	4.8	d,e,f,g
Meal	0	47.8	f	10.6	a
	10	61.9	d,e	5.5	c,d
	20	63.4	d	4.1	g
	30	65.7	d	4.3	f,g
Corn meal		80.1	a,b	3.9	g,h
Rice		81.0	a	6.4	c
LSD (α=0.05)		4		1.1	

a Extrudates punctured by Texture Analyzer with a flat-tipped needle
b Treatments with same letter are not statistically different ($p<0.05$)

Table XV

Average number force peaks and elastic modulus for extrudates made from sorghum with different particle sizes and decortication levels

Groups	# Force peaks		Elastic modulus (N/mm)	
Particle size				
Whole (un-ground)	73.5	a[a]	5.9	a
Coarse	61.6	b	4.3	b
Meal	59.7	b	6.1	a
LSD (α=0.05)	2		0.6	
Decortication %				
0	56.7	d	8.0	a
10	62.2	c	4.6	b,c
20	67.2	b	4.1	c
30	73.3	a	4.9	b
LSD (α=0.05)	2.3		0.6	

a Treatments with same letter are not significantly different ($p<0.05$)

W20 (20% decorticated sorghum, not ground) produced extrudates with texture characteristics closer to those from corn meal (Table XIV). W20 extrudates had a very similar number of force peaks to those of corn and rice, while they were equally stiff to corn meal extrudates. Crunchier extrudates are produced at lower decortication levels as determined by the higher elastic modulus. Extrudates made from coarse sorghum particles were softer than those made from other particle sizes at lower decortication levels.

Water solubility index

The water solubility indexes obtained in this experiment were similar to those reported by Anderson et al (1969) for sorghum extrudates processed at similar conditions but lower than those obtained by Gomez et al (1988). Corn meal and rice developed less soluble material inside the extruder (Table XVI) showing that the gelatinization and dispersion pattern of starch in these materials is different from that of sorghum.

Water solubility of extruded material is greater than that of either the raw material or material extruded at higher moistures or lower temperatures (Gomez and Aguilera 1984). Extrudate WSI increased when sorghum was decorticated (0% decortication vs 10, 20 and 30%) (Table XVII). From this it is inferred that the removal of the pericarp and germ, and consequently lipids and fiber, allowed starch in sorghum to be more easily transformed inside the extruder. This caused an increase in molecular solubility, dispersibility of amylose and amylopectin and probably resulted in the formation of depolymerized starch (Jackson et al 1990).

WSI of extrudates made from coarse particles was higher than those made from whole and meal particle sizes (Fig. 9, Table XVII). This is opposed to the increase of

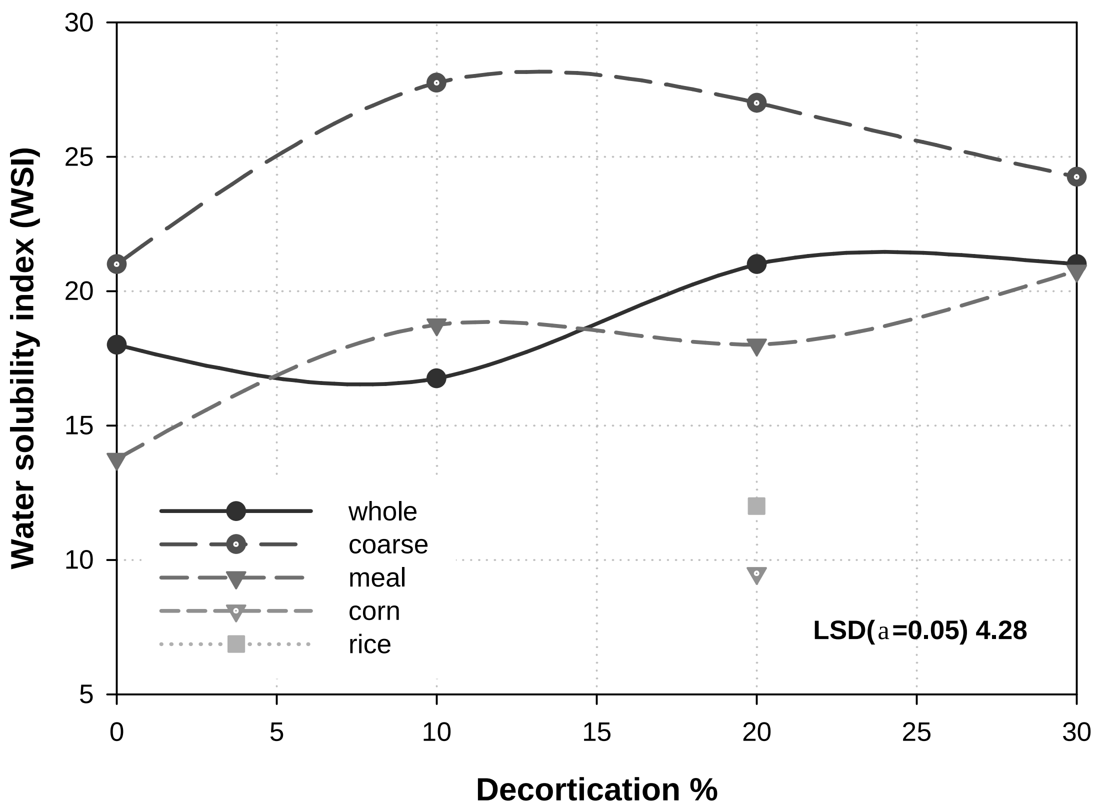

Fig. 9. Effect of decortication and particle size on water solubility index of white sorghum, corn meal and rice extrudates (whole=un-ground particles, coarse= ground and above #20 US Std Sieve, meal=ground and between #20 and #50 US Std Sieve).

Table XVI

WSI of extrudates[a] made from sorghum, rice and corn

Particle size	Decortication %	WSI	
Whole (un-ground)	0	18.00	c,d[b]
	10	16.75	c,d
	20	21.00	b,c
	30	21.00	b,c
Coarse	0	21.00	b,c
	10	27.75	a
	20	27.00	a
	30	24.25	a,b
Meal	0	13.75	d,e
	10	18.75	c
	20	18.00	c,d
	30	20.75	b,c
Corn meal		9.50	e
Rice		12.00	e
LSD (α=0.05)		4.28	

a Ground extrudates passing through a US 40 standard sieve
b Treatments with same letter are not statistically different ($p<0.05$)

Table XVII

Average WSI for extrudates[a] made from sorghum with different particle sizes and decortication levels

Groups	WSI	
Particle size		
Whole (un-ground)	19.2	b[b]
Coarse	25	a
Meal	17.8	b
LSD (α=0.05)	2.2	
Decortication %		
0	17.6	b
10	21.1	a
20	22	a
30	22	a
LSD (α=0.05)	2.5	

a Ground extrudates passing through a US 40 standard sieve
b Treatments with same letter are not significantly different ($p<0.05$)

WSI of extrudates made from rice flours with increasing particle size reported by Chauhan and Bains (1985).

Summary

All sorghum extrudates had excellent expansion, characteristic snack appearance and a light color. Whiter, crisper, and more expanded extrudates were produced from white sorghum with increasing decortication level. The coarse particle size yielded extrudates with softer texture and higher expansion. However, decorticated and non-decorticated sorghum kernels were extruded satisfactorily. In general, sorghum extrudates made from raw material similar to corn meal (coarse particle size) were whiter, had a blander flavor and expanded more than either corn meal or rice samples. These properties make white sorghum a feasible option for extrusion.

Decorticated white sorghum was successfully extruded into snacks with comparable expansion, texture, color and flavor to those made from corn and rice. White sorghum extrudates were highly expanded, crunchy and light colored with a bland flavor, allowing the use of many flavorings (Burtea 2001). Decortication of sorghum up to 20% was enough to produce extrudates with expansion and texture similar to those made from corn or rice.

The white sorghum kernels can be extruded even without milling and/or decorticating, which could result in significant savings in time, energy and equipment. This property enables the possibility of developing whole grain, organic snacks. These snacks would provide the benefits of whole grains with high dietary fiber, antioxidants, vitamins and minerals content.

CHAPTER IV

EFFECT OF GRINDING AND REMOVAL OF FINES ON WHOLE SORGHUM EXTRUSION AND EXTRUDATE CHARACTERISTICS

Justification

In chapter III, whole sorghum kernels were successfully extruded into expanded snacks. This is a property unique for sorghum that could result in cost reduction for the production of whole grain snacks. In this chapter, the optimum moisture for whole sorghum extrusion was evaluated. At the same time, ground sorghum samples were extruded to evaluate if there is an improvement in extrudate characteristics or extrusion performance. The effect of fines removal from whole ground sorghum was also evaluated.

Materials and methods

Raw materials

White sorghum hybrid, ATX631xRTX436, grown in College Station, Texas in 2001 was used for extrusion. Yellow corn meal (Archer Daniels Midland Company, 2001) was used as control.

Sorghum was hammer-milled (Fitzpatrick Hammer Mill D, Fitzpatrick Co., Chicago, IL) through a No. 8 US Standard screen (2360 μm). Some of the ground sorghum was sieved to remove the fines using a 50 US Standard sieve (300 μm). Thus, three samples with different particle size distributions were utilized: whole (not ground), ground whole sorghum with fines and ground whole sorghum without fines (Figs. 10 and 11, Table XVIII). Each sorghum sample with different particle size distribution was tempered at three moisture levels: 12, 14 and 16% moisture. Corn meal was tempered at 14% moisture.

Particle size distribution of raw materials was calculated in triplicate using #10, 20, 30, 40, 60, 80 and 100 US standard sieves and 50 g sample size. The composition of raw materials was determined using standard methods (AACC 2000).

Extrusion

Raw materials tempered at 12, 14 or 16% moisture content 24 hours prior to processing were extruded in a single-screw friction-type extruder (model MX-300I, Maddox Inc, Dallas, TX). The extruder was set at a Length/Diameter ratio of 4 and a die with 4, 1/8 inch (3.175 mm) holes. The number of holes in the die was reduced from 6 (used in the previous chapter) to 4 to increase retention time and friction inside the extruder. A higher expansion of extrudates was expected.

The energy consumed by the extruder (amperes) was monitored during processing on the extruder display. The nominal mechanical power applied by the extruder was calculated using the power formula for a three-phase motor:

$$Power(kW) = \sqrt{3} * Current(Amp) * Voltage(KV) * PF * Eff$$

where PF is the power factor of the motor, and Eff is the motor efficiency. The voltage was 460 V; the power factor of motor was 80%, and the efficiency 93%.

The time necessary to extrude 10 kg of raw materials was registered to calculate feed rate (kg/hr). The specific mechanical energy (SME) applied to the raw materials was calculated dividing the power consumed by the extruder by the feed rate. After extrusion, the samples were baked 100°C for 30 min in a tray convection oven and stored in metallic plastic bags. The baked extrudates (between 1.5 and 3% moisture)

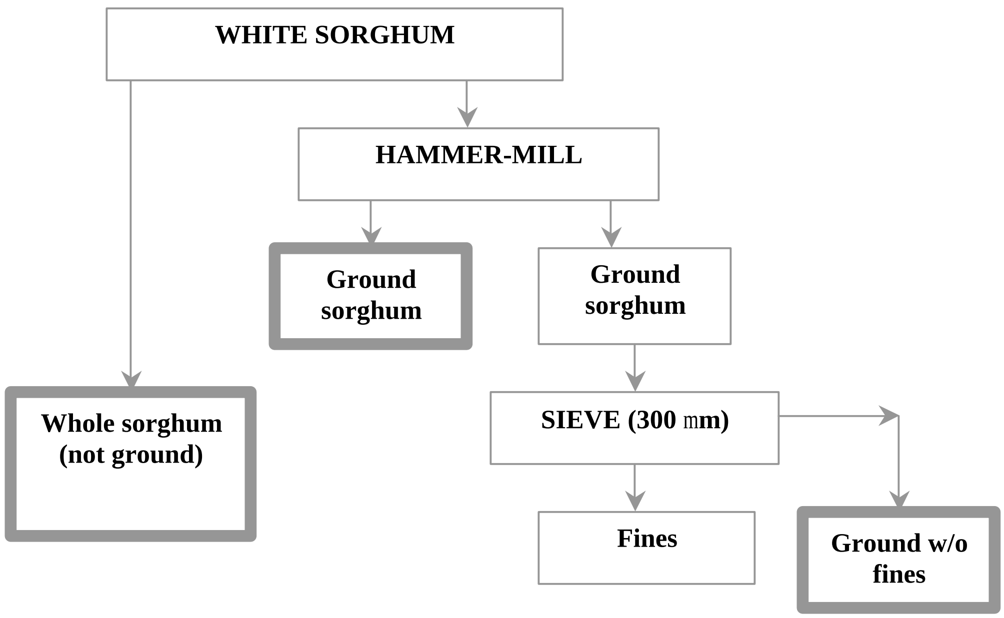

Fig. 10. Flow chart of whole sorghum raw materials preparation (bold line square).

Table XVIII

White sorghum raw materials, moisture content and abbreviation

Moisture / particle	**Whole** (not ground)	**Ground** (ground whole sorghum)	**Ground w/o fines** (ground whole sorghum with particles < 300 µm removed)
12%	W12[a]	G12	GWOF12
14%	W14	G14	GWOF14
16%	W16	G16	GWOF16

a The number in abbreviation refers to tempering moisture content. The letter refers to the particle size (W for unground sorghum, G for ground sorghum, GWOF for ground particles above #50 US Std sieve).

Fig. 11. Appearance of corn meal, whole and ground sorghum utilized in extrusion.

were used for analysis. The sensory and physical properties of extrudates (flavor, texture and appearance) were evaluated subjectively.

Expansion and bulk density

The expansion ratio was determined according to method of Gomez et al (1988). Radial expansion ratio (expansion ratio) was calculated by the ratio of extrudate average diameter / die diameter (3.175 mm). Length of extrudates was also determined. Ten extrudates were measured and averaged. A container full of extrudates with a volume of 15 L was weighed. The weight of the extrudates measured in triplicate divided by the container volume was the bulk density.

Microstructure

Extrudates were mounted on aluminum stubs with conductive adhesive and viewed in an environmental scanning electron microscope (ESEM) (Model E-3, Electroscan Corp., Wilmington, MA) with accelerating voltage of 20 kV to evaluate their microstructure.

Mechanical properties

The mechanical properties of the extrudates were tested using a texture analyzer (model TA.XT2i, Texture Technologies Corp., Scarsdale, NY) using a needle to puncture the extrudates on a flat platform. The needle utilized had a flat tip and a 2 mm diameter.

The mean force, elastic (Young's) modulus, work required to puncture the extrudates and the number of force peaks were recorded. Forty measurements per treatment were conducted and averaged. Elastic modulus was calculated as the slope of the linear region of the curve of force vs. distance, before the extrudate is ruptured.

Bostwick consistometer

The consistency of ground extrudates (passing through a US 40 standard sieve -425 µm) was determined with a Bostwick consistometer. A slurry (70 g) with 10% solids was mixed with a spatula for 2 min and rested for another minute. Then, the slurry was transferred to the consistometer and allowed to flow for 1 min. The distance traveled after 1 min was recorded. The test was performed in triplicate.

Rheological properties

The rheological properties of slurries with 20% solids prepared from ground extrudates passing a US Standard 40 sieve was evaluated with a Rapid Visco Analyzer (RVA) (Model 4, Newport Scientific, Warriewood, Australia). A profile was developed to be able to calculate the consistency coefficient (K) and flow behavior index (n) of the slurries, knowing that starch slurries show pseudoplastic behavior (Tang and Ding 1994).

The viscosity of gelatinized starch slurries decrease with time when a constant shear is applied. This phenomenon is called shear thinning. However, this decrease tends to stabilize and viscosity tends to equilibrate. If rheological properties were tested when this viscosity reaches equilibrium, then the time dependency can be disregarded.

Thus, samples were heated from 50 to 90^{o}C in 2 min while mixed at a constant speed of 120 rpm held for 12 min. The viscosity after 12 min was considered equilibrated. When 12 min elapsed, the speed was changed by increasing 10 rpm every ten seconds starting at 20 rpm until 150 rpm was reached and then the speed was decreased 10 rpm every ten seconds until the initial speed was reached to test for time dependency (Table B.1).

Statistics

The effects of extrusion moisture content and sorghum grinding on extrusion properties were evaluated in a factorial experiment with a completely randomized design. Treatments were separated with Fisher's LSD with an α=0.05. Statistics were performed with SAS statistical software package (SAS 2000).

Results and discussion

Milling yield, particle size and composition

The milling yield for particles above the #20 US Standard Sieve was very high (Table XIX). This is important because they work very well in the extruder (Chapter III). The particle size distribution for the different raw materials was significantly different (Table XX). Yellow corn meal had most of the particles retained on the #30 and #40 US Standard Sieves. Whole sorghum kernels were larger than 2000 µm. Most of ground sorghum particles (with and without fines) were retained on #20 and #30 sieves.

Composition of raw materials was statistically different (Table XXI). Whole and ground sorghum had the same composition, as expected. However, the removal of fines from ground sorghum decreased oil and ash content, but increased protein. The lower oil, ash and protein content of corn meal shows that it is a more refined product than sorghum samples.

Feed rate and specific mechanical energy

Maximum solids feed rate cannot be controlled in the extruder since it depends on how easily the product is conveyed by the extruder from the full bin to the die. Feed rate for all sorghum samples was higher than corn meal, which means that the extruder is able to process them faster (Fig. 12, Table XXII).

Table XIX

Yield of different particle sizes of ground whole sorghum

Particle size	% Weight[a]
Above 20 US Standard (850 μm)	55.5
Between 20-50 US Std. (850-300 μm)	32.4
Below 50 US Std. (300 μm)	12.1

a %Weight is the proportion of particles with a particular size based on total initial ground sorghum weight. For "ground" particle size all fractions were utilized (100% yield). For "ground without fines" overs of the #50 US Standard sieve were used (87.9% yield)

Table XX

Particle size distribution (% weight) of whole sorghum raw materials and corn meal

Sample/ US Std Sieve	#10 (2000 mm)	#20 (850 mm)	#30 (600 mm)	#40 (425mm)	#60 (250 mm)	#80 (180 mm)	#100 (150 mm)	Pan (<150 mm)
Whole sorghum	99.9 a[a]	0.04 c	0 d	0 d	0 d	0 b	0 b	0 b
Ground sorghum	0 b	61.2 a	14.4 c	11.8 c	7.2 a	2.1 a	1.4 a	1.7 a
Ground w/o fines	0 b	63 a	17.5 b	13.9 b	5.5 b	0.1 b	0 b	0 b
Corn meal	0 b	3.5 b	51.2 a	40.8 a	4.1 c	0.3 b	0 b	0 b
LSD (α=0.05)	0.04	3.41	2.09	1.74	0.88	0.69	0.14	0.2

a Treatments with same letter are not significantly different ($p<0.05$)

Table XXI

Composition of the sorghum raw materials and corn meal used for extrusion (dry wt basis)

Sample	% Crude protein[a]	%Ash[b]	% Oil[b]
Whole sorghum kernel	9.5b[c]	1.3a	3.4a
Ground sorghum	9.4b	1.3a	3.5a
Ground w/o fines	10.1a	1.2b	3.0b
Corn meal	9.0c	0.8c	2.1c
LSD (α=0.05)	0.4	0.1	0.2

a Crude protein was calculated using the Dumas method
b Ash and residual oil were calculated using standard methods (AACC 2000)
c Treatments with same letter are not significantly different ($p<0.05$)

Feed rate of whole sorghum was higher than for ground sorghum (Table XXIII), but this difference decreased as moisture content increased (Fig. 12). Feed rate for all sorghum samples tended to decrease with increasing moisture content (Table XXIII), probably due to lower extruder conveying efficiency or lower proportion of volume occupied by solids with increasing moisture content. Feed rate behavior for both of the ground sorghum samples was similar but lower for the one without fines (Table XXIII) probably consequence of empty spaces between the larger particles that the smaller ones usually fill up.

Specific mechanical energy (SME) is an index of how much energy per unit weight a material receives inside the extruder. It is related to product transformations leading to variation in expansion, density and geometric characteristics (Colonna et al 1989).

SME changed significantly for the raw materials utilized in this experiment (Fig. 13). SME was higher for corn meal than for sorghum samples at 14% moisture. Although sorghum kernels are larger than corn meal particles, the extruder required less energy to extrude them. From this, it is inferred that corn meal was more modified inside the extruder than sorghum. This higher SME for corn meal is probably due to the higher lipid and fiber content of the whole sorghum kernels. This results in less power required for extrusion compared to hard endosperm pieces of corn meal, but also cause differences in product characteristics.

At 14% moisture, all sorghum samples had no significant difference in the SME received in the extruder (Table XXII). Removal of fines did not have a significant effect on SME. Whole sorghum kernels, in general, consumed more energy than when sorghum was ground (Table XXIII).

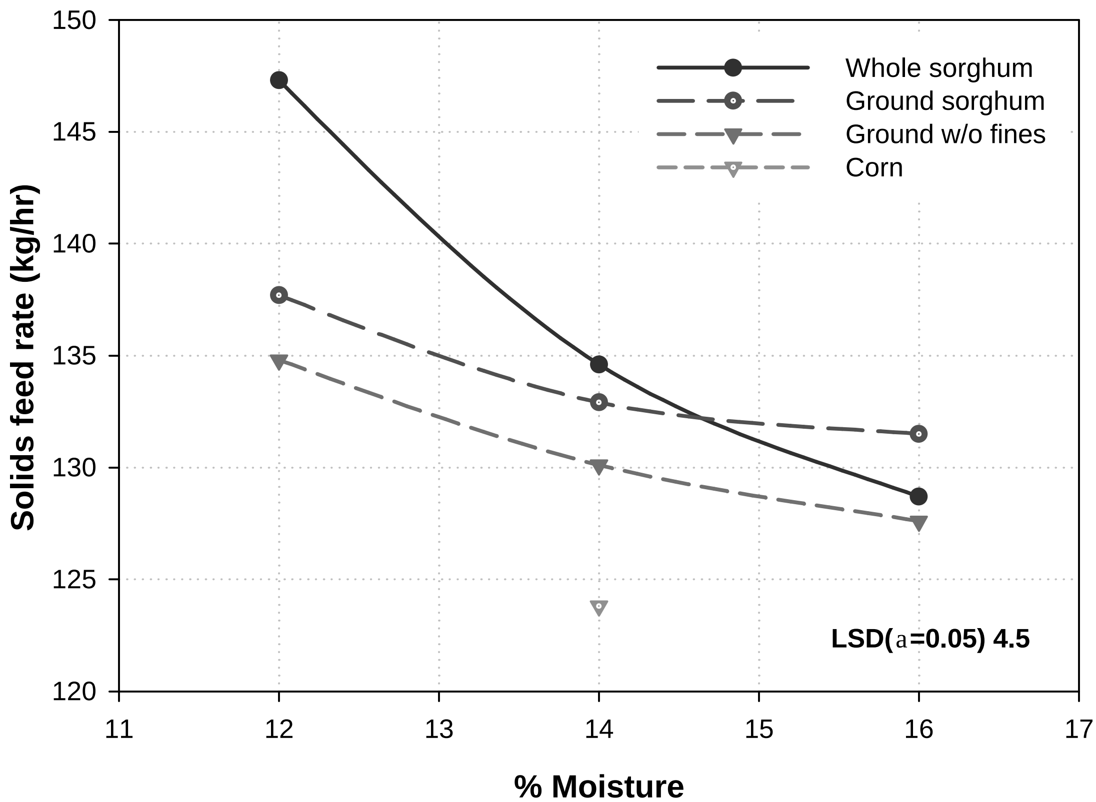

Fig. 12. Effect of sorghum grinding and moisture content on extruder feed rate.

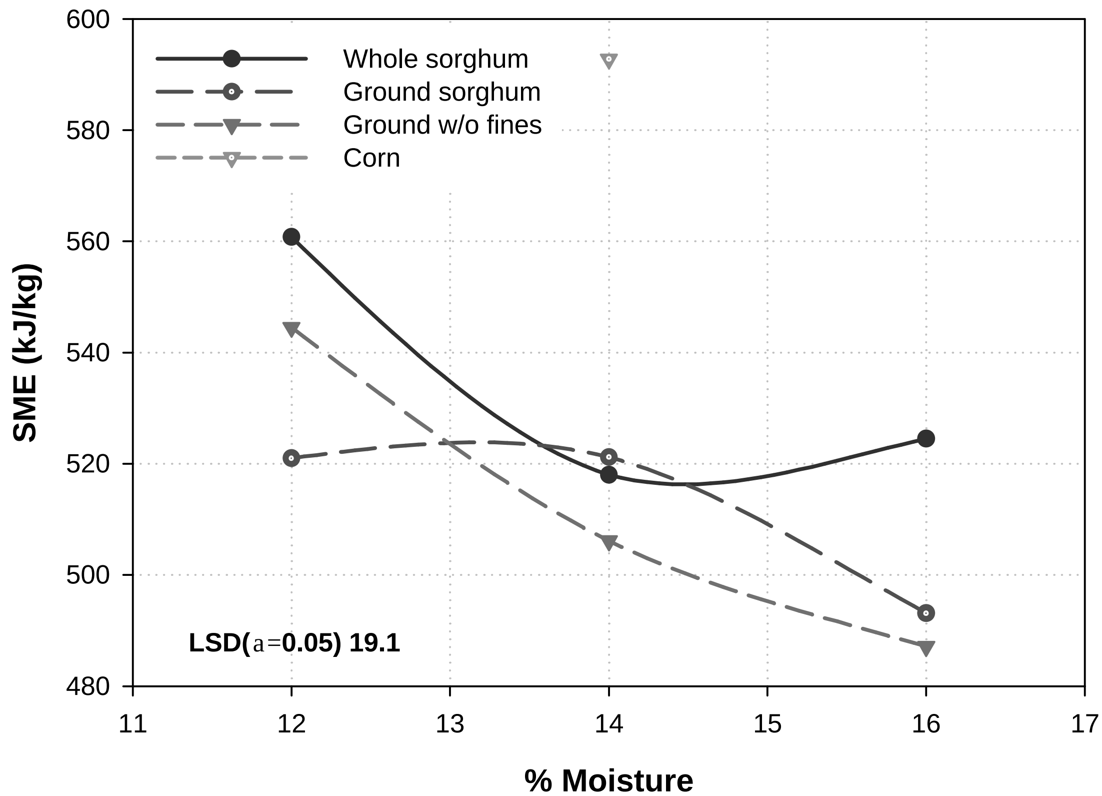

Fig. 13. Effect of sorghum grinding and moisture content on the SME consumed.

Table XXII

Power for extrusion, feed rate and SME of sorghum from different particle sizes and extrusion moistures

Sample	Extrusion moisture%	Power KW	Feed rate kg/hr	SME kJ/kg
Corn meal	14	20.39 b[a]	123.8 g	592.8 a
Whole sorghum	12	22.96 a	147.3 a	560.8 b
	14	19.37 c,d	134.6 b,c,d	518.0 c
	16	18.75 d,e	128.7 e,f	524.5 c
Ground sorghum	12	19.93 b,c	137.7 b	521.0 c
	14	19.24 c,d	132.9 c,d,e	521.2 c
	16	18.01 e,f	131.5 c,d,e,f	493.1 d
Ground sorghum w/o	12	20.39 b	134.8 b,c	544.5 b
fines	14	18.29 e	130.1 d,e,f	506.1 c,d
	16	17.26 f	127.6 f,g	487.1 d
LSD (α=0.05)		0.76	4.5	19.1

a Treatments with same letter are not significantly different ($p<0.05$)

Table XXIII

Average power consumed for extrusion, feed rate and SME of sorghum from different particle sizes and extrusion moistures

Groups	Power kW	Feed rate (kg/h)	SME kJ/kg
Particle size			
Whole	20.36 a[a]	136.9 a	534.4 a
Ground	19.06 b	134.0 b	512.6 b
Ground w/o fines	18.65 b	130.8 c	511.7 b
LSD (α=0.05)	0.45	2.7	11.3
Moisture %			
12	21.09 a	140.0 a	542.1 a
14	18.96 b	132.5 b	515.1 b
16	18.01 c	129.3 c	501.5 c
LSD (α=0.05)	0.45	2.7	11.3

a Treatments with same letter are not significantly different ($p<0.05$)

The average SME decreased as moisture level increased for all sorghum samples (Table XXIII). This agrees with previous works that concluded that increased feed moisture generally decreases SME during extrusion of starchy materials (Colonna et al 1989; Kaur et al 1999) due to lubrication and plasticization caused by water. The SME values obtained in this experiment are very similar to those found by Grenus et al (1993) and Kaur et al (1999) for extrusion of rice flours.

Thus, whole sorghum kernels extrusion could provide significant savings to snack processors compared to corn meal since the extruder consumes less energy, it is processed faster (higher maximum feed rate), but also because decortication and milling steps could be avoided.

Extrudates

The extrudates made from corn meal were more expanded and lighter than sorghum extrudates and had a characteristic yellow color (Fig. 14). On the other hand, extrudates made from sorghum had a lighter color and were less expanded). Extrusion of whole sorghum produced extrudates with higher expansion than ground sorghum (with or without fines).

All sorghum extrudates looked more expanded when the raw materials were tempered at 14%. The removal of fines did not affect extrudates appearance since extrudates made from ground sorghum and ground sorghum without fines had similar expansion, color and texture when extruded at the same moisture content.

Sorghum extrudates had an irregular shape compared to those made from corn meal, especially those made from whole kernels. They also had a stronger flavor and a gritty texture (small, hard particles are present in the product), especially in extrudates made from whole sorghum (not ground).

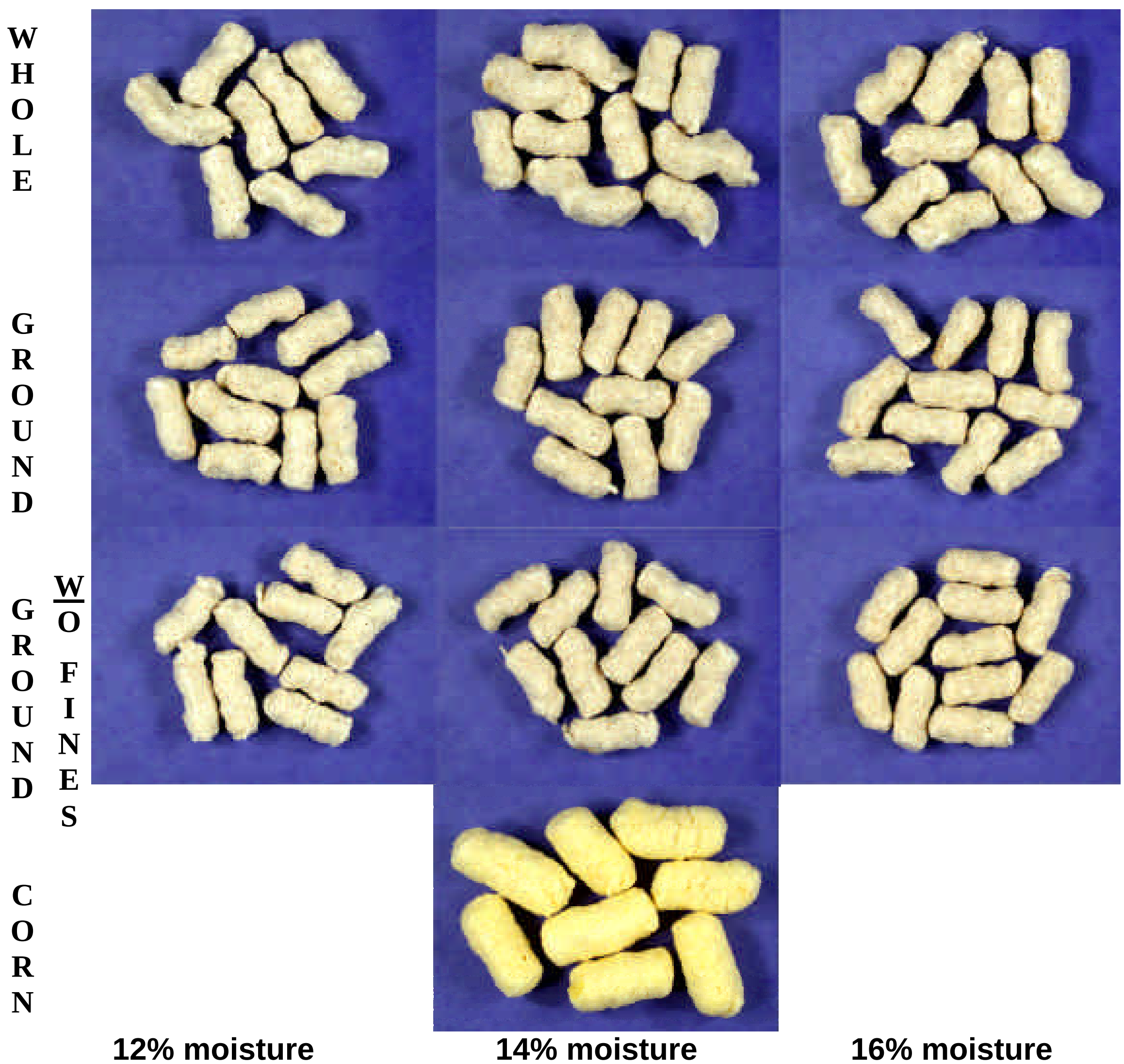

Fig. 14. Physical appearance of whole sorghum and corn extrudates.

Expansion

Extrudates made from corn meal expanded the most, as expected (Fig.15). Also, bulk density of extrudates made from corn meal was lower than for those made from sorghum (Fig. 16). The higher fiber and oil content of the sorghum samples did not allow them to expand as much as corn meal when they were extruded. Whole sorghum extrusion yielded extrudates with higher expansion ratio and lower bulk density than ground sorghum regardless of the moisture content at which they were tempered (Table XXV).

Removal of fines from ground whole sorghum did not significantly affect extrudates bulk density since it was the same for ground sorghum and ground sorghum with fines removed (Tables XXIV and XXV). In fact, removal of fines from ground sorghum actually reduced the expansion ratio compared to whole ground sorghum when extruded at 12% moisture (Table XXIV).

Bulk density was lower and expansion ratio higher for all sorghum extrudates when they were extruded at 14% moisture. Thus, the optimum moisture content for sorghum was 14% regardless of the particle size utilized.

Gomez et al (1988) extruded different varieties of decorticated sorghums at different moisture levels. They concluded that extrudate expansion index increased and bulk density decreased when sorghum was extruded with decreasing moisture content. They obtained the highest expansion ratio at 17.8%, their lower moisture content.

Kaur et al. (1999) and Gujral et al. (2001) also obtained lower expansion and increased bulk density when corn extrusion moisture content was increased from 16 to 24%. The results obtained in this experiment confirm that there is an increase in

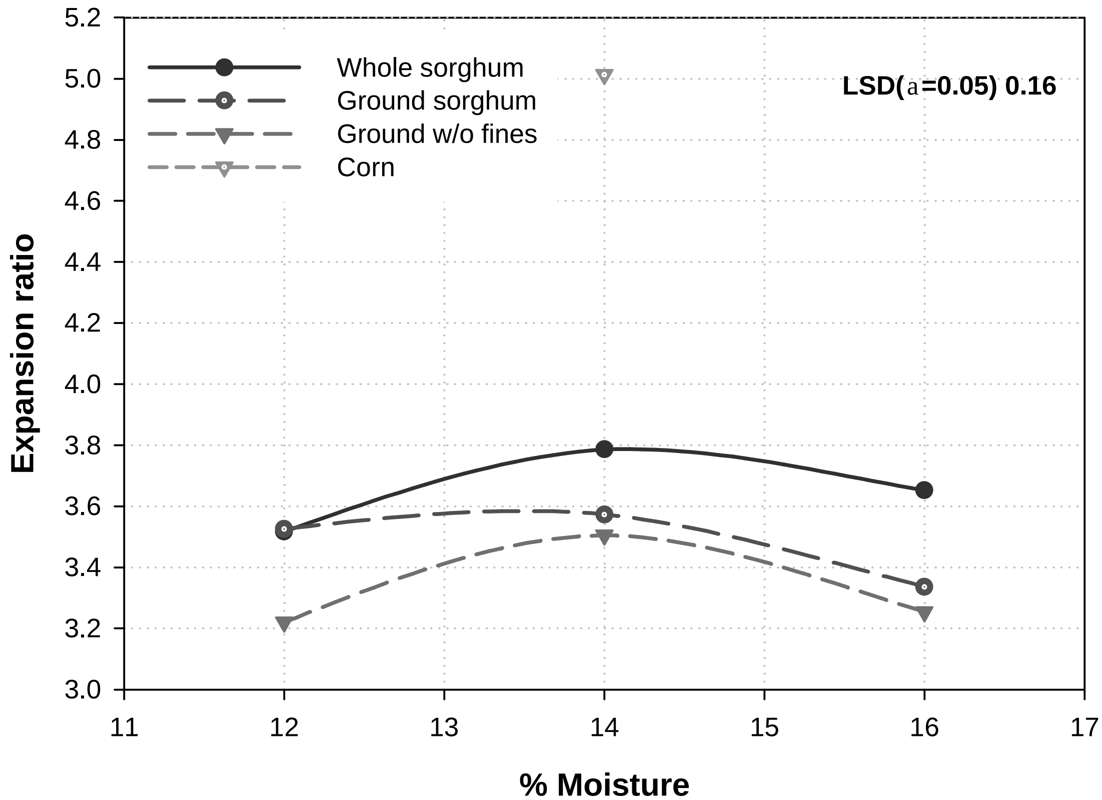

Fig. 15. Effect of grinding and extrusion moisture content on expansion ratio of extrudates made from whole sorghum.

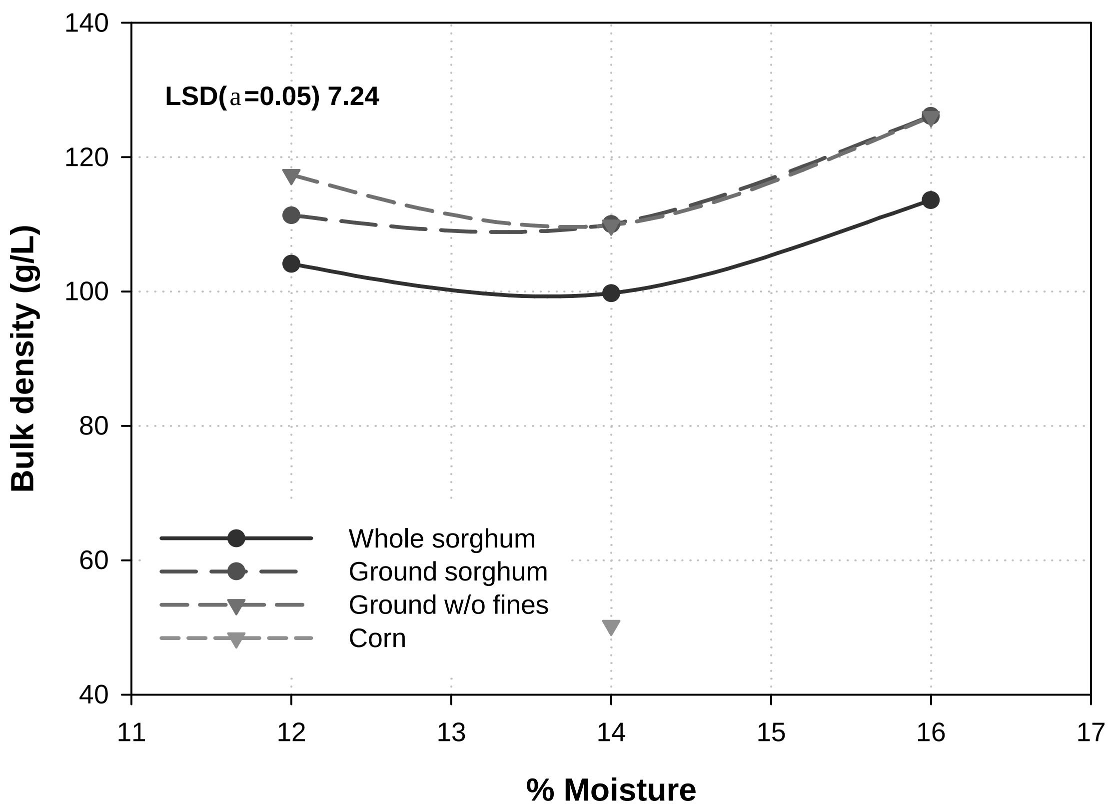

Fig. 16. Effect of grinding and extrusion moisture content on bulk density of extrudates made from whole sorghum.

Table XXIV

Effect of sorghum grinding and extrusion moisture on expansion ratio, length and bulk density of extrudates

Sample	Extrusion moisture%	Expansion ratio		Length (mm)		Bulk density (g/L)	
Corn meal	14	5.01	a[a]	34.51	a	50.3	f
Whole sorghum	12	3.52	c	30.24	b	104.1	c,d
	14	3.79	b	27.27	c	99.7	d
	16	3.65	b,c	29.35	b	89.0	e
Ground sorghum	12	3.53	c	26.74	c	111.3	b,c
	14	3.57	c	27.53	c	110.0	c
	16	3.34	d	26.42	c,d	126.1	a
Ground sorghum w/o fines	12	3.22	d	27.30	c	117.4	b
	14	3.50	c	27.18	c	109.8	c
	16	3.25	d	25.38	d	126.0	a
LSD (α=0.05)		0.16		1.19		7.2	

a Treatments with same letter are not significantly different ($p<0.05$)

Table XXV

Average expansion ratio, length and bulk density of sorghum extrudates from different particle sizes and extrusion moistures

Groups	Expansion ratio		Length (mm)		Bulk density (g/L)	
Particle size						
Whole sorghum	3.65	a[a]	29.0	a	97.6	b
Ground sorghum	3.48	b	26.9	b	115.8	a
Ground w/o fines	3.33	c	26.6	b	117.7	a
LSD (α=0.05)	0.09		0.7		3.6	
Moisture %						
12	3.42	b	28.1	a	110.9	a
14	3.62	a	27.3	b	106.5	b
16	3.41	b	27.0	b	113.7	a
LSD (α=0.05)	0.09		0.7		3.6	

a Treatments with same letter are not significantly different ($p<0.05$)

expansion when sorghum extrusion moisture content is reduced to 14% moisture. However, below that extrusion moisture content expansion actually decreased.

Expansion of extrudates was directly correlated to the SME they received (R^2 = 0.71). This means that, in the conditions range of this experiment, a higher SME applied to raw materials improved expansion. Whole sorghum and corn meal extrudates were more expanded in this experiment than in chapter III. Reduction in the number of holes in the die from 6 to 4 helped to increase expansion of extrudates.

Since a constant knife speed was used, length of extrudates is determined by how easily the material flows through the die. Extrudates made from corn meal were longer than those made from sorghum. All sorghum extrudates (from whole and ground with and without fines) had the same length when extruded at 14% moisture (Table XXIV), but those made from whole sorghum were longer at 12 and 16% extrusion moisture. Length of extrudates from ground sorghum was not affected by fines removal.

Length of extrudates was highly and directly correlated to the SME received by the raw materials (R^2 = 0.88). According to Launay and Lisch (1984), melt viscosity determines the longitudinal expansions. Thus, higher SME resulted in a lower viscosity of the melt inside the extruder and longer extrudates.

Microstructure

Extrudates made from whole sorghum and ground sorghum had very different structures. Extrudates made from whole sorghum had large air cells with thick cell walls (Fig. 17). Large pieces of pericarp were embedded in those cell walls. These pieces of pericarp probably caused smaller bubbles to collapse and form larger bubbles. At the same time, pericarp pieces helped support cell wall structure and retain larger bubbles.

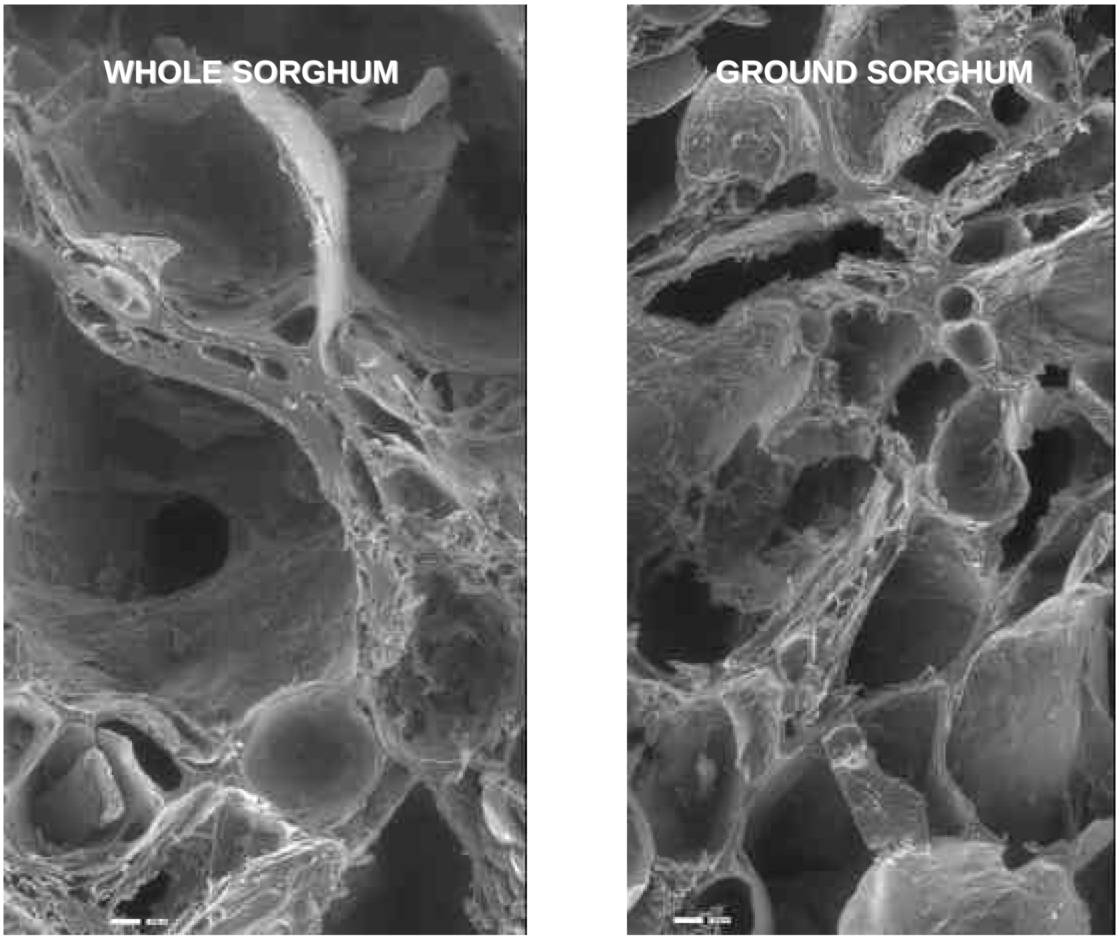

Fig. 17. ESEM photos of extrudates made from whole (left) and ground (right) sorghum (bar=100 µm).

On the other hand, extrudates made from ground sorghum had smaller air cells and thinner cell walls. The milling procedure performed with a hammer mill reduced the particle size of both, endosperm and pericarp pieces. This helped to retain more, smaller bubbles compared to extrudates made from whole sorghum. In addition, air cells in extrudates made from ground sorghum had a more homogenous distribution.

Thus, whole sorghum extrusion produced extrudates with larger air cells and thicker cell walls than ground sorghum. This agrees with the larger cell sizes that Desrumaux et al (1998) found in extrudates made from corn materials with increasing particle sizes.

Mechanical properties

Force peaks are produced when the probe breaks air cells in the product. Thus, more force peaks reveal a higher number of air cells. The number of force peaks was higher for extrudates made from corn meal (Fig. 18, Table XXVI). This means that more air cells were produced and retained during corn meal extrusion compared to sorghum.

Number of force peaks was higher for extrudates made from whole sorghum than those from ground sorghum at 14 and 16% moisture, which were the most expanded. Thus, when processed closer to optimum conditions, whole sorghum extrusion yields extrudates that produce more force peaks compared to ground sorghum.

There were more force peaks during puncturing of extrudates made from sorghum raw materials at 14% moisture for all particle sizes (Fig. 18). This is probably because of the higher expansion that occurred for all raw materials extruded at 14% moisture content, which formed and retained more air cells.

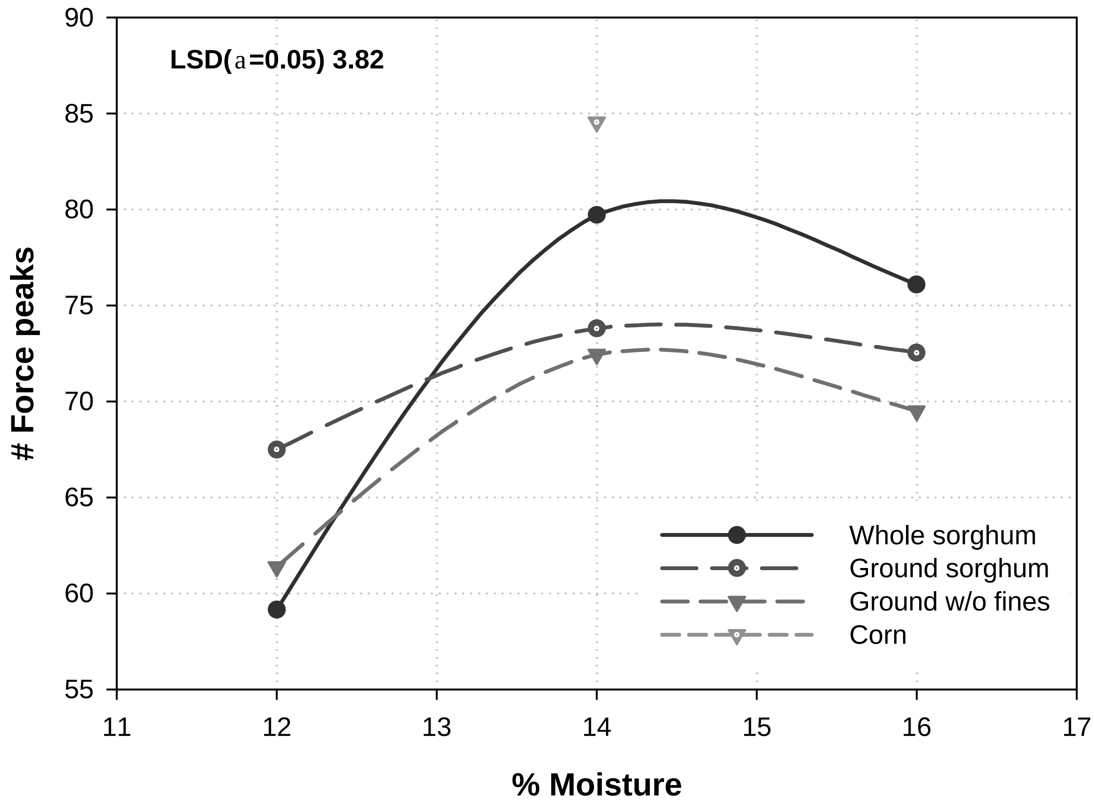

Fig. 18. Effect of grinding and moisture content on the number of force peaks of extrudates made from sorghum.

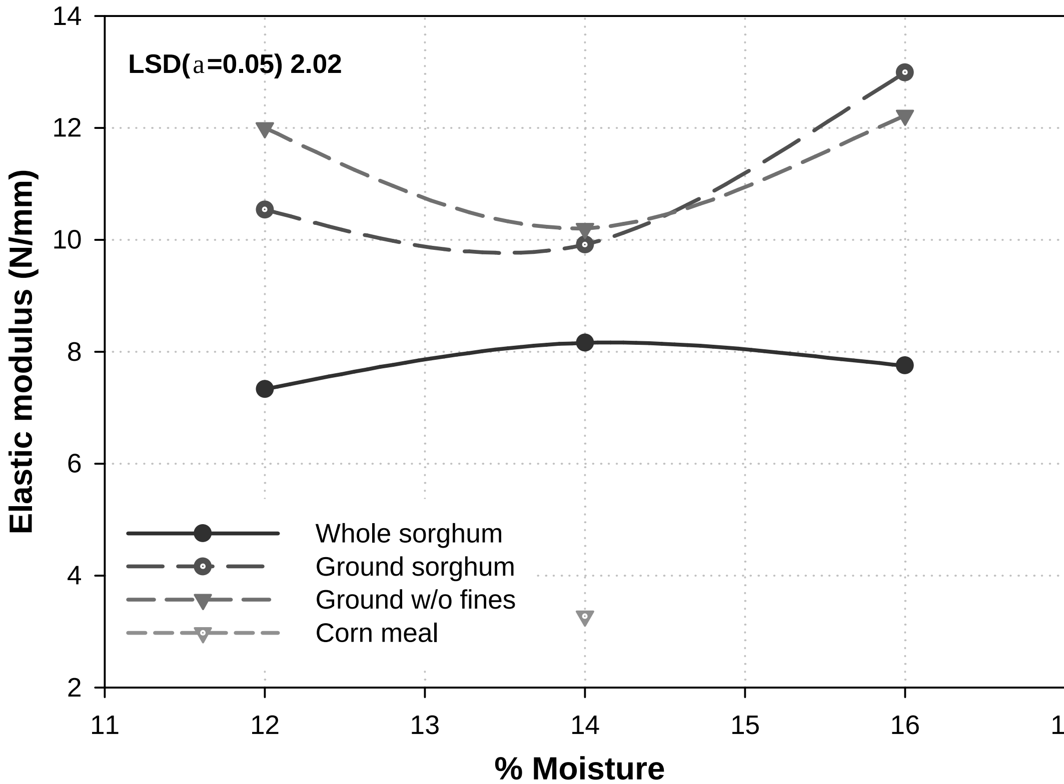

Fig. 19. Effect of grinding and moisture content on elastic (Young's) modulus of extrudates made from sorghum.

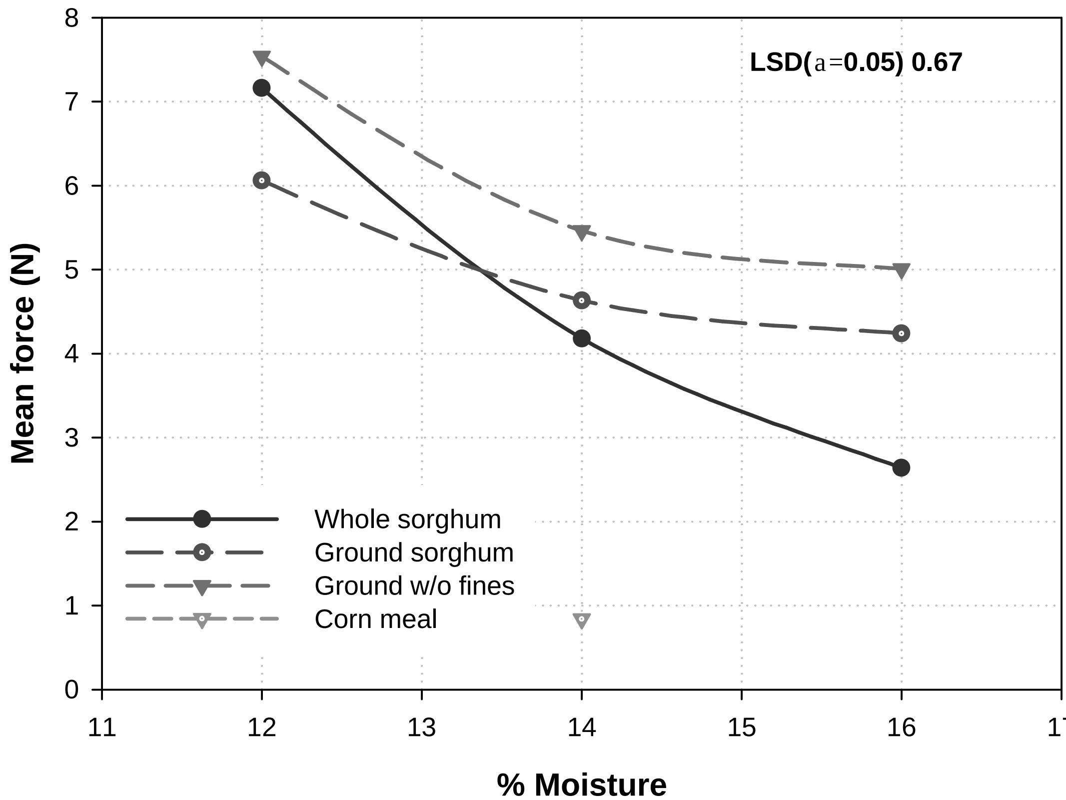

Fig. 20. Effect of grinding and extrusion moisture content on mean force to puncture extrudates made from sorghum.

Table XXVI

Effect of extrusion moisture and particle size on number of force peaks, mean force and elastic modulus of extrudates

Sample	Extrusion moisture%	# force peaks		Mean force (N)		Elastic modulus (N/mm)	
Corn meal	14	84.6	a[a]	0.84	g	3.27	f
Whole sorghum	12	59.2	f	7.16	a	7.33	e
	14	79.7	b	4.18	e	8.16	d,e
	16	76.1	b,c	2.64	f	7.75	e
Ground sorghum	12	67.5	e	6.06	b	10.54	b,c
	14	73.8	c	4.63	d,e	9.91	c,d
	16	72.5	c,d	4.24	e	12.99	a
Ground sorghum w/o fines	12	61.4	f	7.54	a	12.00	a,b
	14	72.4	c,d	5.46	b,c	10.20	b,c
	16	69.5	d,e	5.01	c,d	12.22	a,b
LSD (α=0.05)		3.8		0.67		2.02	

a Treatments with same letter are not significantly different (p<0.05)

Table XXVII

Average number of force peaks, mean force and elastic modulus of sorghum extrudates from different particle sizes and extrusion moistures

Groups	# force peaks		Mean force (N)		Elastic modulus (N/mm)	
Particle size						
Whole sorghum	71.64	a[a]	4.66	b	7.75	b
Ground sorghum	71.27	a	4.98	b	11.15	a
Ground w/o fines	67.76	b	6.00	a	11.47	a
LSD (α=0.05)	2.12		0.41		1.22	
Moisture %						
12	62.67	c	6.92	a	9.96	a,b
14	75.31	a	4.76	b	9.42	b
16	72.69	b	3.96	c	10.98	a
LSD (α=0.05)	2.12		0.41		1.22	

a Treatments with same letter are not significantly different (p<0.05)

The elastic (Young's) modulus was lower for extrudates from corn meal compared to those from sorghum (Fig. 19). This means that the corn meal extrudates were less stiff probably because more air cells with thinner cell walls were retained in their structure. The average elastic modulus of extrudates from sorghum processed at 14% moisture (regardless of grinding) was lower than at 12 and 16% probably also as a result of the higher expansion (Table XXVII). This does not agree with the decrease elastic modulus that Ryu et al (2001) found for extrudates obtained from corn meal with decreasing moisture content.

The elastic modulus was lower for extrudates made from whole sorghum compared to those from ground sorghum with and without fines regardless of the moisture content at which they were extruded (Fig. 19). Thus, extrudates from whole sorghum were less stiff than those from ground sorghum despite the fact that they tended to have thicker air cell walls. Probably, the large pieces of pericarp embedded in the cell walls produced a weaker structure compared to the small pieces in cell walls of extrudates from ground sorghum.

Removal of fines did not have a significant effect on extrudate elastic modulus, since it was the same for extrudates from ground sorghum and ground sorghum without fines when extruded at the same moisture content (Table XXVI). The elastic modulus was highly and directly correlated to the bulk density of extrudates (R^2 = 0.94). Thus, the same factors that affect bulk density have an effect on the stiffness of the extrudates. It is inferred that is the cell wall thickness is the main factor that determines both bulk density and stiffness of extrudates.

The mean force required to puncture the extrudate decreased with increasing extrusion moisture content (Fig. 20), as previously reported by Gomez et al (1988), Mercier and Feillet (1975). The mean force is the average of the force that the texture analyzer required to puncture the extrudates, while elastic modulus is the force to deform only one cell wall.

Mean force was much lower for extrudates made from corn meal than for all of those made sorghum probably as result of their higher expansion (Table XXVI). Removal of fines increased the mean force, making harder extrudates. Whole sorghum extrusion rendered extrudates with softer texture when extruded closer to optimum conditions (W14 and W16).

Bostwick consistometer

The distance the slurry prepared from corn meal extrudate flowed was shorter than those prepared from sorghum extrudates (Fig. 21, Table XXVIII). This means that the viscosity of the extrudates made from corn meal was higher. Thus, corn meal was more dispersed inside the extruder compared to sorghum samples.

Slurries prepared with extrudates from whole sorghum tended to flow shorter distances than those prepared with extrudates from ground sorghum (Table XXIX). The distance the sorghum slurries flowed increased as extrusion moisture increased (Fig. 21, Table XXVIII), meaning that they were less viscous with increasing extrusion moisture content. This agrees with the results obtained by Kaur et al (1999) when they extruded rice flour.

The distance the slurries flowed in the consistometer was inversely related to the SME received by the raw materials (R^2 = 0.87). Thus, the viscosity of extrudates was directly related to starch modifications controlled by the SME. The flowed distanced was also inversely and highly correlated to expansion ratio (R^2 = 0.88). Thus, the higher extrudate viscosity (as measured with Bostwick consistometer), the higher expansion.

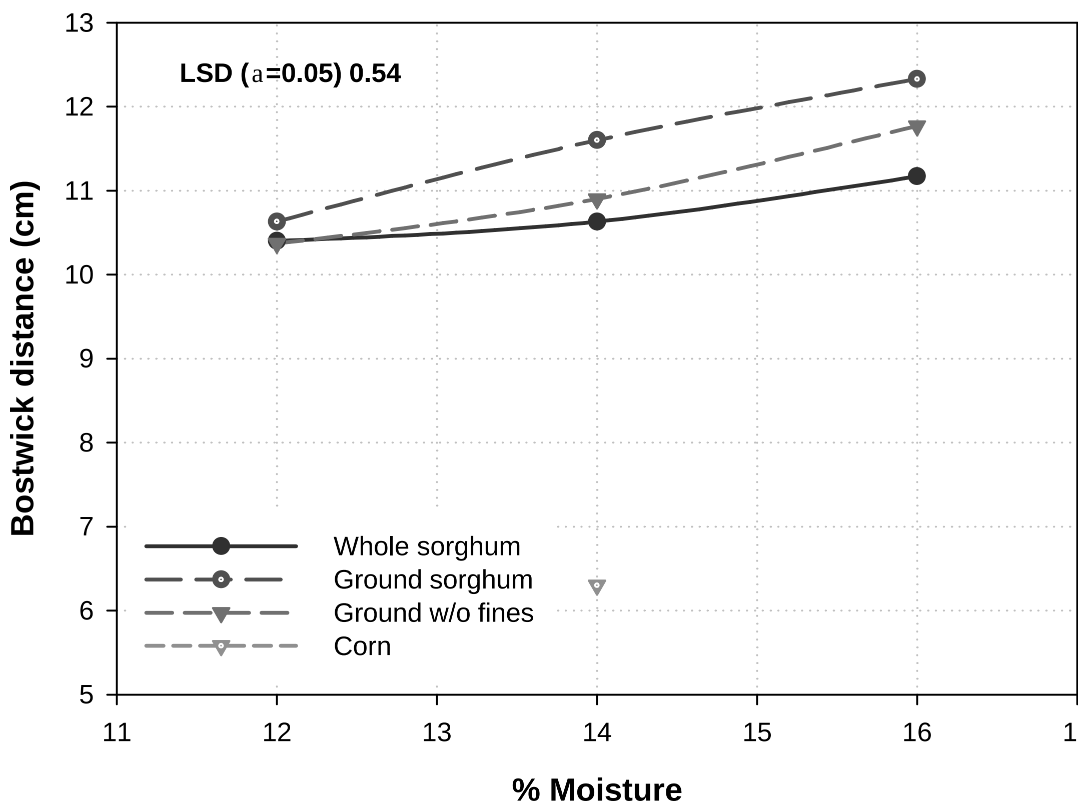

Fig. 21. Effect of sorghum grinding and moisture content on the distance flowed by slurries prepared from ground extrudates (10% solids).

Table XXVIII

Distance flowed in consistometer, K and n values of slurries prepared with extrudates from each treatment

Sample	Extrusion moisture%	Bostwick cm[a]		K[b] (cP*s)		n[c]	
Corn meal	14	6.30	f[d]	7076	g	0.603	b,c
Whole sorghum	12	10.40	e	10200	d,e	0.612	a,b
	14	10.63	d,e	10048	e,f	0.618	a,b
	16	11.17	c,d	8373	f,g	0.632	a
Ground sorghum	12	10.63	d,e	11998	c	0.566	d
	14	11.60	b,c	14485	b	0.553	d
	16	12.33	a	13987	b	0.555	d
Ground sorghum w/o fines	12	10.37	e	11835	c,d	0.576	c,d
	14	10.90	d,e	13435	b,c	0.583	b,c
	16	11.77	b	18630	a	0.555	e
LSD (α=0.05)		0.55		1749		0.028	

a More distance means lower viscosity.
b Consistency coefficient, determined from regressions of curves of viscosity vs. shear rate obtained in a RVA, varying speed from 20 to 150 rpm in 10 rpm increments and back to 20 rpm.
c Flow behavior index also determined from regression of curves of viscosity vs. shear rate obtained in a RVA
d Treatments with same letter are not significantly different ($p<0.05$)

Table XXIX

Average distance flowed in consistometer, K and n values of extrudates slurries from all particle sizes and extrusion moistures

Groups	Bostwick cm[a]		K[b] (cP*s)		n[c]	
Particle size						
Whole sorghum	10.7	b[d]	9480	b	0.621	a
Ground sorghum	11.5	a	13445	a	0.558	b
Ground w/o fines	11.0	b	14270	a	0.567	b
LSD (α=0.05)	0.3		1023		0.016	
Moisture %						
12	10.5	c	11448	b	0.582	a
14	11.0	b	12656	a	0.589	a
16	11.8	a	13134	a	0.574	a
LSD (α=0.05)	0.3		1026		0.016	

a More distance means lower viscosity.
b Consistency coefficient, determined from regressions of curves of viscosity vs. shear rate obtained in a RVA, varying speed from 20 to 150 rpm in 10 rpm increments and back to 20 rpm.
c Flow behavior index also determined from regression of curves of viscosity vs. shear rate obtained in a RVA
d Treatments with same letter are not significantly different ($p<0.05$)

Rheological properties

In order to calculate the average shear rate from the mixer speeds, the following formula was utilized:

$$\dot{g}_a = k'\Omega$$

where the average shear rate is given by the product of the mixer constant (k') and the angular velocity (O, rps). The k' value utilized was the one calculated by Lai et al (2000) for the RVA, which has a value of 20.1 1/rev. Substituting in the previous equation, the average shear rates were calculated from the used mixer speeds.

As mentioned before, starch slurries show a shear-thinning behavior (pseudoplastic) and can be described using the equation (Steffe 1996):

$$h = K\dot{g}^{n-1}$$

where ? is the apparent viscosity, and K and n are constants for each treatment. K is the consistency coefficient of a sample, which is related to viscosity but eliminating the shear rate and material behavior effects. A higher K means that the material is more viscous. On the other hand, n is the flow behavior index and describes if a material is Newtonian (n=1), shear thinning (0<n<1) or shear thickening (n>1). In other words, n describes how the viscosity of a material changes when shear rate is modified. For a Newtonian fluid, apparent viscosity does not change when shear rate is varied. On the other hand, the viscosity of a shear thinning material (e.g. starch slurries) decreases when shear rate is increased.

The curve obtained from the RVA is shown (Fig. B.1). From this curve, only the data after 770 s was utilized for calculation of K and n values, which is the time range where the shear rate was changed. With the average shear rates and the viscosity data for the desired time range, the curves of viscosity vs. shear rate for all treatments were obtained (Fig. B.2). Then, regressions to calculate the K and n values for each treatment were performed using the curve of viscosity vs shear rate.

It is evident that the time effect was small and could be neglected (Fig. B.2) since the viscosity was very similar at a specific shear rate when shear rate was increased from 6.7 to 50.3 (left to right in Fig. B.2) as when it was decreased back from 50.3 to 6.7 (right to left if Fig, B.2). The validity of the assumption that time effect was negligible was proven by the high correlation coefficients (R^2>0.98 for all regressions) that the regressions of viscosity vs. shear rate had.

The K value was lower for corn meal extrudates than for sorghum extrudates (Table XXVIII). Whole sorghum extrudates had lower K values than extrudates made from ground sorghum with or without fines, and also had a higher n value, thus they behaved more like a Newtonian fluid (Table XXIX).

This means that whole sorghum kernels were more transformed (dispersed and partially de-polymerized) in the extruder and the volume of the colloid particles that were damaged by friction in the extruder were smaller than those from ground sorghum (Tang and Ding. 1994), reducing viscosity and behaving more like Newtonian fluids (higher n). This increased starch degradation is probably consequence of the higher SME received by whole sorghum.

The same phenomenon could explain the lower K value for corn meal extrudates compared to sorghum extrudates. The consistency of extrudates made from ground sorghum and ground without fines was the same except when extruded at 16% moisture.

The consistency coefficient (K) was highly correlated to both bulk density (R^2=0.85) and elastic modulus (R^2=0.80). Thus, viscosity of extrudates is related to thickness and/or structure of the cell walls. K was also inversely correlated to extrudate length (R^2=0.77), so higher K corresponded to shorter extrudates.

Although Bostwick consistometer and RVA both measure properties related to viscosity, they had inverse results (R^2=0.62) (higher K corresponded to high distance flowed, thus lower viscosity). This happened because the consistometer measures viscosity caused by structures formed when the extruded melt went through the glass transition. On the other hand, what the used RVA profile measures is the viscosity of the background material after shear destroyed the structure formed during the glass transition. Thus, the obtained K value measures the rheological properties of the dispersed starch that withstood the shear imposed by the RVA to stabilize the viscosity. However, the structure of those components is not known. More studies in this area are needed.

Summary

Extrusion of whole sorghum kernels consumed less SME and was processed faster by the extruder than corn meal at the same moisture content. All whole sorghum samples expanded more when extruded at 14% moisture regardless of whether grinding was performed or not. However, all extrudates made from sorghum were less expanded, harder and stiffer than those from corn meal as a result of lower SME received during extrusion. Thus, less starch dispersion and degradation occurred during extrusion of whole sorghum (ground or not) than when corn meal was extruded.

Extrudates made from whole sorghum were more expanded, less stiff, had larger air cells and thicker cell walls than those made from ground sorghum. Whole sorghum received more SME in the extruder and suffered more starch degradation than ground sorghum. Grinding reduced the size of the pericarp pieces and this allowed the production of extrudates with smaller bubbles, thinner air cell walls and a more homogenous bubble distribution. Removal of fines from ground sorghum did not improve expansion and decreased processing capacity of the extruder.

Whole sorghum can be directly processed into snacks with potential in the healthy food market. Significant savings in processing may be achieved in whole sorghum extrusion since there are no dry matter losses, there is no energy used in decortication or milling, and the extruder consumes less power and processes more material per time unit. Reduction in the number of holes in the die increased expansion of extrudates.

CHAPTER V

COMPARISON OF CORN, DECORTICATED SORGHUM AND WHOLE SORGHUM EXTRUDATES

Justification

Previously, whole and decorticated sorghum were successfully extruded into expanded snacks. Decortication up to 20% was enough to produce extrudates similar to those from corn meal. However, decorticated sorghum samples had different particle size distribution from that of corn meal. Thus, a comparison of extrusion performance, product characteristics and consumer acceptance of extrudates made from sorghum and corn meals with a similar particle size distribution was performed. Whole sorghum and 20% decorticated sorghum were also extruded.

Materials and methods

Raw materials

White sorghum hybrid ATX631xRTX436 grown in College Station, Texas in 2001 was used for extrusion. Yellow corn meal (Archer Daniels Midland Company, February 2001) was used as control.

Sorghum was decorticated in 4 kg batches in a PRL mini-dehuller (Nutana Machine Co., Saskatoon, Canada) to remove 20% of the original weight (Fig. 22). The decorticated grain was cleaned through a KICE grain cleaner (Model 6DT4-1, KICE Industries Inc., Wichita, KS). After cleaning, part of the decorticated sorghum was ground in a hammer mill (Fitzpatrick Hammer Mill D, Fitzpatrick Co., Chicago, IL) through a No. 8 US Standard screen (2360 μm). Trying to mimic corn meal particle size distribution, the decorticated and ground sorghum was sieved to retain particles between #20 and #40 US Standard Sieve (850 and 425 μm, respectively).

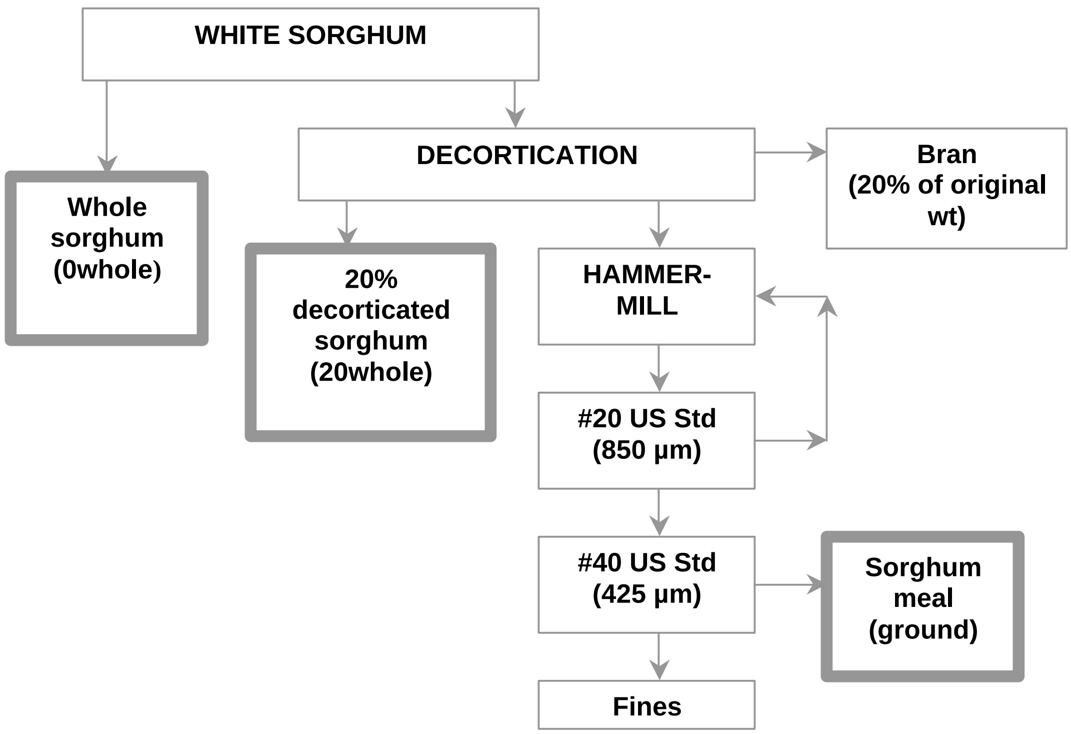

Fig. 22. Flow chart of raw materials preparation procedure from white sorghum (thick line square=treatment).

Particles above #20 US Std sieve were re-ground until all material passed through it. Thus, whole sorghum (whole), 20% decorticated sorghum but not ground (20whole), 20% decorticated sorghum ground and sieved (ground) and yellow corn meal (corn) were used for extrusion. All treatments were tempered (Fig. 23) at 14% moisture.

Particle size distribution of raw materials was analyzed in triplicate using #10, 20, 30, 40, 60, 80 and 100 US standard sieves and 50 g sample size. The composition of raw materials was determined using standard methods (AACC 2000).

Extrusion

Raw materials tempered at 14% moisture 24 hours prior to processing were extruded in a single-screw friction-type extruder (model MX-300I, Maddox Inc, Dallas, TX). The extruder was set at a Length/Diameter ratio of 4 and a die with 4, 1/8 inch holes and two flow plates before the die. The current consumed by the extruder was monitored during processing on the extruder display. The power consumed by the extruder was calculated using the same procedure as in chapter IV. The time necessary to extrude 10 kg of raw materials was observed to calculate feed rate (kg/hr). The SME was calculated dividing the power consumed by the extruder by the feed rate.

After extrusion, samples were baked at 100°C for 30 minutes in a tray convection oven and stored in metallic plastic bags. The baked extrudates (between 1.5 and 3% moisture) were used for analysis. The appearance, texture and flavor of extrudates were evaluated subjectively.

Expansion and bulk density

The expansion ratio was determined according to method of Gomez et al (1988). Radial expansion ratio was calculated by the ratio of extrudate average diameter/die

Fig. 23. Appearance of whole sorghum, 20% decorticated sorghum, sorghum and corn meals utilized in extrusion.

diameter. Length of extrudates was also determined. Fifteen extrudates were measured and averaged. A container full of extrudates with a volume of 15 L was weighed. The weight of the extrudates measured in triplicate divided by the container volume was the bulk density.

Microstructure

Extrudates were mounted on aluminum stubs with conductive adhesive and viewed in an environmental scanning electron microscope (ESEM) (Model E-3, Electroscan Corp., Wilmington, MA) with accelerating voltage of 20 kV to evaluate their microstructure.

Mechanical properties

The mechanical properties of the extrudates were tested using a texture analyzer (model TA.XT2i, Texture Technologies Corp., Scarsdale, NY) using a needle to puncture the extrudates on a flat platform. The needle utilized had a flat tip and a 2 mm diameter.

The mean force, elastic (Young's) modulus, work required to puncture the extrudates and the number of force peaks were recorded. Forty measurements per treatment were averaged. Elastic modulus was calculated as the slope of the linear region of the curve of force vs. distance, before the extrudate is ruptured.

Rheological properties

The rheological properties of slurries with 20% solids prepared from ground extrudates passing a US Standard 40 sieve was evaluated with a Rapid Visco Analyzer (RVA) (Model 4, Newport Scientific, Warriewood, Australia) to calculate the consistency coefficient (K) and flow behavior index (n) of the slurries.

Samples were heated from 50 to 90^{o}C in 2 min while mixed at a constant speed of 120 rpm held for 12 min. The viscosity after 12 min was considered equilibrated. When 12 min elapsed, the speed was changed by increasing 10 rpm every ten seconds starting at 20 rpm until 150 rpm was reached and then the speed was decreased 10 rpm every ten seconds until the initial speed was reached to test for time dependency.

Sensory evaluation

The appearance, flavor, texture and overall preference of flavored and baked extrudates were evaluated by 37 untrained panelists using a hedonic scale. The formulation used for flavoring the extrudates was the same for all treatments (Table C.1). The scale was from 1, dislike extremely, to 9, like extremely. The panelists were students, professors and staff from Texas A&M University, between the ages of 20 and 50.

The hardness and crispness were also evaluated using a 9-point intensity scale from 1 (very soft), to 9 (very hard) for hardness (Camire et al 1991) and from 1 (fractures very difficult) to 9 (fractures easily) for crispness (Rampersad et al 2003). The order in which the samples were given to the panelist was changed in an orderly fashion, so that it did not affect the perception of panelists.

Statistics

Treatments were separated with Fisher's LSD with an α=0.05. Statistics were performed with SAS statistical software package (SAS 2000).

Results and discussion

Milling yield, particle size and composition

Sorghum milling provided a large proportion of particles between #20 and #40 US Standard sieves (Table XXX). More than 75% of the decorticated sorghum gave particles with that size when milled. If decortication is taken into consideration, the total yield for particles with this size was around 60%.

As for sorghum meal, most of yellow corn meal particles were retained in the #30 and #40 US Standard sieves (Table XXXI). However, sorghum meal had a significant higher number of particles above the #20 and less above the #40 US standard sieves. The sorghum samples that were not ground (whole sorghum and 20% decorticated sorghum) had almost all particles with a larger size than 2 mm (#10 US Std sieve). However, the decorticated sorghum (20whole) had more particles smaller than 2 mm but larger than 0.85 mm. This happened because during decortication, some sorghum kernels cracked and smaller particles were produced.

Decortication decreased oil and ash content (Table XXXII) because of the removal of pericarp and germ fractions. Composition of sorghum meal was similar to that of corn meal, except for the higher protein content.

SME and processing capacity

A comparison of whole sorghum feed rate with other sorghum samples shows that decortication increased feed rate but milling decreased it, since feed rate was higher for 20% decorticated sorghum but lower for sorghum meal, compared to whole sorghum (Fig. 24). The highest overall was for decorticated sorghum with 140.73 kg/hr. Feed rate was higher for all sorghum samples compared to corn meal. Thus, the

Table XXX

Sorghum yield of different particle sizes after first grinding, the final grinding and total yield (considering decortication losses)

	First[a] Grinding %	Final[b] Grinding %	Total[c] yield%
#20 US Std. Sieve (850 µm)	53.8	0	0
#40 US Std. Sieve (425 µm)	29.7	75.8	60.6
Below #40 US Std. Sieve	16.5	24.2	19.4

a First grinding% is the proportion of particles with a particular size based on initial 20% decorticated sorghum weight after first pass through the hammer-mill.
b Final grinding% is the proportion of particles with a particular size based on initial 20% decorticated sorghum weight after re-milling overs of #20 US Std sieve in the hammer-mill seven times.
c Total yield% is the proportion of particles with a particular size based on total initial whole sorghum weight.

Table XXXI

Particle size distribution (% weight) of whole and decorticated sorghums, corn and sorghum meals

Sample/ US Std Sieve	#10 (2000 mm)	#20 (850 mm)	#30 (600 mm)	#40 (425mm)	#60 (250 mm)	#80 (180 mm)	#100 (150 mm)	Pan (<150 mm)
Whole Sorghum	99.9a[a]	0.04b	0b	0c	0c	0a	0a	0a
Decorticated sorghum	87.3b	12.6a	0.03b	0c	0c	0a	0a	0a
Sorghum Meal	0c	10.0a	51.1a	34.0b	4.8a	0a	0a	0a
Corn Meal	0c	3.5b	51.2a	40.7a	4.1b	0.3a	0a	0a
LSD (α=0.05)	5.1	5.3	1.81	1.5	0.6	0.5	0	0

a Treatments with same letter are not significantly different (p<0.05)

Table XXXII

Composition of the whole and decorticated sorghum, corn and sorghum meals utilized in extrusion

Sample	Oil[b] %		Crude[a] protein%		Ash[b] %	
Whole sorghum	3.43	a[c]	9.45	b	1.31	a
Decorticated sorghum	2.67	b	8.59	d	0.77	b
Sorghum meal	2.34	b	9.80	a	0.82	b
Corn meal	2.10	b	9.03	c	0.75	b
LSD (α=0.05)	0.66		0.35		0.07	

a Crude protein was calculated using the Dumas method
b Ash and oil were calculated using standard methods (AACC, 2000)
c Treatments with same letter are not significantly different (p<0.05)

extruder was able to process sorghum faster than cornmeal, even when the particle size distribution of sorghum was similar (sorghum meal).

The SME was significantly affected by the different raw materials (Fig. 25, Table XXXIII). It was highest for sorghum meal, followed by corn meal. Whole and 20% decorticated sorghum had the lowest SME and were statistically the same. From this, it is inferred that sorghum meal was more transformed inside the extruder. This can be empirically confirmed by the fact that extrudates made from ground sorghum had a rougher surface (often called alligator skin) (Fig. 26), which is related to over work inside the extruder (Schonauer 1995).

The SME consumed for 20% decorticated sorghum (20 whole) extrusion was significantly lower than for sorghum meal. Although 20% decorticated sorghum particles were larger, they required less power for extrusion.

According to Desrumaux et al (1998), an increase in particle size decreases the contact area between particles and that decreases friction. This could explain the decreased SME required for decorticated (not ground) sorghum extrusion compared to sorghum meal.

Since whole sorghum required less power, followed by 20% decorticated sorghum and sorghum meal, both decortication and grinding tended to increase the power consumed during extrusion. Extrusion of whole sorghum required the least SME for extrusion including corn meal.

This confirms the results obtained in Chapter IV, in which whole sorghum at 14% moisture required less energy than corn meal using the same extrusion conditions. This lower SME was probably due to the higher oil and fiber content of whole sorghum that decreases friction in the extruder.

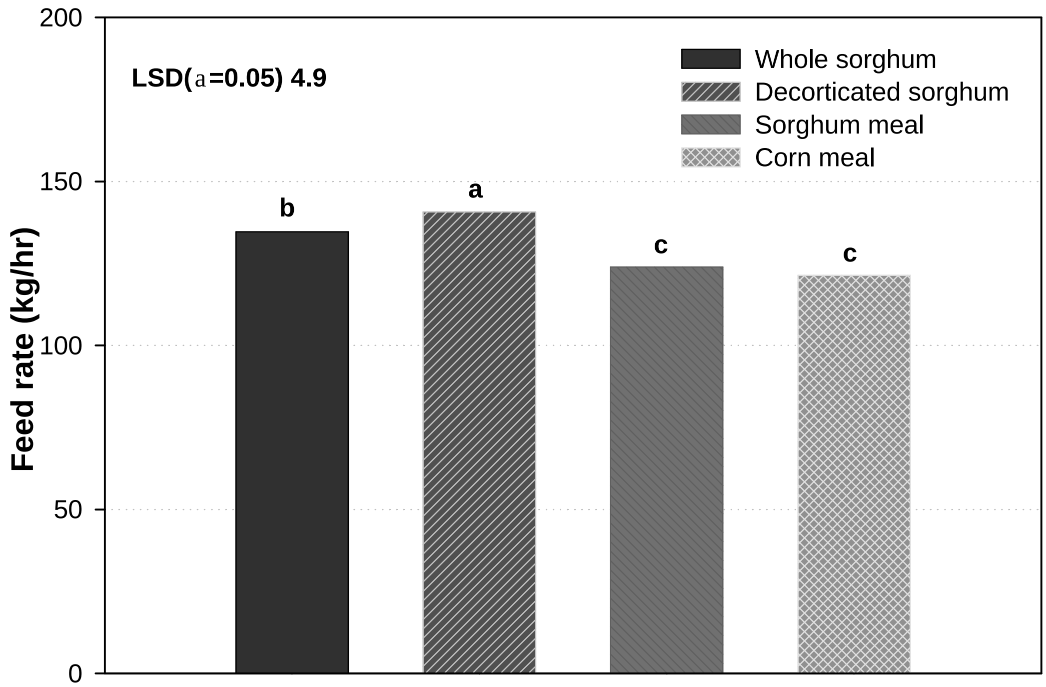

Fig. 24. Feed rate of the extruder when whole sorghum, 20% decorticated sorghum, corn and sorghum meals were processed.

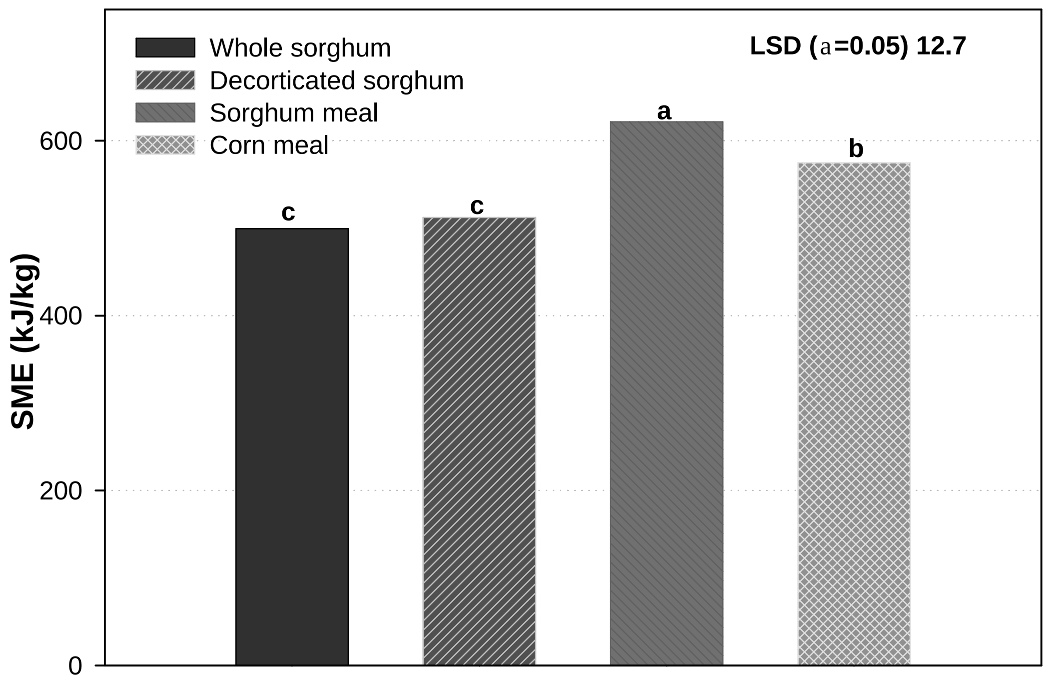

Fig. 25. Specific mechanical energy received by whole sorghum, 20% decorticated sorghum, corn and sorghum meals inside the extruder.

TABLE XXXIII

Power, feed rate and SME for extrusion of whole sorghum, 20% decorticated sorghum, corn and sorghum meals

	Power (kW)		Feed rate (kg/hr)		SME (kJ/kg)	
Whole sorghum	18.7	d[a]	134.6	b	499.4	c
Decorticated sorghum	20.0	b	140.7	a	512.0	c
Sorghum meal	21.4	a	123.8	c	621.5	a
Corn meal	19.4	c	121.4	c	574.8	b
LSD (α=0.05)	0.5		4.9		12.7	

a Treatments with same letter are not significantly different ($p<0.05$)

Extrudates

All extrudates had good expansion (Fig. 26). Extrudates made from ground sorghum were the most expanded and had a rough surface. Extrudates from yellow corn meal were highly expanded with a smoother surface than those made from sorghum meal. The texture of extrudates made from both sorghum meal and corn meal was softer than those made from whole and decorticated sorghums.

Extrudates made from decorticated sorghum expanded more and had a lighter color than those made from whole sorghum as a consequence of pericarp and germ removal. Extrudates from decorticated sorghum also had a smooth surface and a crunchy texture. Whole sorghum extrudates were darker and harder. They had a crunchy, gritty texture with a different mouth feel than the other extrudates. They also had a characteristic whole grain flavor.

Expansion

The expansion index and bulk density of extrudates were statistically different for all treatments (Fig. 27 and 28). Extrudates made from ground sorghum had the highest expansion ratio and also had the lower bulk density. Thus, sorghum meal can expand even more than corn meal when extruded at similar conditions.

As expected, decortication allowed sorghum to expand more when extruded, as proven by the fact that 20% decorticated sorghum expanded more than whole sorghum, which had a similar particle size distribution. Although extrudates from decorticated sorghum had good expansion and low bulk density, they were not as expanded as those from corn meal (Table XXXIV). Thus, the particle size reduction (and fines removal) helped white sorghum to expand more when extruded (sorghum meal).

Fig. 26. Physical appearance of extrudates made from whole sorghum, 20% decorticated sorghum, sorghum and corn meals.

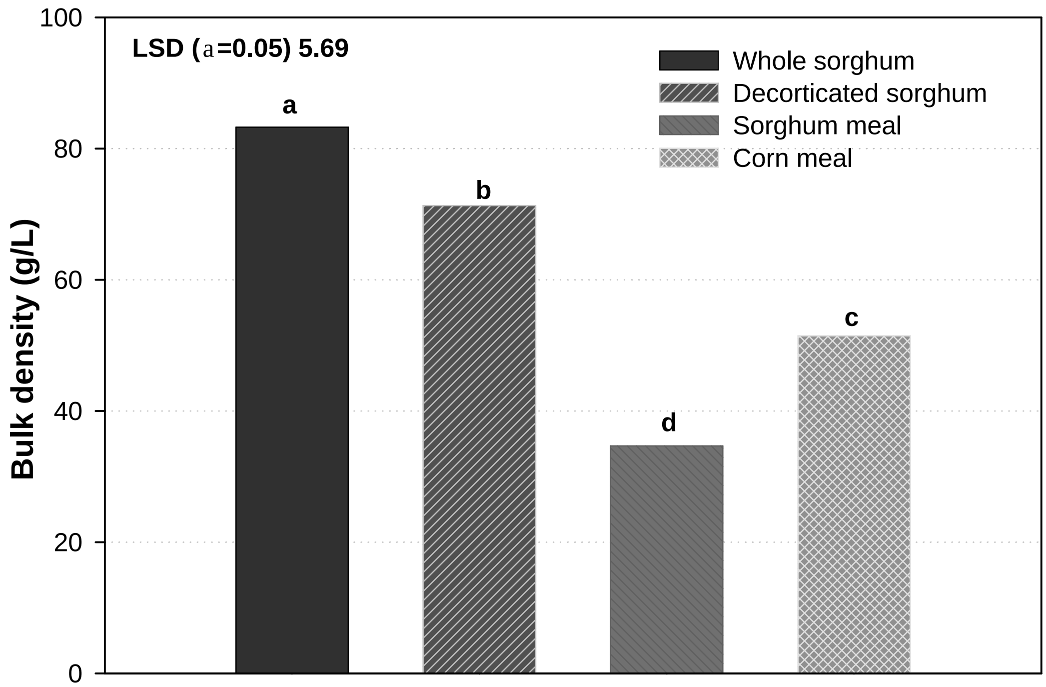

Fig. 27. Bulk density of extrudates made from whole sorghum, 20% decorticated sorghum, corn and sorghum meals.

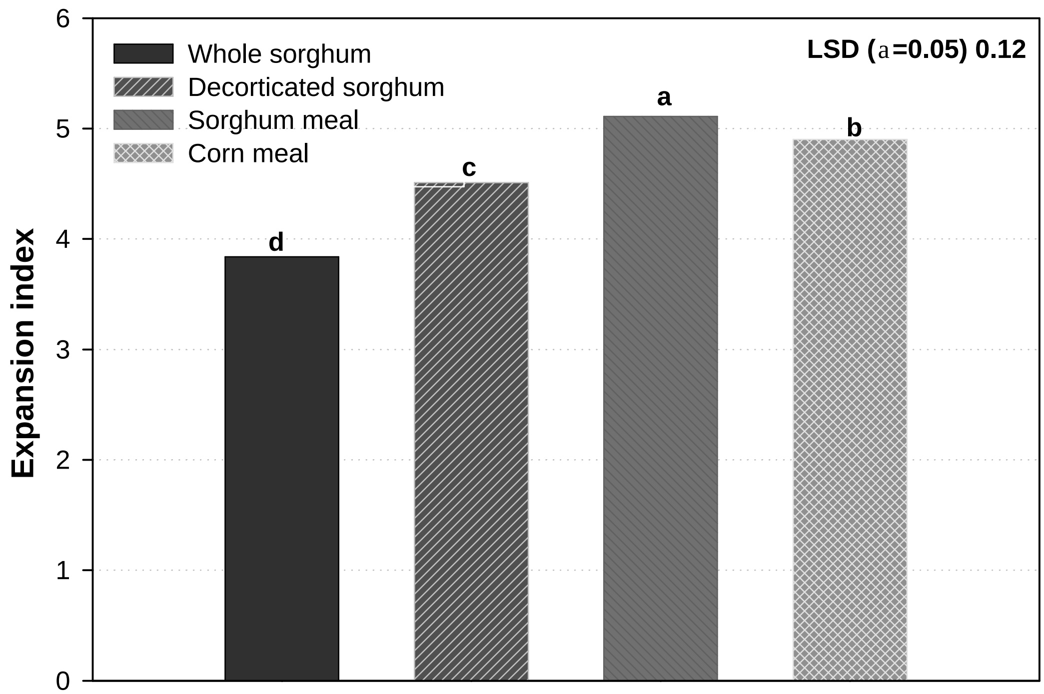

Fig. 28. Expansion ratio of extrudates made from whole sorghum, 20% decorticated sorghum, corn and sorghum meals.

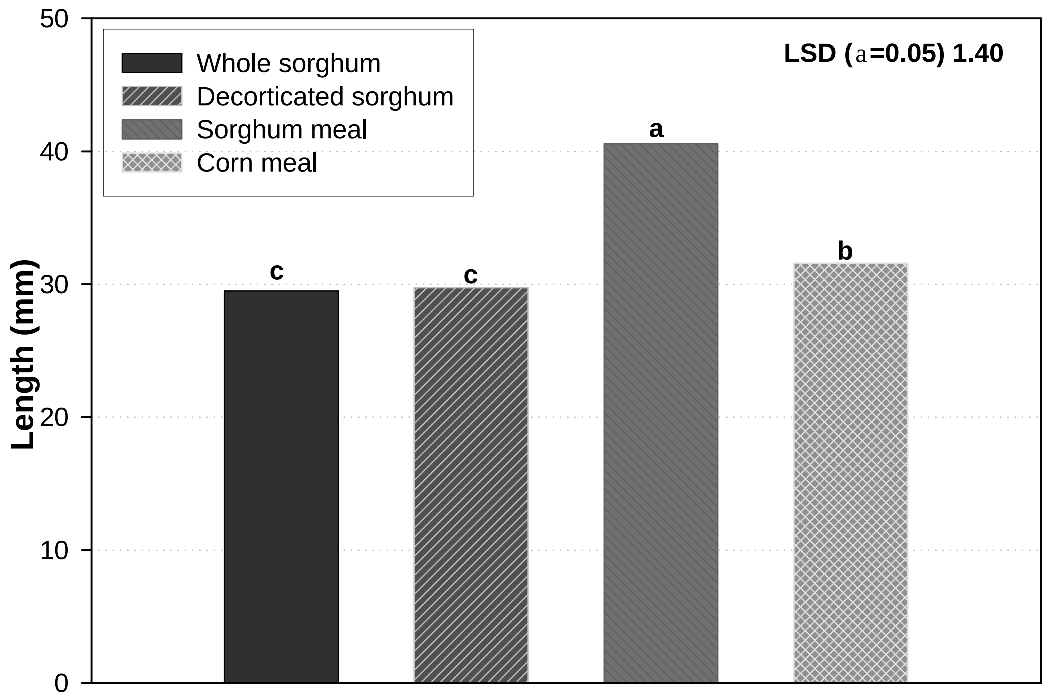

Fig. 29. Length of extrudates made from whole sorghum, 20% decorticated sorghum, corn and sorghum meals.

TABLE XXXIV

Bulk density, expansion ratio and length of extrudates made from whole sorghum, 20% decorticated sorghum, corn and sorghum meals

	Bulk density (g/L)		Expansion ratio		Length (mm)	
Whole sorghum	83.3	a[a]	3.8	d	29.5	c
Decorticated sorghum	71.3	b	4.5	c	29.7	c
Sorghum meal	34.7	d	5.1	a	40.6	a
Corn meal	51.4	c	4.9	b	31.6	b
LSD (α=0.05)	5.7		0.1		1.4	

a Treatments with same letter are not significantly different ($p<0.05$)

Length of extrudates was lower for those made from larger particles (whole and decorticated sorghums) (Fig. 29) compared to sorghum and corn meals probably as a result of a higher melt viscosity inside the extruder (Launay and Lisch 1984; Alvarez-Martinez et al 1988), which made the flow in the die difficult (shorter extrudates at same knife speed).

Extrudates made from ground sorghum were the longest proving that they were more transformed (received more SME in the extruder) and the melt had a lower viscosity. Extrudates made from corn had intermediate length. The length of extrudates was highly correlated to the SME developed during extrusion (R^2=0.82), and thus, to starch degradation and melt viscosity in the extruder.

Microstructure

Extrudates made from raw materials with larger particle size (whole and decorticated sorghum) had larger air cells and thicker cell walls (Fig. 30). This is in accordance with the larger air cells in extrudates made from corn meal with increasing particle size found by Desrumaux et al (1998). Extrudates made from corn meal and sorghum meal had similar internal structures. They had a large number of small air cells with thin and smooth cell walls.

Whole sorghum extrudates had rougher air cell walls, caused by the fiber present in the pericarp (Grenus et al 1993; Andersson et al 1981). Because of the thicker cell walls, extrudates from decorticated and whole sorghum could be considered crunchier by consumers than extrudates from corn and sorghum meals, which may be considered as crisper. Large pieces of pericarp were found in whole sorghum extrudates, which made the cell walls more irregular than those from decorticated sorghum, but also made them thicker.

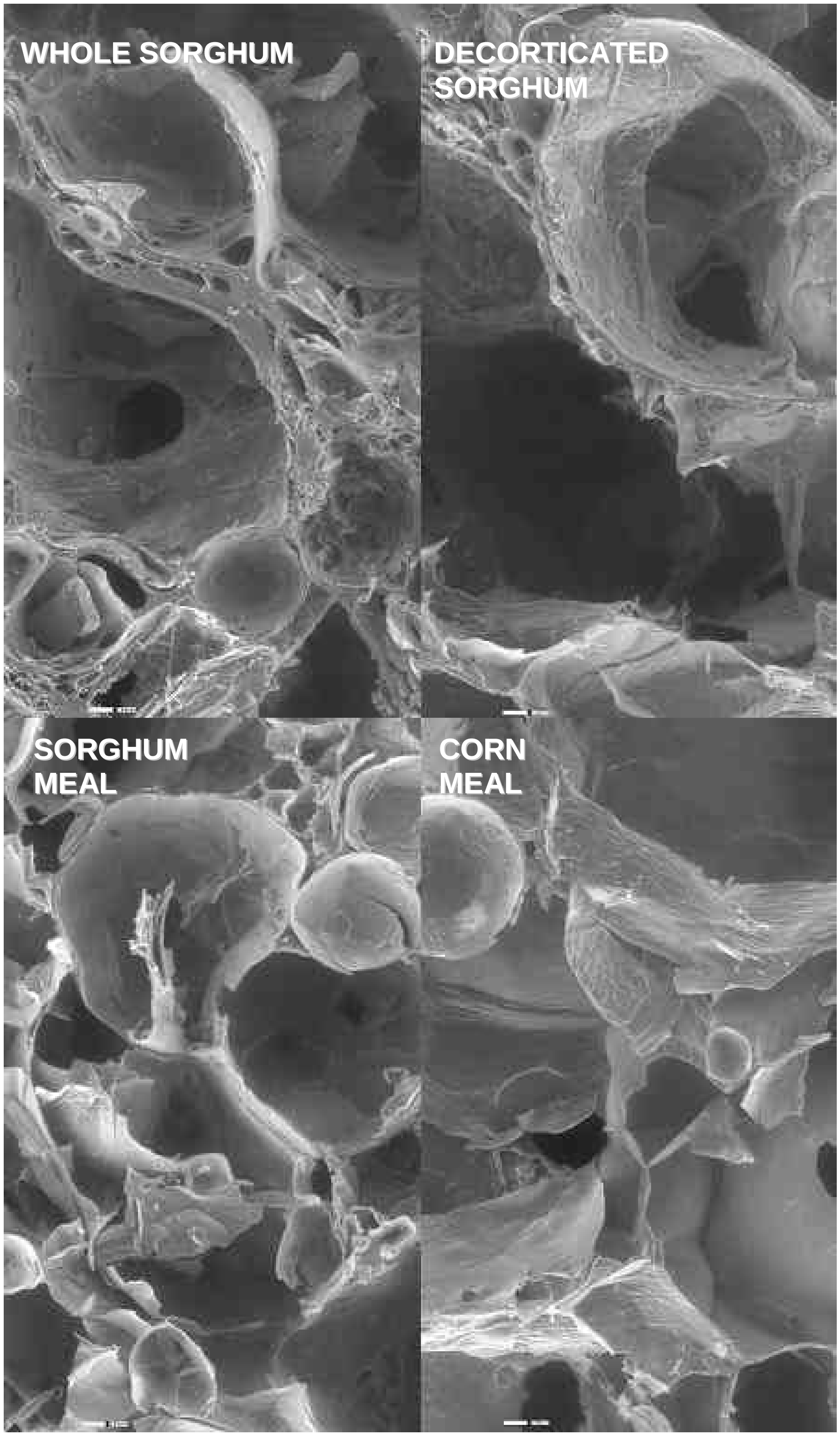

Fig. 30. ESEM photos of extrudates, whole sorghum, 20% decorticated sorghum, sorghum and corn meals.

Mechanical properties

Although extrudates made from decorticated sorghum were not the most expanded, they produced the highest number of force peaks when punctured (Fig. 31 and Table XXXV). Actually, the sample that expanded the most (sorghum meal) had the lowest number of force peaks. Probably, because these extrudates had thinner and smaller cell walls than the other extrudates, which could produce force peaks that were too small for the Texture Analyzer to detect.

The elastic modulus of the extrudates was more affected by particle size than composition, since it was statistically the same for extrudates made from decorticated and whole sorghum, and also the same for sorghum and corn meals (Fig. 32). This agrees with the ESEM pictures, which showed that extrudates made from raw materials with larger particles had thicker cell walls. Thus, the thicker cell wall of extrudates from decorticated and whole sorghums required more force for deformation (more stiff).

Extrudates made from corn and sorghum meals had thinner cell walls and required less force for deformation, giving them crispy texture opposed to the crunchier one of extrudates from whole and decorticated sorghums. Extrudates from whole sorghum were harder than the rest as shown by the higher mean force required to puncture them (Fig. 33).

Extrudates from decorticated sorghum required lower force for puncturing probably because they had thinner cell walls, but probably also due to a lower deformation required to break the cell walls (less mean force to break them). The combination of decortication and milling (sorghum meal) allowed production of extrudates that required even lower force for puncturing. Extrudates from sorghum meal were as soft as those from corn.

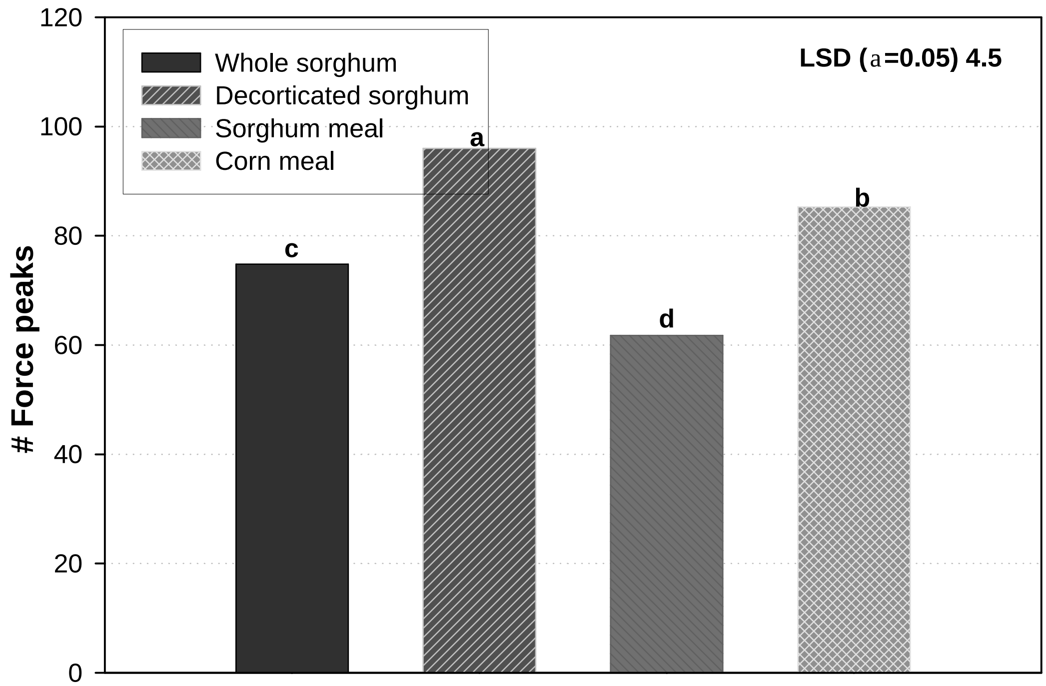

Fig. 31. Number of force peaks produced during puncturing of extrudates from whole sorghum, 20% decorticated sorghum, corn and sorghum meals.

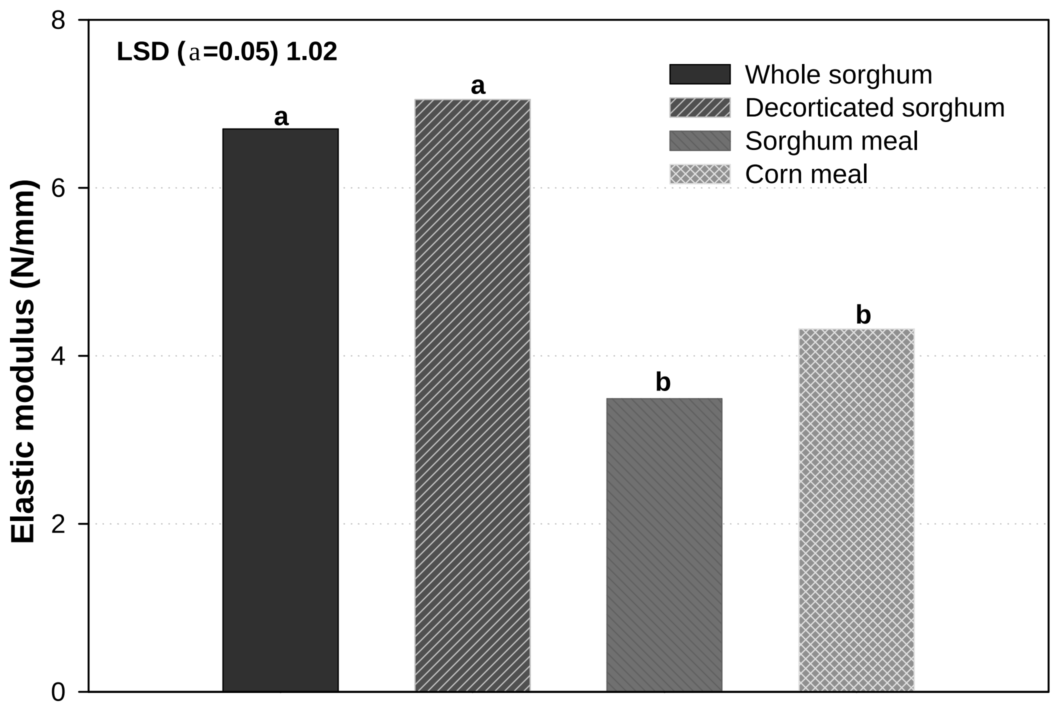

Fig. 32. Elastic modulus of extrudates from whole sorghum, 20% decorticated sorghum, corn and sorghum meals.

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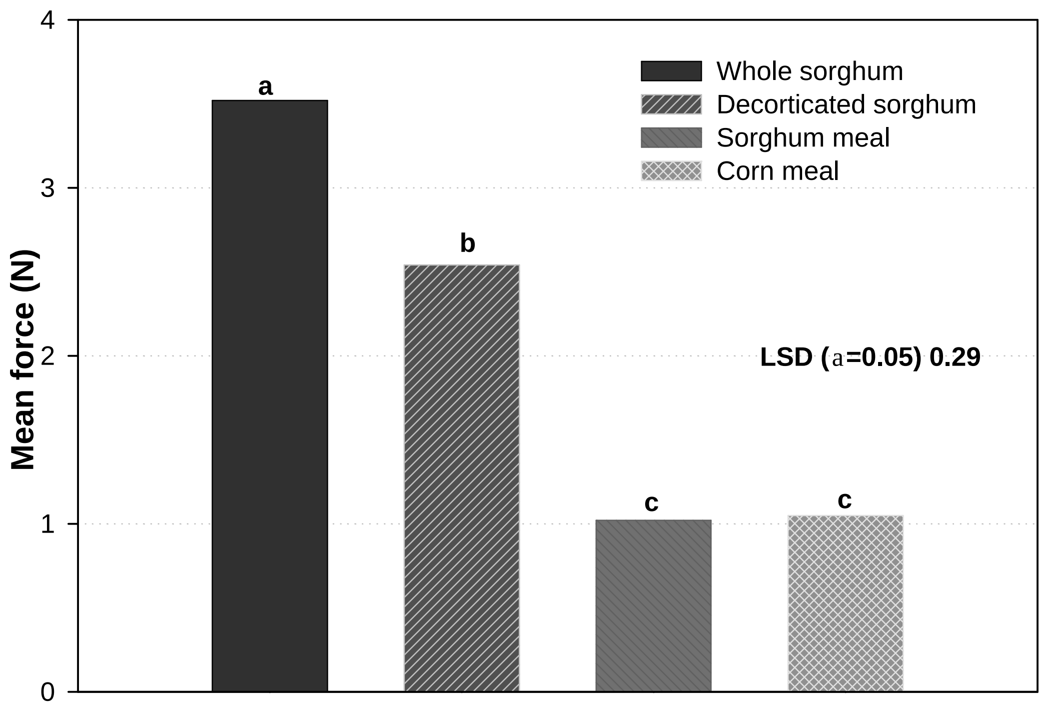

Fig. 33. Mean force to puncture extrudates from whole sorghum, 20% decorticated sorghum, corn and sorghum meals.

TABLE XXXV

Number of peaks, mean force and elastic modulus of extrudates made from whole sorghum, 20% decorticated sorghum, corn and sorghum meals.

	Number of peaks		Mean force (N)		Elastic modulus (N/mm)	
Whole sorghum	74.83	c[a]	3.52	a	6.70	a
Decorticated sorghum	96.03	a	2.54	b	7.05	a
Sorghum meal	61.73	d	1.02	c	3.49	b
Corn meal	85.30	b	1.05	c	4.32	b
LSD (α=0.05)	4.50		0.29		1.02	

a Treatments with same letter are not significantly different ($p<0.05$)

Rheological properties

The K and n values were obtained with the same procedure used in chapter IV. The complete RVA curve (Fig. B.3), and the section of the curve where speed was changed (Fig. B.4) are shown. The K is an index of the viscosity of a sample, eliminating shear rate and sample behavior effects (Newtonian, pseudoplastic, etc).

The K was highest for extrudates from whole sorghum, followed by decorticated sorghum, corn and sorghum meal extrudates (Table XXXVI). From this, it is inferred that starch in sorghum meal was more transformed in the extruder than in the rest of samples, giving a lower K. The opposite happened for whole sorghum, which received lower SME and had a higher K value. Thus, K appears to be related to the extent of starch degradation. This can be proven by the inverse correlation that SME and K had (R^2=0.94).

The n value describes the type of fluid the sample is. Newtonian fluids have n value of 1. Starch slurries are pseudoplastic or shear-thinning fluids (Tand and Ding 1994) and have a value of $0<n<1$. Thus, with higher n, the sample behaves more like Newtonian fluid. With increasing starch degradation, a higher value of n in slurries is expected. This was true for sorghum samples, which was higher for sorghum meal (higher SME) and lowest for whole and decorticated sorghums (lower SME). However, corn meal slurries had a lower n value (with high SME) probably because of differences in starch structure.

So, the lower K and higher n values show that decortication and grinding allowed starch to be more transformed (dispersed and partially de-polymerized) in the extruder (higher SME), reducing the volume of the colloidal particles by friction in the extruder (Tang and Ding 1994), reducing viscosity and behaving more like Newtonian

TABLE XXXVI

Consistency coefficient and flow behavior index of extrudates from whole sorghum, 20% decorticated sorghum, corn and sorghum meals

	K^a (cP*s)		n^a	
Whole sorghum	10976.7	a[b]	0.61	b,c
Decorticated sorghum	9518.3	b	0.63	a,b
Sorghum meal	4427.7	d	0.66	a
Corn meal	8032.9	c	0.59	c
LSD (α=0.05)	1341.1		0.03	

a Determined from regressions of curves of viscosity vs. shear rate obtained in RVA, varying speed from 20 to 150 rpm in 10 rpm increments and back to 20 rpm.

b Treatments with same letter are not significantly different ($p<0.05$)

fluids (higher n). As in chapter IV, K value was highly correlated to bulk density of extrudates (R^2=0.95) and elastic modulus (R^2=0.8), and inversely correlated to length of extrudates (R^2=0.92).

Sensory evaluation

The appearance, flavor, texture and overall preference were evaluated using a hedonic scale from 1 to 9. One was for dislike extremely and 9 for like extremely. The panel was comprised of 73% females and 23% males. 49% of the panelists were in the 20-29 age range, 27% in 30-49, 14% above 50, 5% under 20 and 5% between 40 and 50 years old. The form used for evaluation is shown (Fig. C.1).

Extrudates made from sorghum meal were statistically equally rated in appearance, flavor, texture and overall preference to those made from corn meal (Table XXXVII). Thus, when processed under similar conditions, white sorghum produces extrudates with lower bulk density and equal consumer preference to yellow corn.

The taste panel gave lower scores to extrudates from whole sorghum and decorticated sorghum compared to those produced from corn and sorghum meals. They were perceived as harder and less crispy then the other two, but were also perceived as crunchier. 47% of the panelists were of Hispanic origin, 38% American, 14% Asian and 3% African.

Decortication of sorghum did not increase consumer preference as proved by the similar ratings that extrudates from whole and decorticated sorghum had. The hardness perceived by the test panel was correlated to the elastic modulus determined with the texture analyzer (R^2=0.99). Thus, elastic modulus can be utilized to predict consumer perception of hardness. On the other hand, the mean force to puncture extrudates was inversely correlated to the texture acceptability of extrudates from the

Table XXXVII

Sensory evaluation average scores for all treatments

Sample / parameter	**Appearance[a]**	**Flavor[a]**	**Texture[a]**	**Overall[a] rating**	**Hardness[b]**	**Crispness[c]**
Whole sorghum	5.4 b[d]	6.2 b	5.7 b	5.7 b	7.0 a	3.8 a,b
Decorticated sorghum	5.8 b	6.5 b	6.1 b	6.1 b	7.0 a	4.2 a
Sorghum meal	7.3 a	6.9 a,b	7.1 a	7.1 a	4.9 b	3.1 b,c
Corn meal	7.3 a	7.5 a	7.7 a	7.57 a	5.3 b	2.8 c
LSD (α=0.05)	0.9	0.91	0.84	0.90	0.80	0.86

a Rated in a hedonic scale from 1 (dislike extremely) to 9 (like extremely)
b Rated in a 9 point intensity scale from 1 (very soft) to 9 (very hard)
c Rated in a 9 point intensity scale from 1 (fractures very difficult) to 9 (fractures easily)
d Treatments with same letter are not significantly different ($p<0.05$)

consumer panel (R^2=0.92). So, in general, consumers preferred extrudates with softer textures. Acceptability of extrudate appearance was correlated to the expansion (R^2=0.87)

Although the same flavor and the same amounts were used, consumers detected flavor differences between samples. Corn meal extrudates were preferred over extrudates from whole and decorticated sorghums, but were equally accepted as those from sorghum meal. It is inferred that consumer's perception of flavor was influenced by their perception of texture (R^2=0.98). There were no differences in flavor between sorghum samples. So, consumers did not detect the whole sorghum flavor, probably because it is bland and the flavoring masked major differences.

Summary

As concluded in previous chapters, whole sorghum kernels were successfully extruded into expanded snacks with nutritional benefits from whole grain foods. Extrudates from whole sorghum received lower scores by the taste panelists in appearance, flavor, texture and overall characteristics. They had harder, crunchy but also gritty texture. Although extrudates made from whole sorghum were rated lower than those from corn meal, they were equally rated to decorticated sorghum samples and received acceptable scores.

Sorghum meal, with similar composition and particle size distribution to corn meal, produced extrudates with higher expansion, lower bulk density and equal consumer acceptance to those made from corn meal extruded under similar conditions. On the other hand, sorghum meal extrusion required more energy than when corn meal was processed.

The extruder processed faster whole and decorticated sorghum treatments than corn meal. Feed rate for sorghum and corn meal was the same. Texture of extrudates can be controlled by varying particle size of raw materials, sorghum samples that were not ground (whole sorghum and 20% decorticated sorghum) were crunchier (thick cell walls) and harder compared to those made from sorghum or corn meals which were crisper and softer (thinner cell walls). The consistency coefficient value (K) appears to be related to starch degradation and extrudate properties. Further studies in this area are required.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Whole sorghum extrusion

Whole sorghum kernels were directly processed into whole grain snacks with acceptable texture. Whole sorghum extrusion may produce significant savings in processing since there are no dry matter losses, there is no energy used in decortication or milling, and the extruder consumes less power and processes more material per time unit. However, the higher processing capacity for whole sorghum needs to be confirmed in longer trials.

Grinding and fines removal did not improve whole sorghum extrusion. Extrudates made from sorghum raw materials (decorticated and non decorticated) that were not ground had thicker air cell walls, larger bubbles and harder, crunchier textures compared to extrudates from ground raw materials.

Grinding reduced the size of pericarp pieces, as expected. Larger pericarp pieces in extrudates from whole sorghum kernels made smaller bubbles coalesce into large bubbles with thick cell walls. The best products were obtained when whole sorghum (ground or un-ground) was extruded at 14% moisture.

Extrudates from whole sorghum received lower scores by the test panelists in appearance, flavor, texture and overall characteristics compared to those made from decorticated sorghum or corn meal. Whole sorghum produced expanded snacks with crunchy texture, excellent flavor and with the nutritional benefits of whole grain foods.

The reduction in the number of holes in the die (from 6 in Chapter III, to 4 in Chapters IV and V) improved whole sorghum expansion as consequence of increased friction. Thus, extrudates from whole sorghum with even better characteristics may be obtained by a further increase in friction by using a more powerful extruder. The concept of using direct-expansion of whole sorghum to produce whole grain snacks appears promising.

Decorticated sorghum extrusion

Decortication of sorghum, and the consequent removal of pericarp, germ and aleurone layer improved extrusion performance and product characteristics, allowing the adequate formation and retention of air cells. Decortication to remove 20% of the original sorghum weight was enough to produce extrudates with comparable characteristics to those made from yellow corn meal.

Sorghum raw materials with composition and particle size distribution similar to corn meal produced whiter, more expanded extrudates, with a blander flavor and similar texture. They were equally ranked to extrudates made from corn meal by a taste panel. Polished rice extrudates were less expanded, whiter and had a blander flavor than extrudates made from sorghum.

When processed under similar conditions, sorghum extrusion required more energy than extrusion of corn meal. However, energy consumption during extrusion decreased (lower than corn meal) and feed rate increased (higher than corn meal) when unground decorticated sorghums were processed.

Texture of extrudates is controlled with particle size of raw materials. Sorghum samples that were not ground (decorticated or non-decorticated) produced crunchier, harder extrudates compared to those made from ground raw materials, which were crisper and softer. White sorghum is a feasible option for snack extrusion because of its versatility, product characteristics, cost and processing properties.

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APPENDICES

APPENDIX A

COLOR PARAMETERS a* AND b* USED IN CHROMA CALCULATION

Table A.1

Color parameters a* and b* for sorghum, rice and corn extrudates[a]

Particle size	Decortication %	a*		b*	
Whole (un-ground)	0	1.1	a[b]	15.1	b,c
	10	-0.7	b,c,d	14.8	c,d
	20	-1.2	d	14.5	d,e
	30	-1.2	d	12.9	h
Coarse	0	0.0	b,c	15.3	b
	10	-0.6	b,c,d	14.0	f,g
	20	-1.3	d	13.8	f,g
	30	-1.4	d	13.7	f,g
Meal	0	0.3	a,b	15.3	b
	10	-0.5	b,c,d	14.4	d,e
	20	-0.8	b,c,d	14.1	e,f
	30	-0.9	c,d	13.6	g
Corn meal		-2.7	e	34.3	a
Rice		-1.2	d	10.8	I
LSD (α=0.05)		1.1		0.4	

a Color determined on ground extrudates passing through a US 40 Standard sieve
b Treatments with same letter are not statistically different ($p<0.05$)

APPENDIX B

RVA DATA OF EXTRUDATES

Table B.1. Profile used in the RVA

Time	Speed (rpm)	Temp (°C)
00:00	960	50
00:15	120	55
02:00	120	90
12:00	120	90
12:50	20	90
13:10	30	90
13:20	40	90
13:30	50	90
13:40	60	90
13:50	70	90
14:00	80	90
14:10	90	90
14:20	100	90
14:30	110	90
14:40	120	90
14:50	130	90
15:00	140	90
15:10	150	90
15:20	140	90
15:30	130	90
15:40	120	90
15:50	110	90
16:00	100	90
16:10	90	90
16:20	80	90
16:30	70	90
16:40	60	90
16:50	50	90
17:00	40	90
17:10	30	90
17:20	20	90

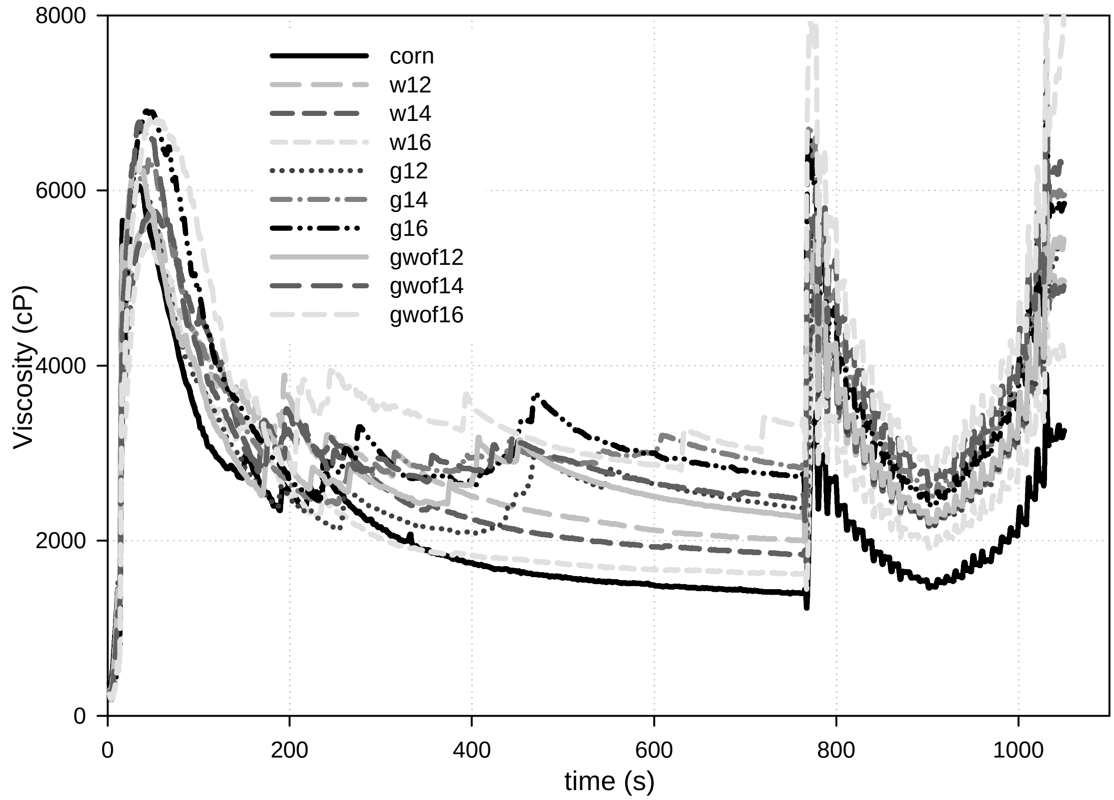

Fig. B.1. RVA curves of sorghum extrudate slurries at 20% solids compared to that from corn meal extrudates (120 rpm and 90°C until 770 s, then only speed was varied from 20 to 150, and 150 to 20 rpm in 10 rpm increments).

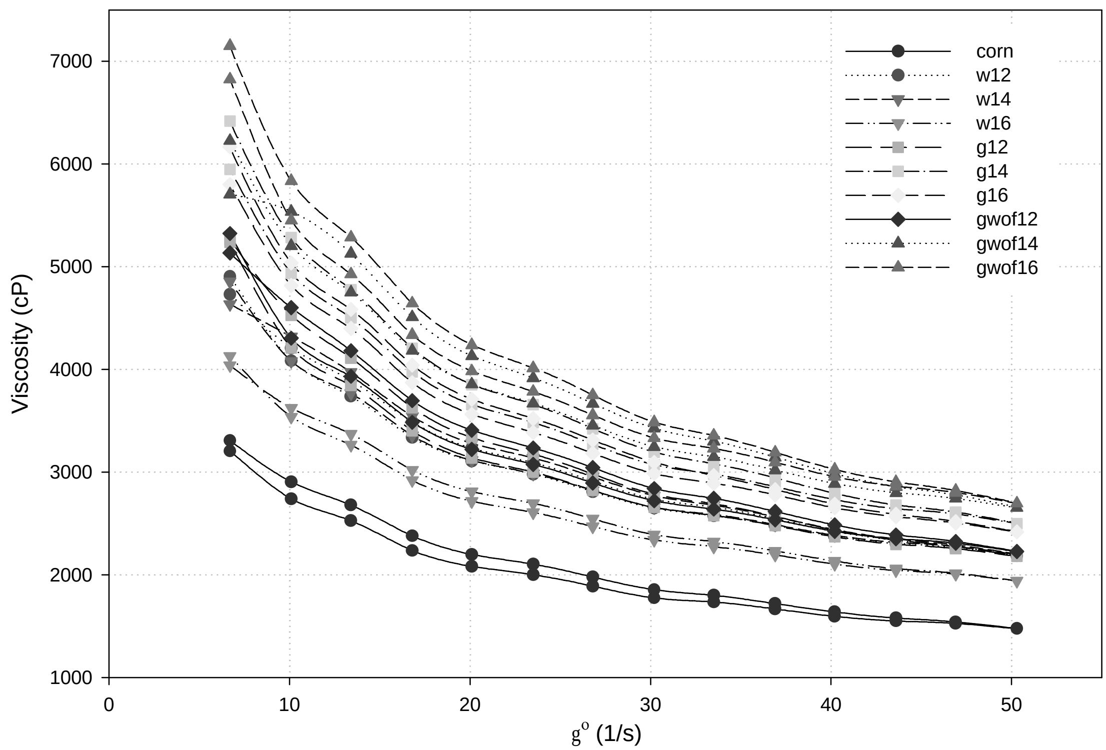

Fig. B.2. Apparent viscosity of whole sorghum and corn extrudate slurries (20% solids) vs. shear rate (at 90°C, speed varied from 20 to 150, and 150 to 20 rpm in 10 rpm increments).

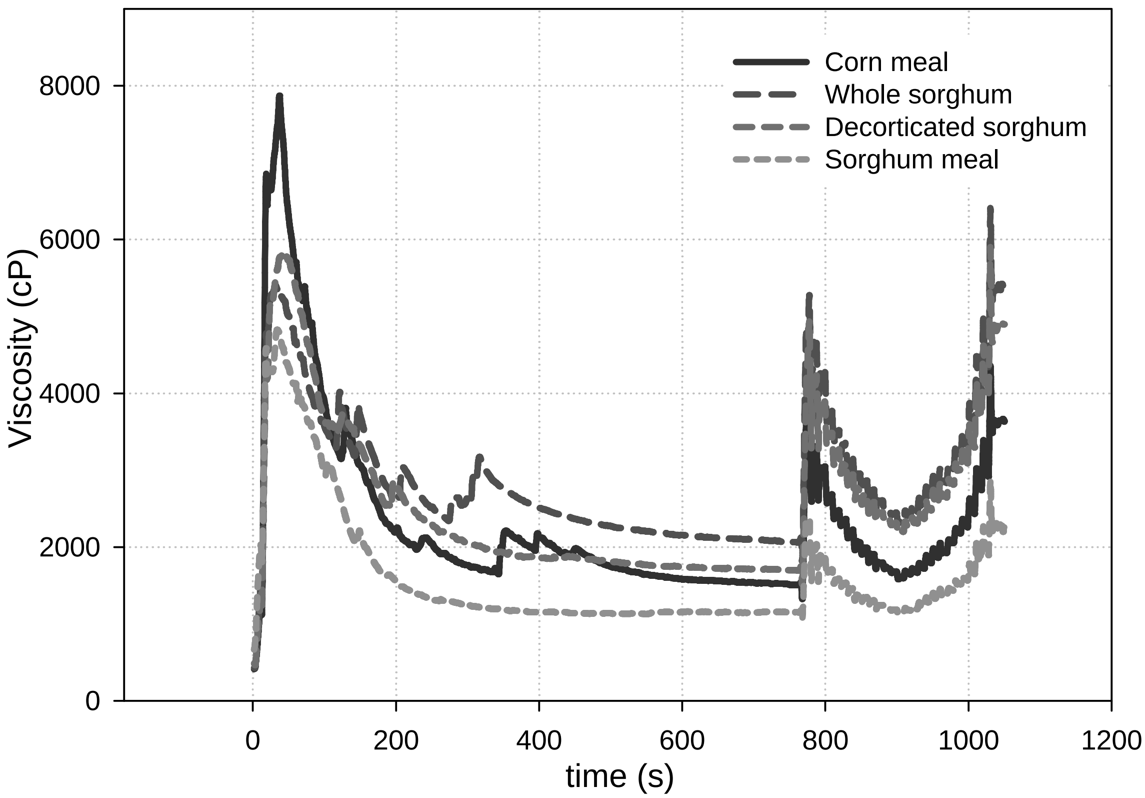

Fig. B.3. RVA curves of whole and decorticated sorghum extrudate slurries at 20% solids compared to that from corn and sorghum meals extrudates (120 rpm and 90°C until 770 s, then only speed was varied from 20 to 150, and 150 to 20 rpm in 10 rpm increments).

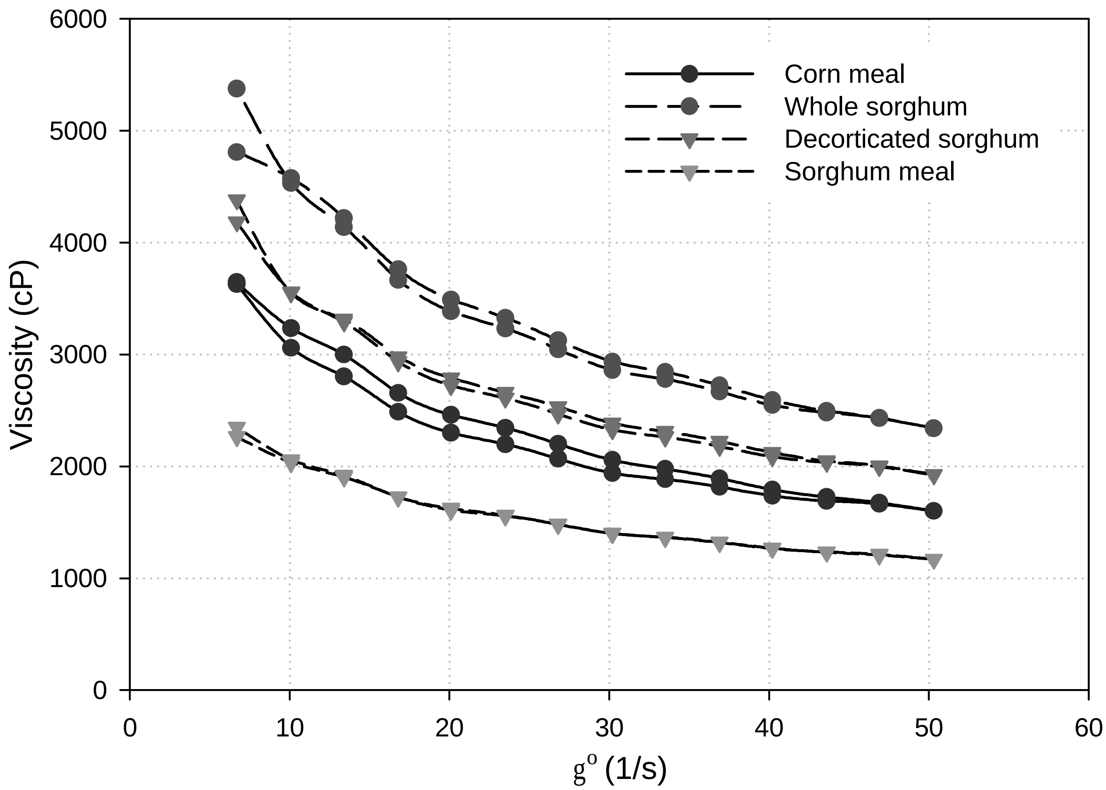

Fig. B.4. Apparent viscosity of slurries of extrudate made from whole and decorticated sorghum (20% solids) vs. shear rate (at 90°C, speed varied from 20 to 150, and 150 to 20 rpm in 10 rpm increments).

APPENDIX C

SENSORY EVALUATION

SENSORY EVALUATION

Thank you for participating in this evaluation.

INSTRUCTIONS: PLEASE, WRITE SAMPLE NUMBER AND CIRCLE THE NUMBER THAT BEST FITS YOUR DESCRIPTION.

Gender Male Female

Age: under 20 20 to 29 30 to 49 40 to 50 above 50

Origin: American Asian Latin European African

SAMPLE_____________

APPEARANCE **(do you like the shape, color, size of the product?)**

1	2	3	4	5	6	7	8	9
Dislike extremely				Neither like or dislike				Like extremely

FLAVOR **(do you like the flavor of the product?)**

1	2	3	4	5	6	7	8	9
Dislike extremely				Neither like or dislike				Like extremely

TEXTURE **(do you like the texture of the product?)**

1	2	3	4	5	6	7	8	9
Dislike extremely				Neither like or dislike				Like extremely

HARDNESS **(how does it feel at first bite?)**

1	2	3	4	5	6	7	8	9
Very Soft				Neither soft or hard				Very hard

CRISPNESS **(does it fractures and crumbles at first bite?)**

1	2	3	4	5	6	7	8	9
Very difficult				Neither easy or difficult				Very easy

Fig. C.1. Form used in the sensory evaluation of baked and flavored extrudates.

Table C.1

Formulation[a] used for flavoring extrudates used in sensory evaluation

Ingredient	%
Extrudates	52.96
Corn oil	29.13
Chipotle cheese flavoring	12.84
Acid whey	4.80
Salt	0.26

a Formulation was a modification of a standard formulation (Huber, 2001)

VITA

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