THE EFFECT OF FLAXSEED HULLS ON EXPANDED CORN MEAL PRODUCTS

A Thesis

by

MARC EDWARD BARRON

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

MASTER OF SCIENCE

May 2007

Major Subject: Food Science and Technology

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Approved by:

Chair of Committee,	Lloyd W. Rooney
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ABSTRACT

The Effect of Flaxseed Hulls on Expanded Corn Meal Products.

(May 2007)

Marc Edward Barron, B.S., Texas A&M University

Chair of Advisory Committee: Dr. Lloyd W. Rooney

Brown flaxseed hulls were added to de-germed corn meal and processed into extrudates with acceptable texture and increased nutritional benefits. The addition of brown flaxseed hulls to a corn based expanded snack increases the dietary fiber, alpha omega 3 fatty acids, and antioxidants levels. The addition of flaxseed hulls to a corn based snack can increase its susceptibility to oxidative rancidity which can limit shelf life. Whole ground tannin sorghum with added brown flaxseed hulls was processed into extrudates and texture, antioxidant activity, and stability were evaluated.

Brown flaxseed hulls were mixed with de-germed yellow corn meal in ratios of 0:100, 15:85, 20:80, and 25:75 (w/w) and extruded with 12 and 15% feed moistures using a twin screw extruder to produce direct expanded extrudates. Expansion of extrudates containing brown hulls decreased as the amount of hulls increased. Dried extrudates had acceptable flavor immediately after processing. Total phenols and antioxidant activity of extrudates containing 20 and 25% brown flaxseed hulls, extruded at 15% feed moisture were higher than de-germed corn meal extruded at 16% feed moisture.

Brown flaxseed hulls were added at 20% to whole ground white and sumac (tannin) sorghums and processed into extrudates. Expansion increased for sorghum extrudates containing brown flaxseed hulls. The addition of brown flaxseed hulls increased antioxidant activity and total phenols of both white and sumac (tannin) extrudates.

The sumac (tannin) extrudates had the longest delay in producing off odor (paint-like odor) and had the lowest p-Anisidine values compared to white (ATX631x RTX

436) sorghum and corn meal with added flaxseed hulls. Corn meal extrudates with 20% brown flaxseed hulls produce off odors more rapidly than other extrudates. This suggests that the tannins in sorghum maybe extending shelf life because of their antioxidant activity.

The addition of brown flaxseed hulls can be used to increase nutritional value and antioxidant levels in a direct expanded product. Also the use of tannins sorghums in products containing flaxseed may help delay oxidation, thus preventing the occurrence of off odors. Further work needs to be done to verify results.

DEDICATON

I dedicate this work to my parents, Edward and Elaine Barron, for their support and teaching me the importance of hard work, kindness, and humility. I also dedicate it to my sisters, Mallori Barron and Kelli Bastow, and brother, Keith Bastow, for their support and encouragement.

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CHAPTER I

INTRODUCTION

Flax (*Linum usitatissimum* L.) is an oilseed that has been cultivated for thousands of years for human consumption and its fiber used for linen production. Since the industrial revolution flaxseed has been utilized as a drying oil in paints and other industrial products (Oomah et al. 1998).

Recently flaxseed has emerged as a functional food source because of potential health benefits. Flaxseed is a rich source of α-linolenic acid (ALA), dietary fiber, lignans, high quality protein, and phenolic compounds. All of these components may be beneficial in reducing risk factors for both coronary vascular disease and certain cancers (Chen et al. 1994; Wirck, 1993; Carter, 1993; Oomah, 2001).

Flaxseed contains 28% dietary fiber, both soluble and insoluble, found mainly in its bran (seed coat). Flaxseed bran also contains phenolic compounds, known as lignans that have been shown to exhibit antioxidant activities (Prasad, 1997). Lignans are phytoestrogens due to their effect on balancing hormones, and may reduce the risk of hormone dependent tumors such as breast and prostate cancer (Haggans et al., 1999; Ososki and Kennelly, 2003). Advances in the flaxseed dehulling process have allowed separation of hulls (bran) from the cotyledon thus concentrating its dietary fiber and lignans. The hull fraction contains lower levels of oil and protein, and over two and half times as much lignan as the dehulled seed (23.9 and 9.0 mg SDG/g, respectively) making the hulls an attractive functional ingredient (Oomah et al. 1998).

Whole flaxseed is added to cereals, baked goods, energy bars, and salads to provide a crunchy texture and increase nutritional content. Whole flaxseed also has a reduced risk of lipid oxidation. Flaxseed contains 41% oil; 57% of its oil is composed of α-linolenic acid a poly unsaturated omega 3 fatty acid. Ground or damaged flaxseed is susceptible to lipid oxidation, but if not chewed properly to expose the nutrients to digestive enzymes they pass undigested through the gastrointestinal tract (Morris and

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This thesis follows the style and format of Cereal Chemistry.

Vaisey-Genser, 2003).

Ground flaxseed is used in dry mixes for muffins, pancakes, waffles, and baked goods, the most common being bread. Studies have shown that α-linolenic acid is stable at baking temperatures (Chen et al. 1994) and during processing and cooking of spaghetti (Manthey et al. 2002). Other studies suggest that ground flaxseed may successfully replace a portion of the wheat flour in yeast breads (Malcolmson et al. 2000) and in chemically leavened products such as muffins (Alpers and Sawyer-Morse, 1996).

Information available on whole flaxseed or its bran (hulls) in extrusion processing is minimal. Oomah (2003) stated processing technologies commonly used in the food industry, such as extrusion, fermentation, microwave, and non-thermal processes, have not been adequately explored in the processing of flaxseed. Work has been done using low shear extrusion, the process used to produce pasta. Manthey (2002) fortified spaghetti with up to 15% ground flaxseed; the ALA remained stable during processing and cooking and an acceptable product was produced. Lee (2004) reported that ALA remained stable during the processing and cooking of semolina based macaroni fortified with 15% ground whole flaxseed or ground flaxseed hulls. Information on the effect of high shear, high temperature extrusion on the stability of α-linolenic acid and product quality was not found.

Direct expanded products, examples being corn curls and breakfast cereals, are extruded using high shear single screw or twin screw extruders at temperatures above 150°C. The effect of the addition of whole flaxseed or its bran to a cereal based expanded product has not been thoroughly studied. Flaxseed and its hulls contain increased amounts of oil (41% and 15%, respectively) making lipid oxidation, product quality, and extruder performance a concern. Rao and Artz (1989) showed lipids are more susceptible to oxidation in extruded products during storage than during extrusion processing. Oil levels greater than 5-6% in formulations caused reduced expansion (Camire, 2000).

To over come the reduced expansion caused by increased lipid and fiber levels these products can be extruded using twin screw extruders. Twin screw extruders incorporate more shear and positive displacement into the material making it more suited for formulations with increased oil and fiber contents (Huber, 2001).

A decrease in expansion may be reversed by the use of a twin screw extruder; however the product is still susceptible to oxidation due to its increased oil content. To delay lipid oxidation antioxidants are added to extruded products. Synthetic phenolic antioxidants such as butylated hydroxyanisole (BHA) and butylated bydroxytoluene (BHT) are used but their volatility can result in low levels in the final product and their safety has been questioned (Namiki, 1990). Camire and Dougherty (1998) reported the addition of cinnamic acid and vanillin up to 1000 ppm to corn meal prior to extrusion was more effective in inhibiting lipid oxidation during storage in extruded/fried products than BHT. Viscidi et al. (2004) used complex phenolics to delay oxidation in extruded oats which contain unsaturated fatty acids. These findings suggest that whole grains containing natural phenolic compounds can be added to an extruded flaxseed or flaxseed hull product to delay lipid oxidation during storage.

The effect of high shear-high temperature extrusion on product quality and α-linolenic acid stability in an expanded product containing flaxseed or its hulls has not been thoroughly documented. The goal of this research is to develop a palatable expanded snack containing flaxseed or flax hulls, high dietary fiber, antioxidants, and α-linolenic acids.

The approach is to add sufficient levels of flaxseed hulls to significantly enhance the nutritional value of expanded corn snacks, and to determine if antioxidant sorghum improves the stability of the product.

Therefore, the objectives of this study were:

1) Determine the effect of the addition of flaxseed hulls have on an expanded corn snack characteristics.

2) Evaluate the affect of high shear-high temperature extrusion on the stability of expanded corn products containing flaxseed hulls.

3) Determine the oil stability of high tannin sorghum extrudates with added flax hulls.

CHAPTER II
LITERATURE REVIEW

Functional Food

The term “Functional Foods”, also referred to as nutraceuticals or designer foods, originated in Japan to describe a category of food products. In the early 1980’s Japan recognized a need for functional food products when demographical studies showed an aging population with life quality expectations in need of costly medical care (Mark-Herbert, 2004). Currently there is no universally accepted definition of functional foods; however they are usually understood as any potentially healthful food or food ingredient that may provide a health benefit beyond the traditional nutrients it contains (ADA Reports, 2004).

The market for functional foods is growing rapidly (Gray et al. 2003). The value of functional foods was $11.3 billion in 1995, $16.2 billion in 1999, and $27 billion in 2003 and is projected to grow to $49 billion in 2010 (Blumenthal, 2003; Draughon, 2004). Obtaining reliable estimates of market demand for functional foods, both globally and in major developed country markets, can be difficult, partly because there is no generally agreed definition of a ‘functional food’.

The Food and Drug Administration, based on certain criteria, classify functional foods into foods, dietary supplements, special dietary foods for medical use, or drugs (Noonan and Noonan, 2003). Regulations must be followed regarding intended use of the product and labeling claims. The category of dietary supplements has shown the most growth due to enactment of the Dietary Supplement Health and Education Act of 1994, which exempts dietary supplements from the more stringent regulations required for foods and food additives (ADA Reports, 2004).

Nutrition related diseases that functional foods target are cardiovascular disease, cancer and obesity. Dietary fiber, omega-3 fatty acids, and antioxidants have been incorporated as ingredients into conventional foods. These ingredients have been report by clinical studies to prevent or reduce the risk of nutrition related diseases (Blumenthal, 2003).

Soluble fiber has been shown to reduce blood cholesterol levels, thus contributing to a reduced risk of heart disease (Milo-Ohr, 2004). Omega-3 fatty acid consumption has been associated with reduced risk of cardiovascular disease (Metcalf et al. 2003). Increased consumption of phytoestrogen containing foods was associated with a decrease in the risk to develop hormone-dependent cancer in epidemiological studies (Adlercreutz, 2002). Flaxseed and its bran (hull) are excellent sources of the previously mentioned components, making it potential choice as an ingredient for use in a functional food.

Dietary Fiber

Different types of fiber are distinguished by their differing physiological properties and systemic effects. Dietary fiber is grouped into two categories: soluble and insoluble. Insoluble dietary fibers are insoluble in aqueous solutions of enzymes that are designed to simulate the human digestive system (Nelson, 2001), and are not digested in the human small intestine but may be fermented by bacteria in the large intestine. Examples of insoluble dietary fiber include cellulose, lignin, and many hemicelluloses. Insoluble fiber is mainly found in plant cell walls and seed coat of grains.

Soluble dietary fibers are soluble in aqueous solutions of enzymes that are typical of the human digestive system. Examples of soluble fiber are pectin, gums, certain hemicelluloses, β-glucans, and storage polysaccharides. Fruits, oats, barley, and legumes contain high amounts of soluble fiber (Anderson et al. 1990). Flaxseed contains mucilage a soluble fiber, which is discussed in more detail in a later section.

Soluble and insoluble fibers function differently in the human body. Soluble fiber increases intestinal transit time, delays gastric emptying, and slows glucose absorption. This action lowers postprandial blood glucose concentrations, decreases serum cholesterol, and produces other metabolic effects (Nelson, 2001). Insoluble fiber decreases intestinal transit time, increases fecal bulk, delays glucose absorption, and slows starch hydrolysis. These effects modify gastrointestinal function, but do not lower serum glucose or cholesterol (Slavin, 2003). However some fibers such as psyllium seed husk, oats, and oat bran may have major benefits attributable to both soluble and insoluble fiber. These fiber sources increase stool weight and improve laxation, as well as lower blood cholesterol levels (Marlett et al. 2002).

Fiber (crude fiber) values were commonly obtained in the past by determining the percentage of organic residue remaining after the acid and alkaline hydrolysis of food and feeds (Van Soest and McQueen, 1973). However, the method of Prosky et al. (1988) is widely used to determine total dietary fiber and soluble fiber. This method uses enzymatic processing to mimic the human digestive system.

There has been significant interest in increasing dietary fiber in the diet due to its nutritional benefits. The Dietary Reference Intakes (DRIs) (Food and Nutrition Board, Institute, National Academies, 2002) for dietary fiber is 38g/d for adult men and 25g/d for adult women. Low dietary fiber has been associated with diverticular diseases, diabetes, coronary heart disease, and bowl cancer (Miraglio, 2003). A high fiber diet has been shown to lower systolic blood pressure 11% and diastolic blood pressure 10% in hypertensive individuals, in addition a high fiber intake promotes weight loss and maintenance through satiety (Anderson et al. 1990).

Alpha-Linolenic Acids (18:3n-3) / Omega-3 Fatty Acids

Alpha-linolenic acid (ALA) is an essential fatty acid, meaning the human body can’t produce it so it must be obtained through the diet. The characteristic feature of omega-3 fatty acid is that their first double bond is located at the third carbon from the methyl end of the hydrocarbon chain (Watkins and German, 1998). ALA is mainly terrestrial derived, primarily present in the leaves of plants and is also a minor component of seed oils. Sources include perilla, soybean, rapeseed, canola, and walnut. Flaxseed is the most abundant source of alpha-linolenic acid.

Dietary alpha-linolenic acid can be metabolized in three ways: 1) it undergoes β-oxidation to produce energy; 2) its stored in triacylglycerols (triglycerides) and phospholipids of cell membranes; and 3) its converted to longer-chain omega-3 fatty acids like eicosapentaenoic acid (EPA) and docosahexanoic acid (DHA) (Morris, 2003).

Eicosapentaenoic acid (EPA) and docosahexanoic acid (DHA) are marine derived long-chain omega-3 fatty acids and are primarily obtained from cold water fish. As previously mentioned ALA serves as the metabolic precursor for the production of the long chain polyunsaturated fatty acids (EPA & DHA) in animals. Humans convert ALA to EPA and DHA through a series of alternating desaturations and elongations (Watkins and German, 1998). This metabolic pathway is an important source of these long-chain omega-3 polyunsaturated fatty acids for strict vegetarians, who do not consume fish (Beare-Rogers, 1988).

Linoleic acid, an omega-6 fatty acid, and ALA go through a series of metabolic steps as a series of elongation and desaturation reactions to be converted to usable compounds: linoleic acid to gamma-linolenic acid and arachidonic acid; alpha-linolenic acid to EPA and DHA. This competition of the omega-3 and omega-6 pathways for enzymatic activity is one of the main arguments in favor of direct consumption of long-chain omega-3 fatty acids such as DHA and EPA in marine oil (Morris, 2003). However safety and fish oil supply issues currently have caused a concern regarding omega-3 fatty acids from marine sources. Some types of fish have been found to contain high levels of mercury, PCB's (polychlorinated biphenyls), dioxins and other environmental contaminants (Hernandez, 2004). Terrestrial derived omega-3 fatty acids (alpha-linolenic acids) found in flaxseed, are considered safer from the point of view of contaminants.

The Dietary Reference Intakes (DRIs) (Food and Nutrition Board, Institute, National Academies, 2002) for α-linolenic acid (ALA) is 1.6 g/d for adult men and 1.1 g/d for adult women. Omega-3 fatty acids may help prevent and treat a wide range of conditions and diseases such as arthritis, and inflammation, auto-immune disease, type 2 diabetes, hypertension, kidney and skin disorders, and cancer (Haumann, 1997).

Omega 3 fatty acids are highly oxidative thus limiting their use in certain foods. However fish oil rich in DHA and EPA omega-3 fatty acids are used to fortify products such as sausage, luncheon meat, and margarine spreads. The use of flaxseed oil to fortify products has shown promise. Studies have reported the stability of flax oil at baking temperatures (Chen et al. 1994), and different steps during the processing and cooking of spaghetti and macaroni (Manthey et al. 2002). Also margarine spreads fortified with flaxseed oil are currently on the market.

Phytoestrogens

Phytoestrogens, phyto- meaning plant derived, structurally or functionally mimics mammalian estrogens and therefore are considered to play an important role in the prevention of cancers, heart disease, menopausal symptoms and osteoporosis (Setchell, 1998; Adlercreutz, 2002, Ibarreta, 2001). Phytoestrogens can be divided into three main classes: isoflavones, coumestans, and lignans.

Isoflavones from soy are the best known of the phytoestrogens, and the most heavily researched (Osoki and Kennelly, 2003). Soybeans and soy foods are the most significant dietary sources of isoflavones (Coward et al. 1993). After normalization for differences in isoflavone molecular weights, they contain approximately 0.2-1.6 mg of isoflavones/g dry weight. Chick peas and other legumes, as well as clover, toothed medic, and bluegrass, have also been identified as isoflavone sources (Price and Fenwick, 1985). Studies have characterized the concentrations and distribution of isoflavones in commercial soybean foods, and also the influence of processing on isoflavane levels (Wang and Murphy, 1994).

Coumestans are another group of plant phenols that show estrogenic activity. The most significant sources include sprouts of clovers and alfalfa (Franke et al. 1995), with coumestrol contents of 5.6 and 0.7 mg/g dry weight, respectively. Split peas, kala chana seeds, lima bean seeds, and soybean sprouts also contain small amounts of coumestrol (15-80 μg/g dry weight) (Kurzer and Xu, 1997). Coumestans are less common in the human diet than isoflavones, yet similar to isoflavones, in that they are also found in legumes, particularly food plants such as sprouts of alfalfa and mung bean (Adams, 1995). The comestrol content in plant material has been reported to vary according to plant variety, stage of growth, cutting, and presence of disease, location and insect/fungal attacks (Price and Fenwick, 1985)

Lignans were first identified in plants and later in biological fluids of mammals. As a class of compounds they contain a dibenzylbutane skeleton in plants they aid in the formation of lignin used to construct the plant cell wall (Satchell and Adlercreutz, 1988). Lignans are widespread in foodstuff such as cereals, fruits and vegetables and have not been studied as thoroughly as isoflavones and coumestans. Flaxseed is the richest plant sources of lignans, with about 0.8 mg of secoisolariciresinol/g dry weight (Kurzer and Xu, 1997). Flaxseed lignans are discussed more in a later section.

Extrusion

Extrusion has been defined as simply the operation of shaping a plastic or dough-like material by forcing it through a restriction or die (Riaz, 2000). Extruded materials for food and feed products are subject to transformations, including starch gelatinization, fragmentation, and protein denaturation, which has an affect on the properties of the final product. The extrusion process has been used for the production of commercial food and feed products for the past 70 years. In the mid-1930's pasta became the first commercial product produced using a continuous single screw extruder (Riaz, 2000). Now various food products which include ready to eat cereals, pretzels, second generation snacks (direct-expanded), and third generation snacks (pellets) are produced using extrusion. The application of extrusion to food processing has resulted in a decrease in raw material costs and production time. These savings can be contributed to several processing steps being combined in the extruder. Liquids, steam, and solids can be continuously and uniformly combined, eliminating the need for additional pieces of complex equipment, resulting in more compact installations (Huber, 2001).

According to Rokey (2000) extruders are ranked into three categories depending on shear stress and product produced. The first category are low-shear stress extruders, these extruders run at low rpm's and impart low levels of mechanical energy per unit of throughput. Products produced are dense and generally high in moisture, an example being pasta. The second category is medium-shear stress extruders. These extruders are common in the pet food and aquatic feed industry. Products have higher moisture levels than those of low-shear stress, and have higher mechanical energy inputs. The third category is the high-shear stress extruders which produce highly expanded products. The mechanical energy inputs are high, and the product moisture level and bulk density are low.

High Shear - Single Screw Extruders

Expanded products are commonly produced using high shear single screw extruders. Direct expanded products only require a short barrel single-screw extruder with no preconditioning, only a small amount of water injected into the barrel during processing (Huber, 2001) or added to the ingredients prior to extrusion.

Bake extruders, also known as dry extruders, are a type of high-shear single screw extruder used to produce expanded or puffed products. The moisture content of raw material for expanded products can be 14-18%. The bake extruder has a short barrel measuring 12-16 inches in length, with a length-over-diameter ratio (L/D) of 4 or less. They are considered autogenous, because heat is developed by the conversion of mechanical energy to thermal energy in the extruder barrel. Because of this they do not require an external heating source during processing. Material exit temperature can reach as high as 150^{o}C (Burtea, 2001). Material in a bake extruder is subjected to high shear and high temperature conditions; however because of the short barrel design there is a low residence time.

Twin Screw Extruders

In recent years twin screw extruders have become increasingly popular in the food and feed industry due to their versatility. As the name implies instead of one screw, two screws are contained in the extruder barrel. Twin screw extruders are commonly divided into several classifications: a). co-rotating intermeshing, b). co-rotating non-intermeshing, c). counter-rotating intermeshing, d). counter-rotating non-intermeshing, e). conical intermeshing (Riaz, 2000). Of these, the co-rotating intermeshing is most commonly used in the food and feed industry. This type of twin screw extruder provides increased positive displacement over a single screw extruder. This can be contributed to the intermeshing of the screws, extruded feed material with increased levels of oil or moisture may stick to the screw surface; the adjacent screw crest will wipe it from the companion screw flank as the two screws intermesh, thus conveying the extrudate forward (Huber, 2001).

The increase in the positive displacement pumping action in twin screw extruders, allows for the possibility of products with increased levels of moisture, proteins, lipids, and fiber to be produced. An expanded corn based product fortified with flaxseed or its hulls will contain increased amounts of these components in its formulation. Twin screw extruders also allow for more mechanical energy input into the material thus promoting expansion. Single screw extruders are limited to the levels of moisture, proteins, lipids, and fiber added to a formulation decreasing the product range in can produce.

Factors Affecting Expansion

There are numerous variables that influence expansion in extruded products. The composition and quality of the raw material have been studied. Amylose to amylopection ratio has been shown to influence the degree of expansion (Chinnaswamy, 1993). Desrumaux et al. (1998) reported that particle size of extruded corn grits was important to the final extrudate quality. The addition of protein (Camire and King, 1991) and fiber (Mendonca et al. 2000; Jin et al. 1994) to corn meal has been shown to have a negative affect on expansion. Processing variables such as barrel temperature and moisture content of the raw material also affect expansion (Mercier and Feillet, 1975; Chinnaswamy and Hanna, 1988a, b).

Lipids in Extrusion

When extruding expanded products, increasing levels of lipids have a negative affect on the final product. Lipids at levels >5-6% can act as a lubricant in the extruder barrel, decreasing torque because of slip in the extruder barrel. Decrease in torque reduces the amount of mechanical energy input causing insufficient pressure to develop in the extruder barrel, thus decreasing expansion (Camire, 2000). Lipid content also affects starch dispersion, Guy (2001) stated that at oil levels >2%, starch granules may be melted during extrusion but not dispersed; thus the extrudate will be cooked but have no expansion.

Oil content of a product appears lower after the extrusion process because the lipids form complexes with amylose. The amylose-lipid complex formed during extrusion has been extensively studied. Lipids can also complex with protein, although to a lesser extent than amylose. Manthey et al. (2002) found in processing spaghetti, containing up to 15% flaxseed, that there was a decline in lipid content during the dough development in the extrusion process. This decline was contributed to lipids binding to gluten (Youngs et al. 1970, Kobrehel and Sauvaire, 1990).

The advantage of using extrusion is that the short residence time during the extrusion process causes lipid oxidation to be limited. Suzuki et al. (1988) reported DHA and EPA were retained in chum salmon muscle extruded with 10% wheat flour, making rancidity of an extruded product more of a concern during storage (Camire, 2000). Expanded products have increased susceptibility to lipid oxidation due to the larger surface area created by the air cells in the extrudate. Lin and Huff (1998) found that lipid oxidation of extruded dry pet food, containing different types of animal fats (beef tallow and poultry fat), appeared to be affected mainly by the degree of expansion. Lin and Huff (1998) noticed products with a higher degree of expansion, which had larger cells and thinner cell walls, were more susceptible to oxidation.

Lipid oxidation is more of a concern in finished extruded products that contain high percentages of unsaturated fatty acids. This deterioration affects the flavor, color, texture and nutritive value. Lipid oxidation involves the generation of unstable free radicals that catalyze the production of more free radicals. Thus, it is a chain reaction that can quickly spread to all the susceptible fatty acids. The rate of oxidation is influenced by many factors including temperature, trace metal composition, light, pH and oxygen concentration. A major factor in the rate of oxidation is fat composition.

Factors such as screw wear and processing temperature can affect the storage stability of lipids in extruded products. Screw wear promotes lipid oxidation due to metals, such as iron, interact with the extruded material and act as a pro-oxidant (Artz et al. 1992). Rao and Artz (1989) extruded corn meal/ starch with soybean oil and reported that an increase in temperatures (115-175^{o}C) led to an increase in transition metal content. The sample extruded at 175°C had an iron concentration 6 times that of the non-extruded corn starch/soybean oil mixture.

In some cases extrusion processing can help delay lipase induced lipid oxidation by enzyme inactivation. Shin and Gray (1983) found that the amount of oxidation was greater in raw barley powder than in twin screw extruded barley after 4 months of storage. The complexes formed between the lipids and starches can bind or encapsulate the lipids making them unavailable for oxidation unless the extrudates are ground allowing contact with oxygen (Camire, 1998).

Flaxseed

Flaxseed is referred to as linseed in most countries, other than those in North America, and has been part of the diet of humans for thousands of years. Canada is the largest producer and exporter of flaxseed in the world producing 33% of world production with 74% of the world exports in 2002 (Johnson and Jimmerson, 2003). North Dakota is the largest producer of flaxseed in the United States. World production is estimated at 2.1 million tonnes (Mt), representing 0.6% of the production of the ten major oilseeds (Agriculture and Agri-Food Canada, 2002). Flaxseed is best adapted to production in areas with lower growing temperatures and longer day lengths, where oil content and iodine values are optimized.

In the United States flaxseed is mainly grown for its oil. Flaxseed oil possesses rapid oxidation properties which make it especially useful for the production of linoleum, paints, stains, and surface coatings. The by product of flaxseed oil extraction is flaxseed meal and cakes. This meal is considered a high protein source and is used in feed formulations (Oomah and Mazza, 1994). Flaxseed is now common in poultry diets to produce eggs enriched with omega-3 fatty acids, and in pig diets to alter the fatty acid composition of pork products (Matthews, 2003). As interest in flaxseed as a functional food has grown, more products containing flaxseed are available such as breakfast cereals, salad dressings, breads and extruded products: spaghetti and pasta.

Structure and Composition

Flaxseed is flat, oval and somewhat beaked, having average dimensions of 2.5 mm x 5 mm x 1 mm and an average weight of 3-13 mg per seed. Seeds range in color from light to dark reddish brown or golden yellow. Its structure is composed of an embryo or germ, a thin endosperm, and two cotyledons encased in a seed coat. Test weight for flaxseed ranges from 55-70 kg/hL with no relationship between test weight and oil content (Daun et al. 2003). The seed coat (hull) of flax is where the majority of the fiber, soluble and insoluble, is located. Lignans, known as phytoestrogens, are also concentrated in the hull portion. Flaxseed proteins considered to be of high quality are found mainly in the cotyledons (Oomah and Mazza, 1993). The cotyledons are the major oil storage tissue, containing about three-quarters of the seed oil (Tzen et al. 1993). The typical flaxseed composition is in Table I.

Table I

Proximate analysis of flaxseed (Source: Flax Council of Canada)

Sample	**Fat**	**TDF**[a]	**Protein**	**Moisture**	**Ash**
		(g/100g)			
Flaxseed	41	28	20	7	4

[a] Total dietary fiber

Flaxseed Oil

Flaxseed's oil has been the primary focus of commercial flaxseed processing for industrial utilization. The oil is extracted by cold pressing and/or solvent (hexane) extraction. Cold pressed flaxseed oil is one of the most recognized functional foods by health-conscious consumers (Oomah, 2003) due to it nutritional value. Flax oil is the richest source of α-linolenic acid, which makes up 55-60% of total fatty acids. Other major fatty acids include palmitic (~5%), stearic (~3%), oleic (~18%), and linoleic (~14%). The degree of unsaturation is affected by environmental conditions and agronomic practices (Gubbels, 1993). Similar to other oilseeds, flaxseed contains a group of vitamin E compounds, including tocopherols and at least one tocotrienol (Daun et al. 2003).

Flaxseeds high percentage of unsaturated oil fatty acids makes it susceptible to lipid oxidation. For this reason flaxseed oil is usually stored in opaque bottles that have been flushed with nitrogen, but when opened must be refrigerated (Daun et al. 2003; Malcolmson et al. 2000). For food applications flaxseed oil is recommended for “cold” applications like salad dressings, vinaigrettes, and margarine spreads. It has been used in stir-frying as long as the frying temperature remains less than 150°C (Hadley, 1996). Studies have shown α-linolenic acid to stabile at baking temperatures and during spaghetti processing (Manthey, 2002).

Flaxseed oil’s rapid oxidation properties limit its use in food products. To make flaxseed and its oil more attractive for use as an ingredient in food products, varieties of flaxseed with different levels of fatty acids have been developed. Linola™ developed by Agricore United is a cultivar of Solin. Solin oil contains less than 5% α-linolenic acid (Green, 1986) compared to more than 50% in flaxseed oil, producing light oil suitable for cooking (Table II). Canadian Grain Commission Standards specify that solin varieties have a yellow seedcoat to distinguish it from brown flaxseed. By decreasing the level of α-linolenic acid in the seed flaxseed oil, it can compete with unhydrogenated canola or soybean oil for use in products such as salad oils and margarines. The reduction in α-linolenic acid makes Solin oil more sutable for use in cooking oil; however it increases the amount to consume in order to reach the Dietary Reference Intake (DRIs) (Food and Nutrition Board, Institute, National Academies, 2002) for α-linolenic acid.

Table II

Fatty acid variation in *Linum usitatissimum*
(Source: Canadian Grain Commission Grain Research Laboratory)

Sample	**C16:0**	**C18:0**	**C18:1**	**C18:2**	**C18:3**
			(%)		
Flax	4.8	3.6	21.0	22.8	57.4
Solin	5.6	3.4	15.4	71.9	2.2
High (ALA)	4.5	2.3	10.0	10.7	71.8

Flaxseed Dietary Fiber

Flaxseed contains digestible carbohydrates which include simple sugars and starch. Bhatty and Cherdkiatgumchai (1990) reported less than 1-2% soluble sugars in analysis of various flaxseed samples. Therefore a large amount of the flaxseed carbohydrates are considered dietary fiber, due to being resistant to the action of human digestive enzymes. Flaxseed contains 28% dietary fiber including insoluble and soluble, the majority contained in the hull (Oomah and Mazza, 1998). The ratio of soluble to insoluble fiber ranges from 20:80-40:60 depending on the methods of extraction and chemical analysis used (Vaisey-Genser and Morris, 1997).

The insoluble fiber consists of non-starch polysaccharides, cellulose and lignin, mainly found in the cell walls. Research is limited on the insoluble fiber fraction of flaxseed due to the soluble fraction receiving more of the research and nutritional attention.

Typically soluble fiber comprises about 33% of the total fiber in flaxseed. Flax's soluble fiber consists of mucilage, a water-soluble hydrocolloid. Flaxseed mucilage, also referred to as flaxseed gum, is a heterogenic polysaccharide and contributes largely to the soluble fraction of flaxseed which is suggested to have hypoglycaemic effect in humans (Cunnane et al. 1993). Flaxseed mucilage has potential industrial uses because its emulsifying properties are better than those of Tween 80, gum arabic and gum tragacanth (Minker et al. 1973). Functional properties of the isolated mucilage (Mazza and Biliaderis, 1989) and its use as a thickening and stabilizing agent have been reported (Dev and Quensel, 1989). High water absorption capacity of the flaxseed meal (Wanasundra and Shahidi, 1994) is mainly attributed to the presence of these polysaccharides in the seed coat (Fredeniuk and Biliaderis, 1994).

Flaxseed mucilage is commonly removed using aqueous extraction (Fedeniuk and Biliaderis, 1994). This enables the concentration of the mucilage for use in food applications, but this can be an expensive process. However advances in flaxseed dry dehulling have led to more economical separation to obtain flaxseed mucilage. Dehulling removes the outer bran from the flaxseed thus producing a fraction high in soluble fiber and low oil content, and a fraction high in protein, and oil containing the cotyledon (Oomah and Mazza, 1998). The bran can be incorporated into food products to increase the soluble fiber content as well as be used as a viscosity builder or emulsifier.

Flaxseed bran added to a cereal based direct expanded extruded product could be used as an extrusion aid due to its emulsification properties. The use of soluble fiber in extrusion decreases extruder torque (Maga and Fapojumo, 1986). The decrease in torque could lead to a decrease in power consumption. The nutritional benefit of flax fiber added to snack product, as well as the physicochemical and textural properties need to be studied further.

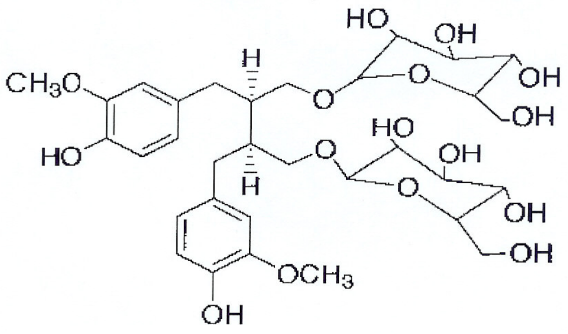

Fig. 1. Chemical structure of SDG (secoisolariciresinol diglycoside)

Flaxseed Lignans

Lignans are phytoestrogens, as explained earlier. Flaxseed is the richest sources of lignans providing 75-800 times more than other plants (Meagher and Beecher, 2000). Lignans comprise approximately 0.7 to 1.5% of flaxseed (Thompson et al. 1991), and are concentrated in the hull. The major lignan found in flaxseed is SDG (secoisolariciresinol diglycoside) a diphenolic compound formed by two cinnamic acid residues and comprised of 2,3 dibenzylbutane nucleus (Fig. 1). Bacteria in the digestive tract structurally modify SDG by removal of the sugar moiety to form mammalian lignans Enterodiol, and Enterolactone.

Interest has grown regarding lignans because of suggestions that lignans are protective against chronic diseases including cancer, cardiovascular disease, and diabetes (Heinonen et al. 2001; Aldercreutz, 2002; Ward and Thompson, 2001; Setchell and Adlercreutz, 1998). There is no established optimum level and frequency of flaxseed and lignan intake necessary to produce the health benefits. This is due to incomplete information concerning lignan bioavailability, including lignan absorption, distribution, metabolism, and excretion, because of difficulties in the analysis of lignans in flaxseed to determine intake levels, and in body fluids and tissues (Thompson, 2003).

Flaxseed lignans have strong antioxidant properties. Kitts et al. (1999) measured the antioxidant value of SDG and matairesinol, enterodiol, and enterolactone using the Ferric Reducing/Antioxidant Power assay (FRAP) and determined that these lignans had a higher antioxidant activity than even ascorbic acid. Prasad (1997) found that SDG isolated from flaxseed was a ·OH scavenger. Yu Wu (2004) reported that 25 to 52% of lignans compounds were lost after extrusion of a corn based expanded product. Yu Wu found that higher percentages of flaxseed meal, up to 15%, and higher screw speeds, up to 400 rpm's, favored higher retention of the lignan compounds, with increased feed moisture having the opposite effect. The decrease of lignans in an expanded product using flaxseed hulls, where the lignans are concentrated was not reported.

Sorghums and Tannins

Sorghum (Sorghum bicolor L. Moench) is the world's fifth most important cereal after wheat, rice, maize, and barley (Serna-Salvador and Rooney, 1995). Its drought tolerance and adaptation to tropical conditions makes it the major food staple in many African countries and India. Sorghum is also a staple food for millions of people around the world where it is utilized to make porridges, beers, other alcoholic and non-alcoholic beverages, and leavened and unleavened breads. Japanese snack producers use white sorghum for a variety of extruded snacks. Acosta (2003) showed that white food grade whole sorghum could be extruded to produce a direct expanded whole grain product with a favorable texture.

Sorghum contains approximately 7-16% protein, 55-75% starch, 0.5-5% lipids, 2-5% crude fiber, and 1-2% ash, on a dry weight basis (Serna-Saldivar and Rooney 1995). The sorghum kernel is roughly spherical in shape and composed of three main components: (1) the pericarp and testa; (2) the embryo or germ and (3) the endosperm. The endosperm forms 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 pigmented testa or seed coat if present derives from the ovule integuments and contains tannins. The aleurone layer is actually part of the endosperm and is rich in protein and ash. The germ, rich in oil and proteins, is diploid and is formed by the fusion of male and female gametes.

Recently certain sorghums have shown potential for use in functional foods. Sorghums containing tannins have displayed high antioxidant activity comparable to those of high antioxidant fruits like blueberries and plums (Awika, 2003). Tannins are 15-30 times more effective at quenching peroxy radicals than simple phenolic or Trolox (Hagerman et al. 1998). Consumption of tannin sorghums is associated with the reduced risk of certain types of cancer, and promotes cardiovascular health in animals when compared to other cereals (Van Rensburg, 1981; Chen et al. 1993).

Tannins have been defined as water-soluble polyphenolic compounds with molecular weights between 500-3000 that have the ability to precipitate, gelatin, and other proteins. Vegetable tannins are structurally divisible into two major classes: (a) the hydrolyzable and (b) the non hydrolyzable or condensed tannins. Condensed tannins, also referred to as proanthocyandins, are a major phenolic component of sorghums with pigmented testa.

Whole grain high tannin sorghums and brans have been added to food products such as cookies and breads to increase their dietary fiber and antioxidant content. Despite thermal processing the retention of antioxidant activity is considered high. Direct expanded extrudates from black and tannin sorghums had acceptable product characteristics with a high retention of total phenols, tannins, and antioxidant activities (Turner, 2004).

CHAPTER III

DETERMINE EFFECTS OF ADDED BROWN AND GOLDEN FLAXSEED HULLS ON CORN BASED DIRECT EXPANDED EXTRUDATES

Justification

Studies have evaluated the incorporation of dietary fiber from various sources into a corn based expanded snack to increase nutritional benefits (Mendonca, et al. 2000; Lue et al. 1991). Flaxseed hulls are a rich source of soluble and insoluble (dietary) fiber, and contain a very high concentration of the lignan, secoisolariciresinol diglycoside (SDG), (Oomah and Mazza, 1993), which exhibits high antioxidant activity (Niemeyer and Metzler, 2003). A major component of flaxseed fiber is mucilage, a water soluble hydrocolloid, which has better emulsifying properties than gum Arabic (Oomah and Mazza, 1994).

Advances in the dehulling process of flaxseed have led to the production of a hull-rich fraction high in dietary fiber and lignans, and low in protein and oil content. The objective of this experiment was to determine the effect of brown or golden flaxseed hulls addition on the characteristics and nutritional quality of corn based direct expanded snacks.

Material and Methods

Raw Materials

Materials used were golden and brown flaxseed hulls (Fortigrad™, Pizzey's Milling, Angusville, MS, Canada, 2005) and yellow de-germed corn meal (Cargill Inc., Minneapolis, MN 2005).

Proximate Analysis of Raw Materials and Extrudates

Moisture content of raw materials and extrudates was determined using the air oven per AACC method 44-19 (AACC 2000). Samples were dried in a forced air draft oven for 2 hr at 135°C. Moisture was determined by weight lost.

Crude fat of raw materials and extrudates was determined using AACC method 30-26 (AACC 2000). Oil was extracted using petroleum ether with a butt type apparatus for 5 hr. Ash was determined using AACC method 08-03 (AACC 2000). Samples were placed in an electric muffle furnace at 600 ^{o}C for 2 hr. Ash was determined by weight lost.

Crude protein of raw materials and extrudates was determined by the Dumas combustion method with a Leico apparatus.

Preparation of Blends

Brown or golden flaxseed hulls were mixed with degermed yellow corn meal to obtain flaxseed hull/corn meal blends in ratios of 0:100, 15:85, 20:80, and 25:75 (w/w); then mixed for 10 min. in a Hobart mixer with a mixing paddle to obtain a uniform sample (Fig. 2). Blends were extruded in a twin screw extruder immediately after mixing. Yellow de-germed corn meal was the control.

Extrusion Processing

Blends were extruded using a Wenger TX-52 twin screw extruder, with 6 zones, and a length/diameter ratio of 16.5/1. The screw configuration was typical for expanded snacks and was supplied by Wenger Manufacturing (Sabetha, KS., USA). A 2 to 1 back flow plate was placed prior to the die plate. A three hole die, with 4 mm (0.16 in.) openings and 2 cutting blades was used. The extrudates were cut at a fixed speed.

Blends were fed into the extruder inlet using an Accurate Feeder at a feed rate of 72 kg/hr. The screw speed was 325 rpm, and temperature for zones 4, 5, and 6 were set at 80, 90, and 110^{o}C. Water was injected directly into the extruder barrel at two different levels (0.062 kg/min. and 0.022 kg/min) to obtain moisture contents of 12 and 15% in the feed material of each blend. Independent variables such as feed rate, screw speed and zone temperatures were kept constant, however changes in dependent variables such as motor load (%) and head pressure (psi) were recorded.

After extrusion the extrudates were dried at 100^{o}C for 15 min. and then cooled in a Wenger One Pass Dryer. The dried samples (2-3% moisture) were placed in a plastic bag until they were analyzed.

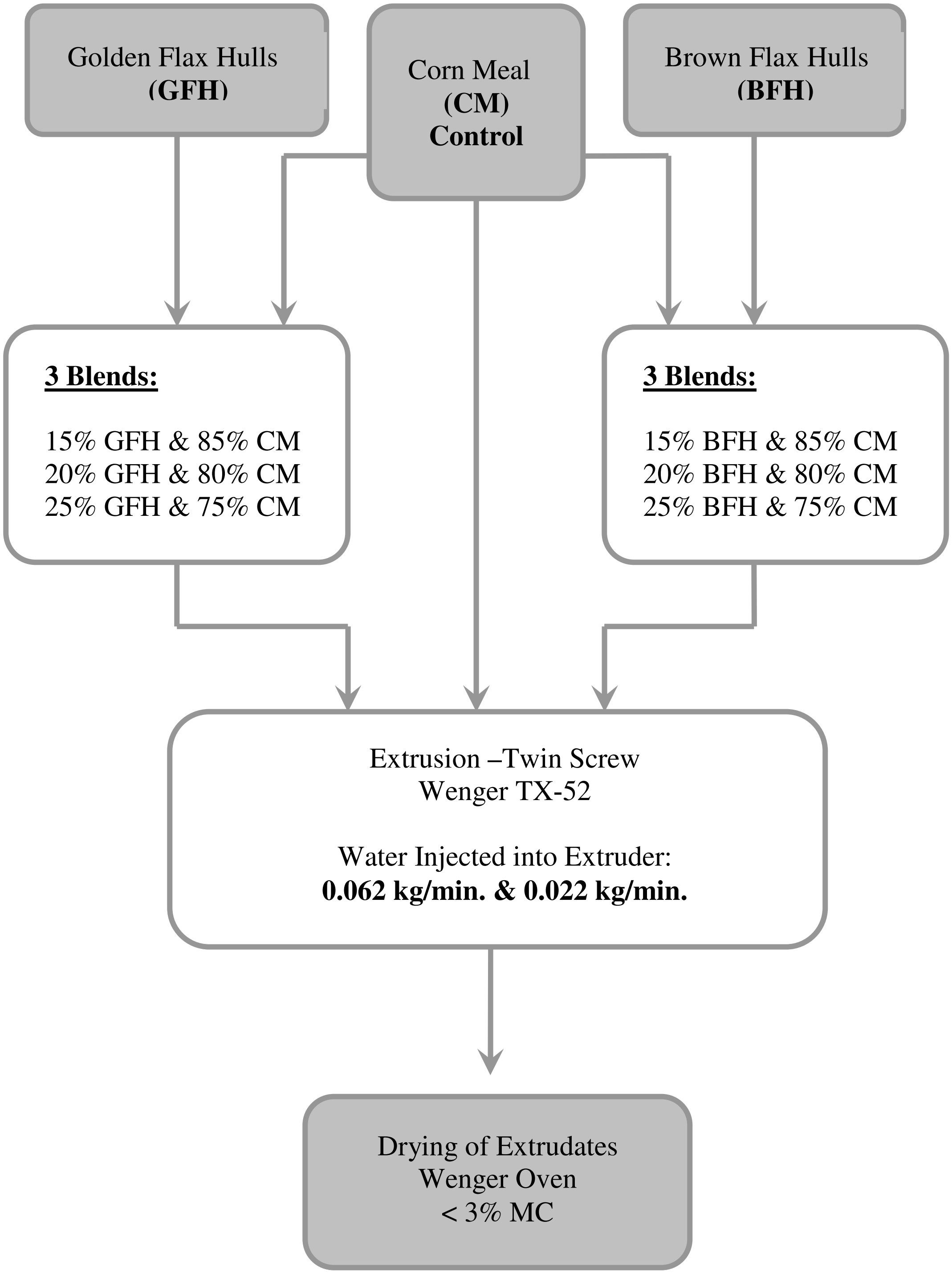

Fig. 2. Flow chart of preparation and twin screw extrusion processing of flaxseed hull-corn meal blends.

Particle Size Distribution and Color

Particle size distribution of raw materials and blends was measured on 50 g samples with US standard sieves #20, 30, 40, 60, 80, and, 100. Results were reported as % material retained on each sieve. Samples were done in duplicate.

Color of raw materials and extrudates was evaluated in triplicate with a colorimeter (Model CR-310 Minolta Co., LTD. Ramsey, NJ) using CIE L*a*b* color scale. The test was performed on randomly selected extrudates that were ground then passed through a US #10 standard sieve (Hsieh et al. 1993). Color values were measured in triplicate and recorded as L* = lightness (0 = black, 100 = white), a* (-a* = greenness, +a* = redness) and b* (-b* = blueness, +b = yellowness).

Expansion Ratio, Longitudinal Expansion and Bulk Density

The expansion ratio was determined according to Gomez et al. (1988). Twenty-five randomly chosen extrudates were measured for longitudinal and radial expansion using an electronic caliper. Expansion ratio was calculated by the extrudate average diameter divided by the die diameter (0.16" or 4 mm). Bulk density was calculated by weighing a filled container of known volume with extrudates and dividing the weight of the sample by the volume.

Specific Mechanical Energy

Specific mechanical energy (SME) was calculated using the equation provided by Wenger, Mfg. (Sabetha, KS) for the TX-52 twin screw extruder:

$$SME = \frac{\left(L - L_e\right) \cdot \frac{N_a}{N_b} \cdot P_e \cdot 36}{\dot{m}}$$

SME = specific mechanical energy **(kJ/kg)**, **L** = extruder drive motor load **(%)**, **L_e** = Extruder drive motor load (**%, Empty extruder barrel conditions**), **N_a** = Actual screw speed **(rpm)**, **N_b** = Base screw speed **(402 rpm)**, **P_e** = Rated power of extruder drive motor **(22.4 kW)**, and $\dot{m}$ = Mass flow rate **(kg/hr)**.

Macrostructure

Cross sections of selected extrudates from each blend were cut with a razor blade. Pictures of the internal structure of the extrudates were taken with a digital camera (Coolpix 995, Nikon, Inc., Mellvile, NY).

Microstructure

Cross sections of extrudates from selected blends were analyzed by microscopy. Extrudates were mounted on aluminum stubs with conduction adhesive and viewed with Environmental Scanning Electron Microscope (ESEM, model E-3, Ectroscan Corp., Willington, MA) with an accelerating voltage.

Texture Characteristics

Hardness (shear force) of the extrudates were tested using a texture analyzer (model TA.XTi2, Texture Technologies Corp., Scarsdale, NY) using the Kramer shear press cell. A 10 g. sample of extradates from each blend were tested for texture, this was done 10 times for each sample blend.

Antioxidant Activity: ABTS [2,2'- azinobis (3-ethyl-benozthiaziline-6- sulfonic acid)]

Antioxidant activity was determined for brown and golden flaxseed hulls and selected extrudates. The ABTS method described by Awika et al. (2003a) was used for antioxidant activity for $\text{ABTS}^{\cdot+}$ generation from ABTS salt, $K_2S_2O_8$ will be reacted with ABTS salt in distilled, deionized water for 16 hr. at room temperature in the dark. The $\text{ABTS}^{\cdot+}$ solution will then be diluted with a pH 7.4 phosphate buffer solution containing 150 mM NaCl (PBS). Absorbance will be measured at 730 nm Trolox standard.

Analysis of variance (ANOVA) was performed using SPSS v11.5 for Windows (SPSS Inc.). Differences were analyzed with Duncan's test. A confidence level of 95% was used.

Phenols

A modified Folin Ciocalteu method (Kaluza et al., 1980) was used to determine total phenols for brown and golden flaxseed hulls.

Condensed Tannins

The vanillin HCl method was used to determine tannins of brown and golden flaxseed hulls.

Statistical Analysis

Analysis of variance (ANOVA) was performed using SPSS v11.5 for Windows (SPSS Inc.). Differences were analyzed with Duncan's test. A confidence level of 95% was used.

Results and Discussion

Visual Inspection of Flaxseed Hulls

An initial visual inspection of the brown and golden flaxseed hulls was done prior to extrusion (Fig. 3). The brown flaxseed hulls used had few visible pieces of cotyledon, although a small amount of powder was visible on one side of the brown hulls (Fig. 4B). Oomah and Mazza (1994) stated that flaxseed hulls contain much oil due to an adhering layer of endosperm tissue, indicating contamination from the endosperm (which contains minuscule amounts of oil and protein) that was not efficiently removed during the aspiration process.

Numerous large pieces of cotyledon were visible in the golden flaxseed hulls used (Fig. 4A), which are the major oil storage tissue, containing about three quarters of the seed oil. The presence of cotyledons indicates poor removal after dehulling. Fredeniuk and Biliaderis (1994) noted that differences in cultivars cause them to respond differently to dehulling. He stated that brown-pigmented seed coats were easily separated between layers, whereas yellow-pigmented seeds coats were difficult to separate into cellular layers because they generally fragmented perpendicular to the long axis of the seed coat. The producer of the golden flax hulls acknowledged the difficulties in separating the hulls and cotyledon pieces of golden flaxseed (Pizzey, 2004).

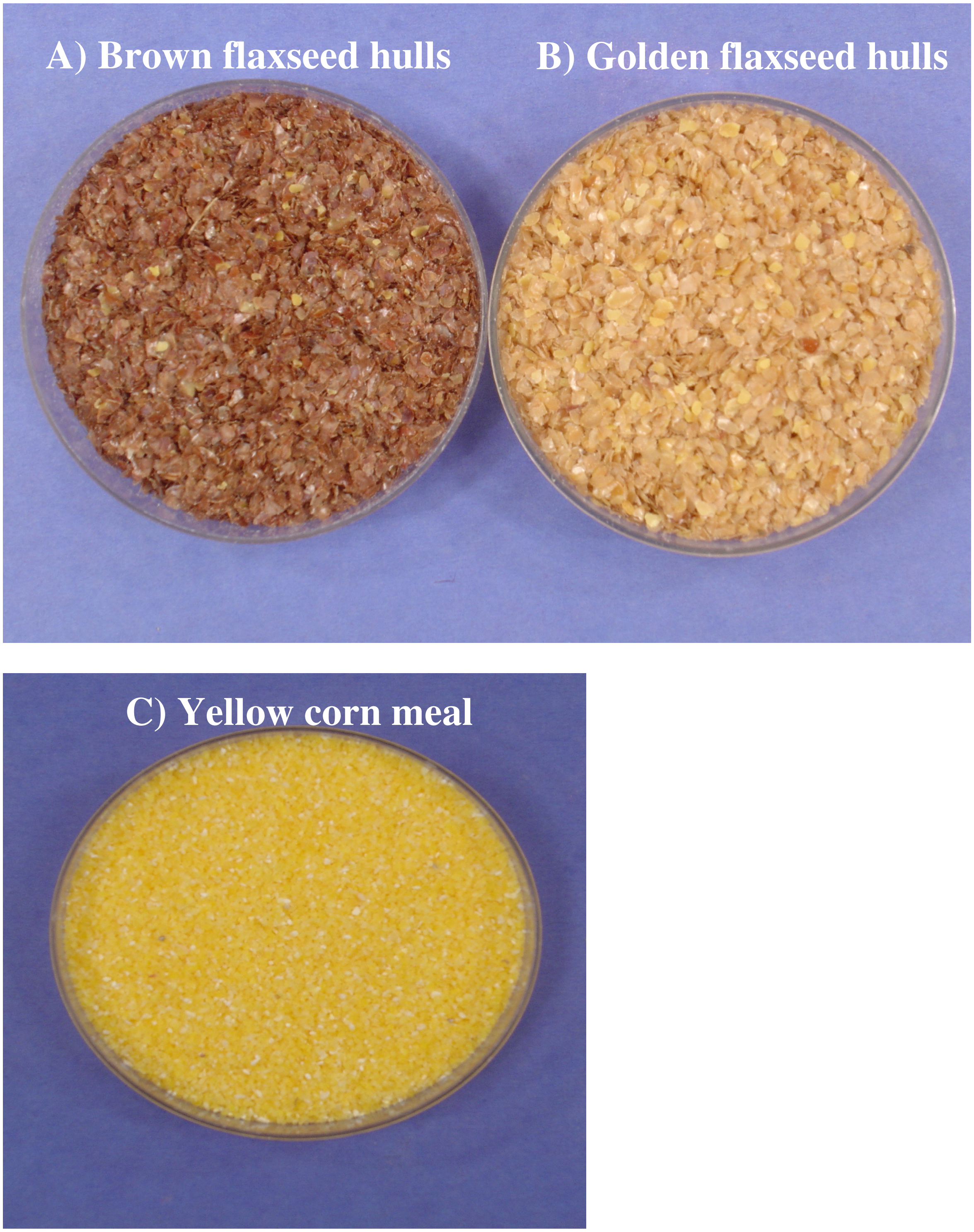

Fig. 3. Raw materials used A. Brown flaxseed hulls, B. Golden Flaxseed Hulls, and C. Yellow De-germed Corn Meal

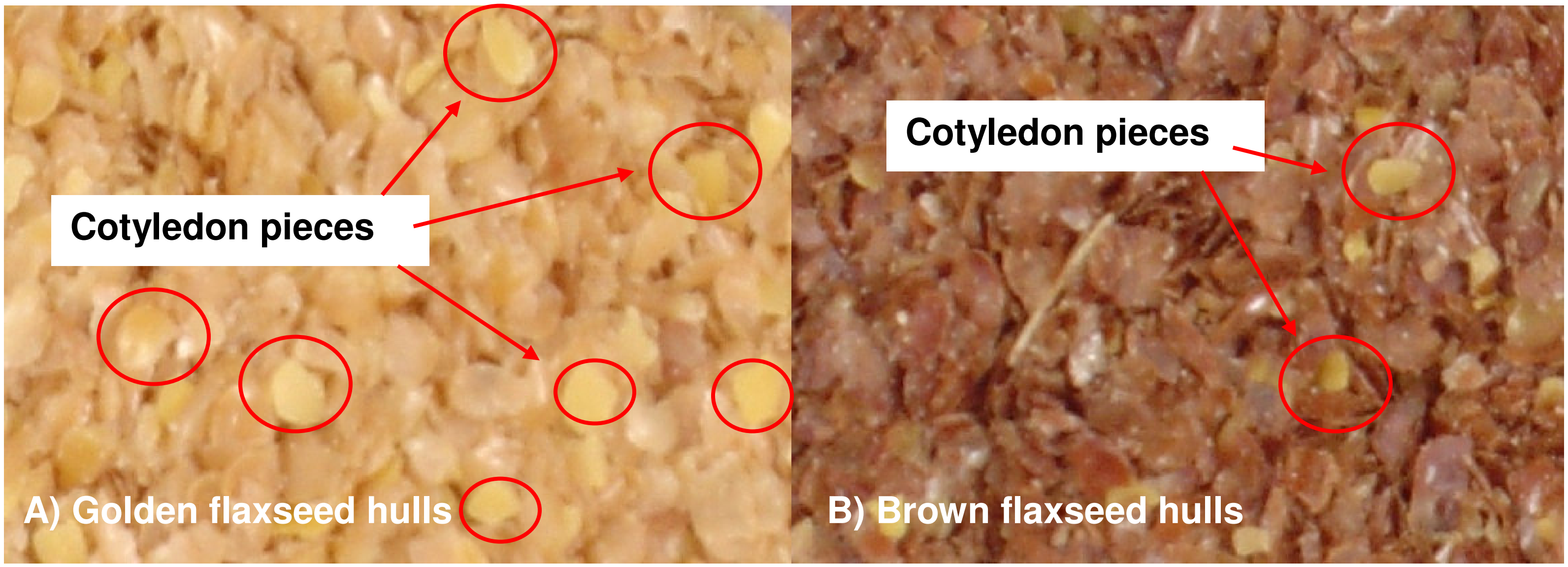

Fig 4. Hull fractions A) Golden flaxseed hulls B) Brown flaxseed hulls.

Table III

Composition and color of corn meal, brown and golden flaxseed hulls (% d.b.)

	Corn Meal	**Brown Flaxseed Hulls**	**Golden Flaxseed Hulls**	**[a] Commercial Specifications (range)**
Oil (%)	0.7 c	16.8 b	29.9 a	10-15
Crude Protein (%)	8.0	[c]9.2	[c]22.0	6-8
Dietary Fiber (%)	-	-	-	50-60
Soluble Fiber (%)	-	-	-	25-35
Insoluble Fiber (%)	-	-	-	22-29
Ash [b] (%)	0.3 c	3.6 a	3.4 b	-
Moisture (%)	11.7	6.6	6.9	8-13
Color [b]				
L*	79.9 a	44.7 c	57.6 b	-
a*	5.7 c	6.5 b	8.3 a	-
b*	50.8 a	10.9 c	19.8 b	-

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[a] Typical specification for commercial brown flaxseed hulls provided by Pizzey's Milling (Angusville, MS, Canada)

[b] Values followed by the same letter within a row are not significantly different ($p < 0.05$)

L* indicates lightness, a* indicates hue on a green (-) to red (+) axis, and b* indicates hue on a blue (-) to yellow (+) axis

[c] Crude Protein for flaxseed hulls was calculated with a conversion factor of N x 5.41

Table IV
Phenol levels (mg GAE/g), ABTS antioxidant activity (µmol TE/g), Tannins (mg CE/g) of defatted brown and golden flaxseed, and their hulls[a]. Values are means of 3 replicates

Materials (defatted)	Phenols mg [b]GAE/g	Antioxidant Activity ABTS µmol [c]TE/g	Tannins mg [d]CE/g
Brown Flaxseed Hulls	**8.8 a**	**123.7 a**	**2.8 a**
Brown Flaxseed (whole)	4.3 b	49.5 b	0.4 b
Golden Flaxseed Hulls	**3.2 d**	**37.9 d**	**0.1 b**
Golden Flaxseed (whole)	3.6 c	40.9 c	0.2 b

[a] Values followed by the same letter within a column are not significantly different ($p < 0.05$)
[b] GAE = Gallic acid equivalent, [c] TE = Trolox equivalent, and [d] CE = Catechin equivalent

Proximate Analysis of Raw Materials

Daun et al. (2003) reported the hull makes up 36% of flaxseed and contains 22% of the oil. The brown and golden flaxseed hull fractions had 17 and 30% oil content, respectfully. Compared to (Pizzey's) commercial specifications for brown flaxseed hulls (*Note*: golden flaxseed hulls were not commercially available), the brown flaxseed hulls used were similar in oil and crude protein content (Table III). The brown flaxseed hulls had dietary fiber content between 50-60% with 25-30% soluble fiber. The golden flaxseed hulls used were significantly higher in oil and crude protein content (Table III). Both hulls fractions contain components that have a negative impact on expansion; high fiber content (Mendonca et al. 2000; Jin et al. 1994), and increased protein and oil contents (Camire and King, 1991; Camire, 2000). The yellow degermed corn meal used as the control had typical values for oil and crude protein content.

Corn meal color had the highest L* and +b values (lighter and yellow). Golden flaxseed hulls had higher L* and +b values compared to the brown flaxseed hulls. The brown flaxseed hulls were darker producing a lower L, a*, and b* value compared to the corn meal and golden flaxseed hulls (Table III).

ABTS Antioxidant Activity, Phenols, and Tannins of Flaxseed and Flaxseed Hulls

Brown flaxseed and its hulls were higher in phenols and antioxidant activity content than golden flaxseed and its hulls (Table IV). Hulls form brown flaxseed contained the highest content of phenols, antioxidant activity, and tannin content of the material tested. Research has reported that the dehulling process concentrates the major lignan in flaxseed secoisolariciresinol diglycoside (SDG) in the hull fraction. Prasad (1997) and Kitts et al. (1999) reported the hydroxyl radical-scavenging property of SDG isolated from flaxseed. Flaxseed compared to other oilseeds, contains low levels of phenolic acids (Wanasundara and Shahidi, 1994; Oomah et al. 1994), and tannin content of flaxseed meal was reported to be low (125 to 137 mg/100g of defatted meal) when compared to that of high glucosinolate rapeseed and canola (Wanasundara and Shahidi, 1994). Low antioxidant activity in the brown flaxseed could be due to dilution of the phenolic compounds by its high protein and content.

Hulls from golden flaxseed were significantly lower in phenol and antioxidant activity compared to the whole golden flaxseed (Table IV). The dehulling process used for golden hulls was ineffective in removal of the cotelydon (Table III), since the crude protein content of the golden flaxseed hulls (22.0%) is similar to that of the golden flaxseed (22.5%).

Table V

Particle size distribution of corn meal, brown and golden flaxseed hulls[a]

Materials	Sieve US#20 (850µm)	Sieve US#30 (600µm)	Sieve US#40 (425µm)	Sieve US#60 (250µm)	Sieve US#80 (180µm)	Sieve US#100 (150µm)	Bottom Pan (<150µm)
Corn Meal	0.00 c	45.9 a	52.7 a	1.1 b	0.3 b	0.0 b	0.1 ab
Brown Flaxseed Hulls	79.6 b	10.4 b	4.0 b	3.5 a	2.0 a	0.4 a	0.3 a
Golden Flaxseed Hulls	95.5 a	4.0 c	0.3 c	0.1 c	0.1 b	0.0 b	0.0 b

[a] Values followed by the same letter within a column are not significantly different ($p < 0.05$). Values are the percent overs of each sieve.

Table VI
Oil content of sieved fractions of flaxseed hulls (% d.b.)

	Brown Flaxseed Hulls	Golden Flaxseed Hulls
Oil Content of material retained on **US# 20**	12.7 [a]	21.6 [a]
Oil Content of material retained on **US# 30,40,60,80,100 & Bottom pan**	4.1 [b]	8.3 [b]
Total oil content	16.8	29.9

[a] Oil Content in hulls on sieve US#20 (850µm) (AACC, 30-26)
[b] Calculated oil contents of material on Sieve US#30 to Pan (determined: oil content of material retained on sieve #20 – total oil content of flaxseed hulls = oil content of material retained on US# 30,40,60,80,100 & Bottom pan).

Particle Size Distribution of Raw Materials

The particle size distribution of the corn meal is typical for production of a direct expanded snack; the majority of the material was retained on US# 30 and 40 sieves (Table V) (Burtea, 2001).

Brown and golden flaxseed hulls had 80 and 96% of material retained on US#20 sieve (850μm), respectfully. Table VI indicates that the material retained on US#20 contained the majority of the oil in each of the hull fractions. The high oil content in the golden hull fraction retained on US#20 sieve indicates the presence of cotyledons.

Composition and Particle Size Distribution of Blends

Calculated oil and protein contents increased in all blends as the percentage of hulls were added (Table VII). The blend with 25% golden flaxseed hulls contained 43% more crude protein than the blend with the same percentage of brown flaxseed hulls. Calculated oil contents for blends with 15, 20, and 25% brown and golden hulls were 3.5, 4.4, 5.3%, and 5.7, 7.3, 9.0%, respectfully. There was an increase in material retained on US#20 sieve for all blends as increasing percentages of flaxseed hulls (brown or golden) were added reducing the material retained on US# 30 and 40 sieves (Table VIII).

Table VII

Moisture, oil, and crude protein (% d.b.) for blends extruded using the twin screw extruder at 72 kg/hr feed rate

Blends	**Moisture** (%)	[d] **Moisture (%)** 0.022 kg/min	 0.062 kg/min	**Oil** (%)	(%)[e]**Crude Protein (N x 6.25)**
Corn Meal (Control)	11.7	13.3	16.0	0.8	9.6
15% [a]BFH + 85% [c]CM	10.9	12.5	15.3	3.5	10.1
20% BFH + 80 %CM	10.7	12.3	15.1	4.4	10.2
25% BFH + 75 %CM	10.4	12.0	14.8	5.3	10.4
15% [b]GFH + 85% CM	11.0	12.6	15.4	5.7	12.8
20% GFH + 80 %CM	10.7	12.3	15.1	7.3	13.9
25% GFH + 75 %CM	10.5	12.1	14.9	9.0	14.9

[a] BFH: Brown flax hulls, [b] GFH: Golden flax hulls, [c] CM: De-germed corn meal (Cargill)
[d] Water injected into extruder barrel, [e] Calculate Crude Protein

Table VIII

Particle size distribution of corn meal and blends[a]

Materials	Sieve US#20 (850µm)	Sieve US#30 (600µm)	Sieve US#40 (425µm)	Sieve US#60 (250µm)	Sieve US#80 (180µm)	Sieve US#100 (150µm)	Bottom Pan (<150µm)
[b]CM (Control)	0.0 g	45.9 a	52.7 a	1.1 c	0.3 c	0.0 b	0.1 a
85% CM + 15% [c]BFH	11.7 f	40.4 c,d	46.0 b	1.5 b	0.5 b	0.1 b,a	0.0 a
80% CM + 20% BFH	15.4 d	39.0 d,e	43.1 c	1.7 b	0.7 a	0.1 a	0.0 a
75% CM + 25% BFH	19.6 b	36.8 f	40.8 d	2.1 a	0.7 a	0.1 a	0.1 a
85% CM + 15% [d]GFH	14.6 e	43.7 b	40.7 d	0.9 c	0.2 c	0.0 b	0.0 a
80% CM + 20% GFH	19.1 c	42.0 c,b	36.2 e	1.0 c	0.2 c	0.1 a	0.1 a
75% CM + 25% GFH	24.3 a	38.3 f,e	37.5 e	1.1 c	0.3 c	0.1 a	0.1 a

[a] Values followed by the same letter within a column are not significantly different ($p< 0.05$)
[b] CM = De germed corn meal; [c]BFH = Brown flaxseed hulls; [d]GFH = Golden flaxseed hulls
Values are the percent overs of each sieve

Table IX

Twin screw extrusion processing parameters for corn meal and blends

Blends	[a]FM	Motor Load (%)	Head Pressure (psi)	SME kJ/kg
13% Feed Moisture				
Corn Meal (Control)	13.3	52	1000	471.7
16% Feed Moisture				
Corn Meal (Control)	16.0	49	1000	444.5
12% Feed Moisture				
15% [b]BFH + 85% [c]CM	12.5	39	1000	353.8
20% BFH + 80 %CM	12.3	38	*1050**	344.7
25% BFH + 75 %CM	12.0	35	*1050**	317.5
15% Feed Moisture				
15% BFH + 85% CM	15.3	39	950	353.8
20% BFH + 80 %CM	15.1	39	950	353.8
25% BFH + 75 %CM	14.8	33	850	308.4
12% Feed Moisture				
15% [d]GFH + 85% CM	12.6	42	*1500**	381.0
20% GFH + 80 %CM	12.3	41	*1600**	372.0
25% GFH + 75 %CM	12.1	36	*1500**	326.6
15% Feed Moisture				
15% GFH + 85% CM	15.4	37	1200	335.7
20% GFH + 80 %CM	15.1	35	*1200**	317.5
25% GFH + 75 %CM	14.9	33	*1200**	299.4

[a] FM: Feed Moisture Content, [b] BFH: Brown Flax Hulls, [c] CM: Corn Meal,
[d] GFH: Golden Flax Hulls
* *Oil Visible on Outside Extruder Barrel*

Extrusion Processing

During extruding the feed rate, screw speed, and zone temperatures were fixed, however the properties of the extrudates were still influenced by changing the feed moisture. Moisture content influences the starch cooking process and the overall viscosity of the system. Decreasing feed moisture translates into higher viscosity, which more efficiently transfers mechanical stress to the extruded material. Beecher and Starer (1998) reported during extrusion of corn meal as moisture levels were reduced the die pressure, die temperature, and energy input increased. This was seen in the processing of the corn meal (Table IX; Fig. 5A). Corn meal at 13% feed moisture had a higher motor load (%) and SME than corn meal with 16% feed moisture indicating higher mechanical energy transfer and increased viscosity for corn meal with lower feed moisture (Table IX).

Extruder head pressure (psi) was higher for brown flaxseed hull blends processed at 12% feed moisture compared to 15% (Table IX), this can be explained by the decrease in moisture. At both 12 and 15% feed moisture SME and motor load (%) decreased (no difference in head pressure) as the percentage of brown hulls increased. As mentioned previously the brown hulls contain a higher percentage of mucilage. Various hydrocolloids have been shown to decrease torque during extrusion (Maga and Fapojuwo, 1986). Extruding of 20 and 25% brown flaxseed hull blends at 12% feed moisture produced visible signs of oil on the exterior of the extruder head (Fig. 4B); no oil was present during extruding of the other brown flaxseed hull blends.

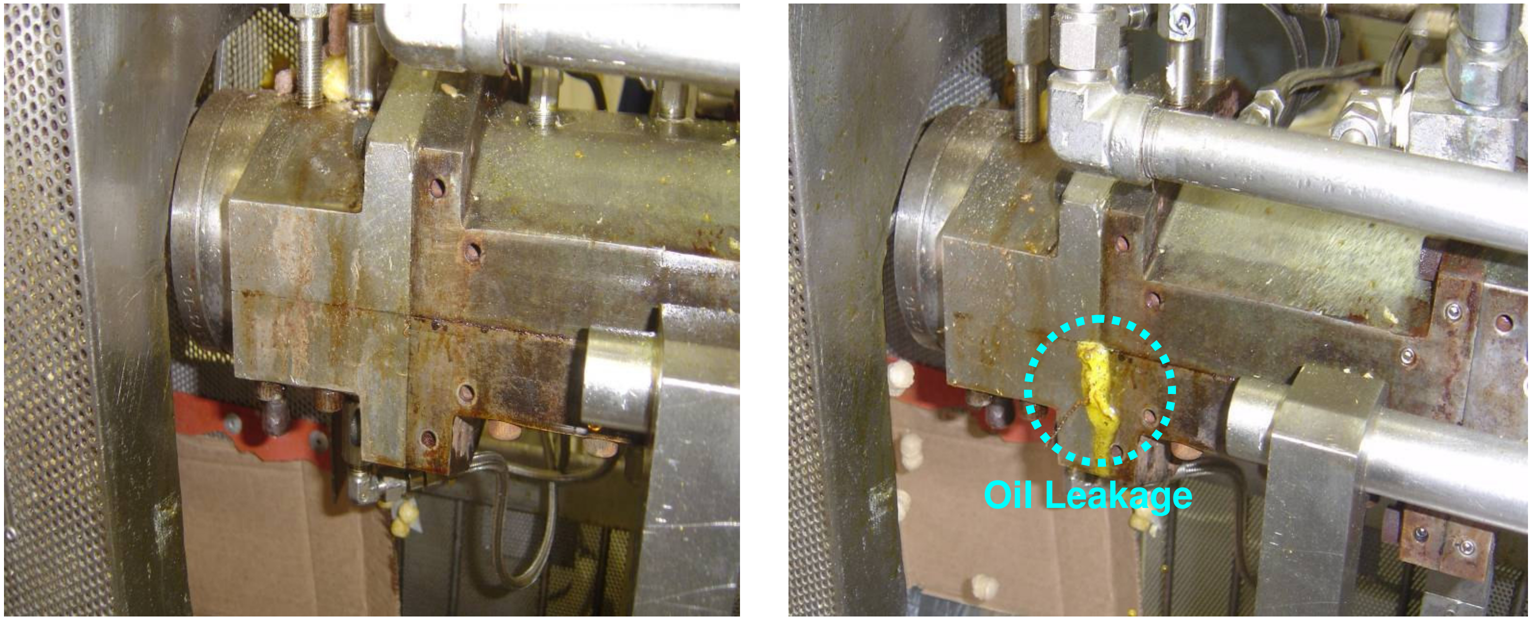
Blends with 15, 20, and 25% golden flaxseed hulls extruded at 12% feed moisture produced a higher motor load, head pressure, and SME (Table IX), than blends extruded at 15% feed moisture. This was caused the decrease in moisture as mentioned by Beecher and Starer (1998). Although water acts as a plasticizer decreasing viscosity thus decreasing SME, the increase in feed moisture was not fully responsible. Oil in the golden flaxseed hulls acted as a lubricant, thus causing a decreased motor load, head pressure, and SME as the level of golden flaxseed hulls was increased. The lipids reduce friction between the dough and the screw/barrel during extrusion.

Excess oil was seen on the extruder barrel during the extrusion of all but one of the golden flaxseed hulls blends (Fig. 5B). Camire (2000) found that formulations with lipid levels > 5-6% impair extruder performance, decreasing torque due to slip with in the extruder barrel. The extrusion cooking and physical (mechanical) disruption of the hull cell walls may cause a release of oil increasing head pressure. As oil is essentially pressed out of the extruder there is a decrease in oil content in the material extruded, thus no decrease in expansion as typically seen in other material extruded with increased oil contents (Camire and King, 1991).

Extrudates Appearance and Color

All blends produced extrudates with acceptable appearance (Fig. 6 & 7). Blends extruded with the lower feed moisture of 12% (13% for corn meal) produced extrudates with rough uneven surfaces. The ridged surface distortion is referred to as "sharkskin". Similar surface distortion was observed in extrudates containing sugar beet fiber and oat flour (Lue et al. 1991). The "sharkshin" is caused by the rapid acceleration of the surface layers of the extrudate when polymer leaves the die. The stretching rate is too high; thus surface layer of the polymer actually fails and forms the characteristic ridges. It was noticed as the feed moisture was decreased in this experiment.

Extrudates containing brown flaxseed hulls had the lowest L* values (darkest) (Table X). Extrudates containing brown flaxseed hulls had higher a* values (indicating red hue) and lower b* values (less yellow hue). Extrudates containing golden flaxseed hulls had high b* values (more yellow hue). There was a significant decrease in the b* values between golden flaxseed hull extrudates extruded with a feed moisture of 12% compared to 15% (Table X). Darker products were obtained with the addition of brown flaxseed hulls which is typical for products with added bran fiber. However golden flaxseed hulls can be added to corn meal to increase fiber content without producing a darker colored product, if desired.

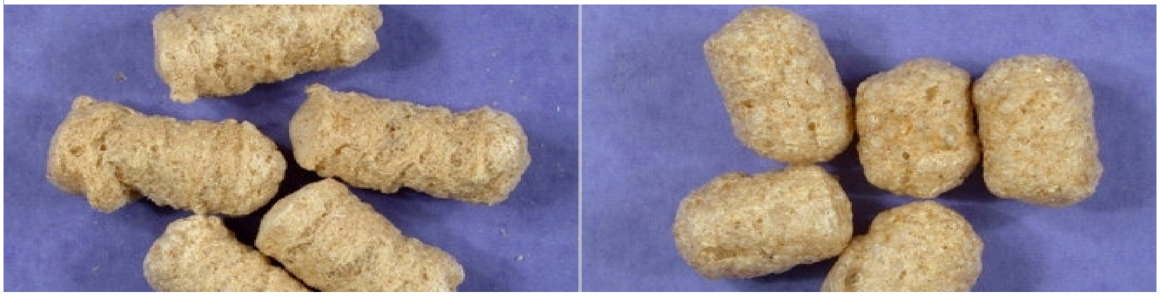


A) No external oil present on extruder barrel

B) External oil present on extruder barrel

Fig. 5. Visible oil leakage on external of extruder head barrel **A)** No external oil **B)** Exterior oil

Corn Meal - 13% Feed Moisture **Corn Meal - 16% Feed Moisture**



15% Brown Flaxseed Hulls
12% Feed Moisture

15% Brown Flaxseed Hulls
15% Feed Moisture

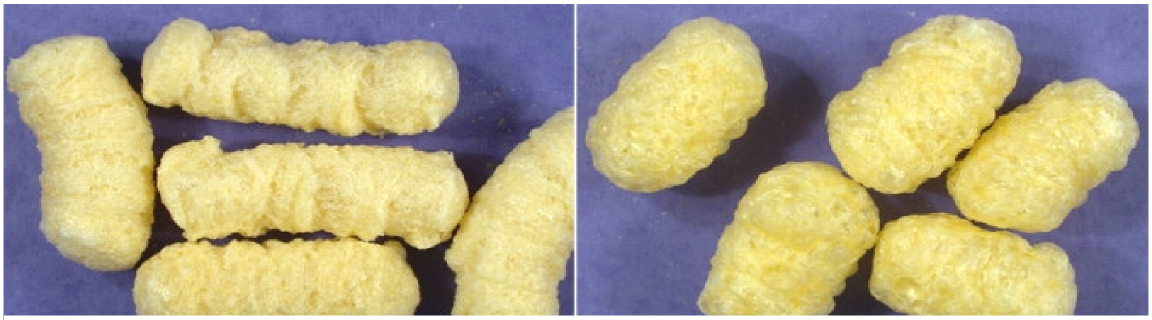
20% Brown Flaxseed Hulls
12% Feed Moisture

20% Brown Flaxseed Hulls
15% Feed Moisture

25% Brown Flaxseed Hulls
12% Feed Moisture

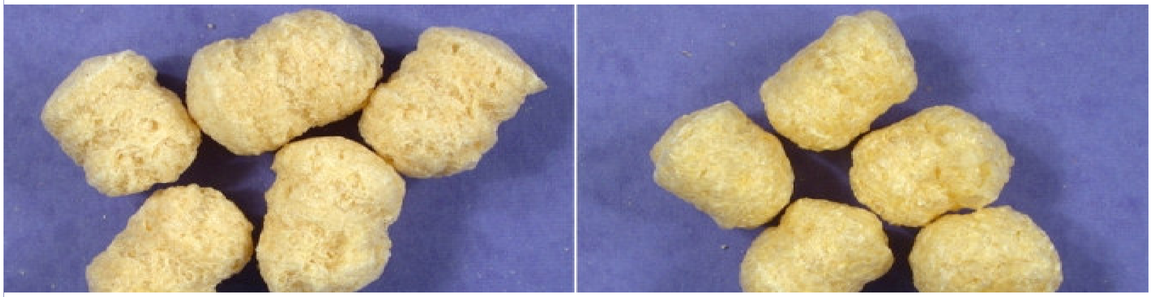
25% Brown Flaxseed Hulls
15% Feed Moisture

Fig 6. Brown Flax Hull-Corn Meal extrudates with 12 and 15% feed moisture.



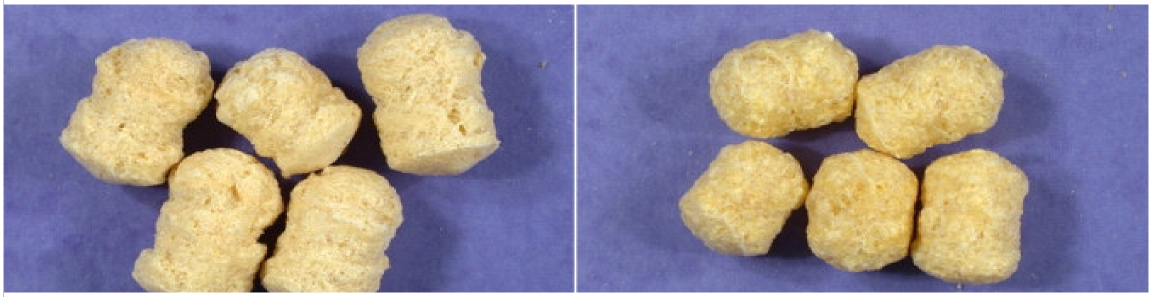
Corn Meal - 13% Feed Moisture

Corn Meal - 16% Feed Moisture



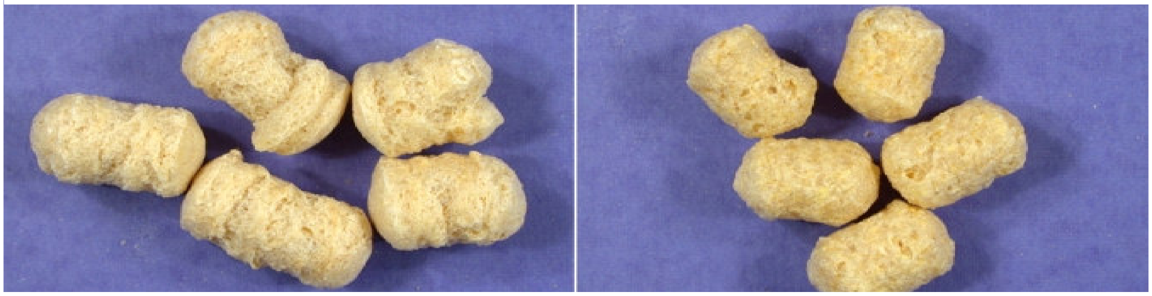
15% Golden Flaxseed Hulls
12% Feed Moisture

15% Golden Flaxseed Hulls
15% Feed Moisture



20% Golden Flaxseed Hulls
12% Feed Moisture

20% Golden Flaxseed Hulls
15% Feed Moisture



25% Golden Flax Hulls
12% Feed Moisture

25% Golden Flax Hulls
15% Feed Moisture

Fig. 7. Golden Flaxseed Hull-Corn Meal Extrudates with 12 and 15% Feed Moisture.

Table X

Color of extrudates[a]

% Feed			Color	
Moisture	Extrudates	L*	a*	b*
13	[b]CM (Control)	82.1 b	0.0 i	38.8 b
16	CM (Control)	84.7 a	-0.9 j	38.1 a
12	15% Brown [c]FH + 85% CM	66.4 g	3.7 c	19.2 h
12	20% Brown FH + 80% CM	64.3 h	4.2 b	17.9 j
12	25% Brown FH + 75% CM	62.2 j	4.6 a	15.8 m
15	15% Brown [c]FH + 85% CM	64.0 h	3.6 d,c	18.5 i
15	20% Brown FH + 80% CM	62.8 i	3.5 d	17.4 k
15	25% Brown FH + 75% CM	59.3 k	4.6 a	16.8 l
12	15% Golden [c]FH + 85% CM	75.7 c	1.8 g	27.1 g
12	20% Golden FH + 80% CM	75.7 c	2.0 g.f	25.7 f
12	25% Golden FH + 75% CM	75.1 d	2.0 f,e	25.3 e
15	15% Golden [c]FH + 85% CM	75.5 d,c	1.2 h	31.6 b
15	20% Golden FH + 80% CM	74.0 e	1.8 g	30.4 c
15	25% Golden FH + 75% CM	73.1 f	2.2 e	28.7 d

[a]Values followed by the same letter within a column are not significantly different ($p < 0.05$)

[b]CM = Corn meal; [c]FH = flaxseed hulls;

L* indicates lightness, a* indicates hue on a green (-) to red (+) axis, and b* indicates hue on a blue (-) to yellow (+) axis

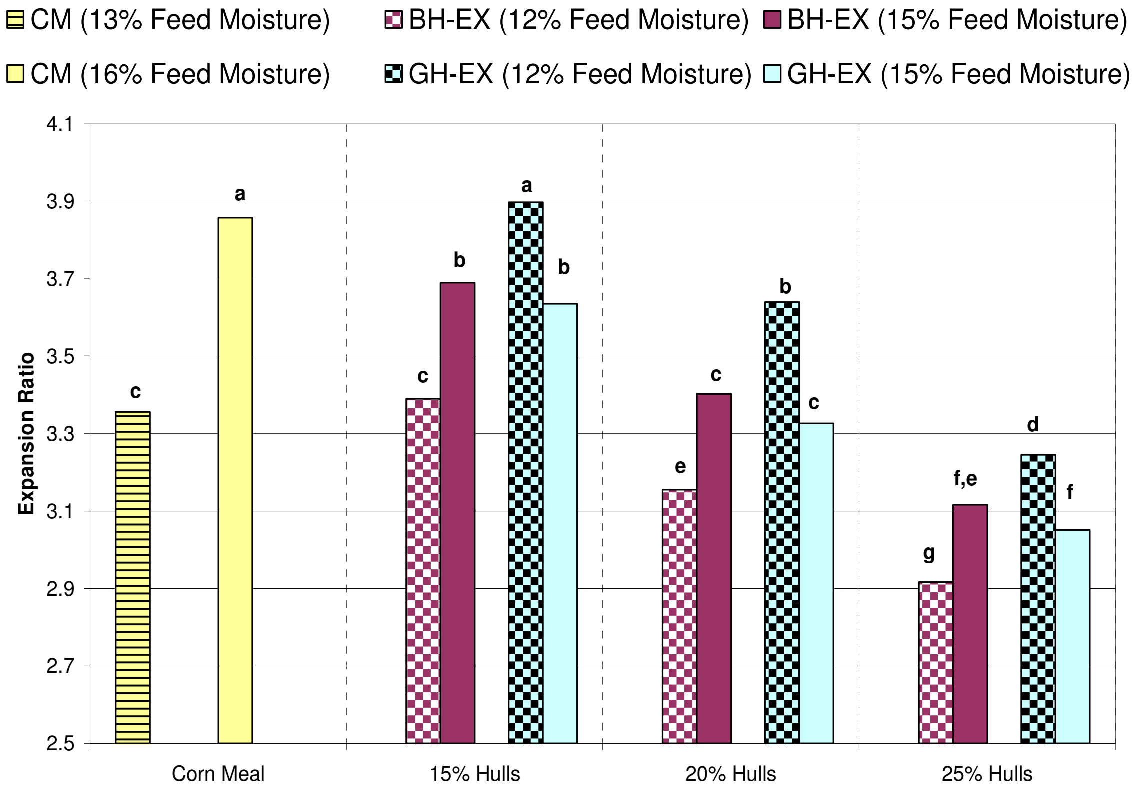


Fig. 8. Expansion ratio of brown and golden flaxseed hull/corn meal extrudates extruded at 12 and 15% feed moistures.
[a]Values with same letter are not significantly different ($p < 0.05$)

CM=corn meal, **BH-EX**= brown flaxseed hull extrudates, **GH-EX**= golden flaxseed hull extrudates.

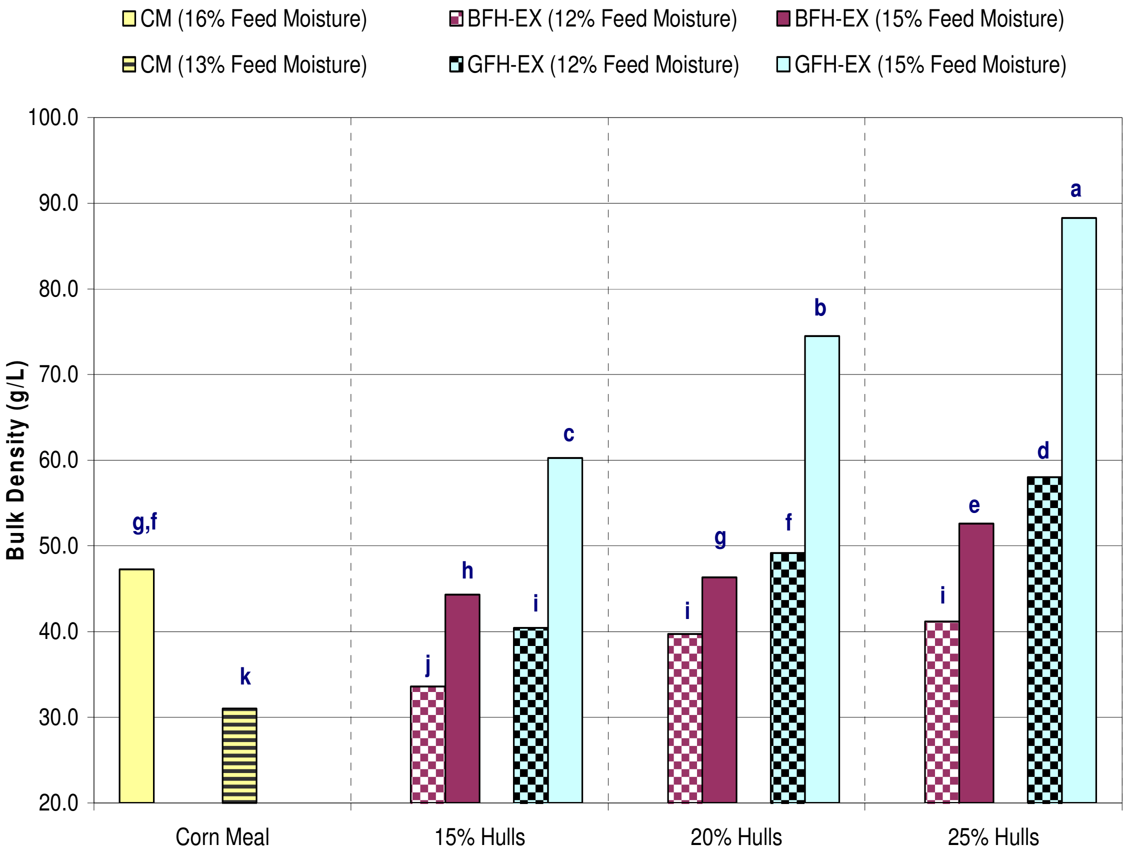


Fig. 9. Bulk Density (g/L) of brown and golden flaxseed hull/corn meal extrudates extruded at 12 and 15% feed moistures.

[a]Values with same letter are not significantly different ($p < 0.05$)

CM=corn meal, **BH-EX**= brown flaxseed hull extrudates, **GH-EX**= golden flaxseed hull extrudates.

Table XI

Expansion ratio, bulk density, and length of extrudates[a]

% [d]FM	Extrudates	[e]ER	Bulk Density (g/L)	Length (mm)	Shear Force(N)
13	[b]CM (Control)	3.4 c	31.0 k	38.1 a	239 g,f
16	CM (Control)	3.9 a	47.2 g,f	26.0 d,c	153 i
15	15% Brown [c]FH + 85% CM	3.7 b	44.3 h	20.8 h,g	172 h
15	20% Brown FH + 80% CM	3.4 c	46.3 g	21.2 g	245 f,e
15	25% Brown FH + 75% CM	3.1 f,e	52.6 e	22.3 f	245 f,e
15	15% Golden [c]FH + 85% CM	3.6 b	60.3 c	20.1 h	226 g
15	20% Golden FH + 80% CM	3.3 c	74.5 b	18.8 i	309 c
15	25% Golden FH + 75% CM	3.1 f	88.3 a	17.9 j	390 a
12	15% Brown [c]FH + 85% CM	3.4 c	33.6 j	28.0 b	220 g
12	20% Brown FH + 80% CM	3.2 e	39.7 i	25.6 d	260 e
12	25% Brown FH + 75% CM	2.9 g	41.1 i	26.6 c	288 d
12	15% Golden [c]FH + 85% CM	3.9 a	40.4 i	23.5 e	249 f,e
12	20% Golden FH + 80% CM	3.6 b	49.1 f	22.2 f	286 d
12	25% Golden FH + 75% CM	3.2 d	58.0 d	21.5 g,f	368 b

[a] Values followed by the same letter within a column are not significantly different ($p < 0.05$)

[b] **CM**= Corn meal, [c] **FH** = Flaxseed hulls, [d] **FM** = Feed Moisture, [e] **ER** = Expansion Ratio

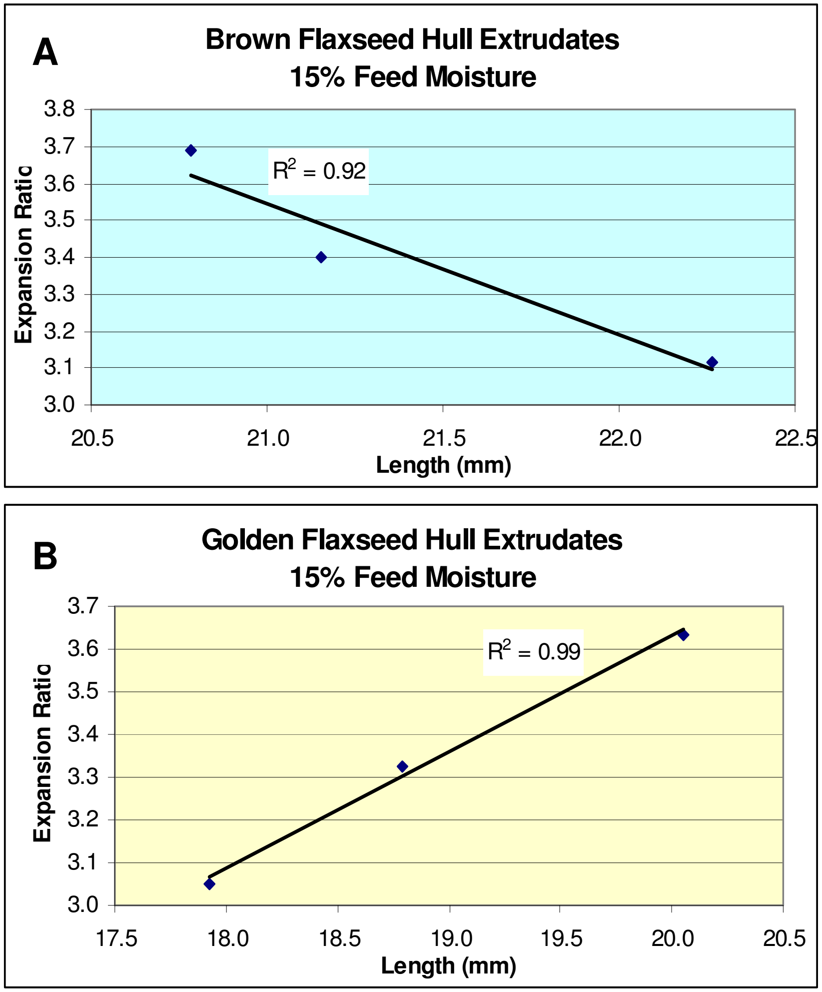


Fig. 10. Correlation between extrudate length (mm) and expansion ratio of extrudates A) Brown flaxseed hull extrudates at 15% feed moisture, B). Golden flaxseed hull extrudates at 15% feed moisture

Expansion Ratio, Longitudinal Expansion, and Bulk Density

All blends extruded at 12 and 15% feed moisture produced extrudates that decreased in expansion ratio and increased in bulk density as the percentage of brown or golden hulls increased (Fig. 8 & 9). Addition of fiber into an expanded product has been reported to reduce expansion (Anderson et al, 1981). Decreased expansion has been contributed to fiber disrupting air cell formation or puncturing cell walls, thus leading to a dense and compact product increasing bulk density (Beecher and Starer, 1998).

At 15% feed moisture the brown flaxseed hull extrudates increased in length as the percentage of hulls increased (Table XI). The increase in extrudate length was negatively correlated (r^2=0.92) (Fig. 10A) with expansion ratio. Lue et al. (1991) reported a decrease in expansion and an increase in extrudate length with the addition of fiber. In this study the increased length of brown hull extrudates was due to the soluble fiber in the hulls. The soluble fiber is mucilage a water soluble hydrocolloid. Low viscosity water soluble gums act as extrusion aids and lubricants without increasing viscosity (Mercier and Feillet, 1975). An increase in the percentage of brown hulls caused a decrease in viscosity; thus decreasing motor load (%) and SME (Table IX) and increased extrudate length (Table XI). The bulk density of the brown hull extrudates containing 15 and 20% brown flaxseed hulls was lower then the corn meal (control) extruded with feed moisture of 16%, this would be the opposite of studies that report an increase in bulk density and harder texture with added fiber (Lue et al. 1990). The fiber in the flaxseed hull did not significantly disrupt cell structure of the extrudate.

Golden hull blends extruded at 15% feed moisture produced extrudates that were higher in bulk density and shorter in length then the brown flaxseed hull extrudates extruded at the 15% feed moisture. Extrudate length was positively correlated (r^2=0.99) (Fig. 10B) with expansion ratio. The decrease in expansion and extrudate length is caused by the high oil and protein content of the large cotyledon pieces (>#20 mesh) in hull fraction. The proteins and lipids may have interfered with the ability of the thermoplastic starch melt to expand (Faubion and Hoseney, 1982). There was a decrease in motor load (%) and SME as increasing percentages of golden hull were added, these findings are similar to Camire (2000). Higher lipid contents decrease expansion and produce a denser extrudate. The larger pieces of cotyledon may have disrupted cell formation thus decreasing expansion, thus producing a product with a higher bulk density.

Brown and golden flaxseed hull blends extruded at 12% feed moisture produced longer extrudates with lower bulk density than at 15% feed moisture (Fig. 9; Table XI). Decreasing feed moisture causes decreased bulk density in corn meal and rice extrudates (Beecher and Starer, 1998); this was evident in the corn meal control as feed moisture was decreased from 16 to 13% (Table XII). At 12% feed moisture, bulk density of extrudates increased as the percentage of hulls was increased (Fig. 9). Lue et al. (1990) reported similar results in extrudates with added oat flour. Extrudates containing golden flaxseed hulls had higher bulk densities than brown hull extrudates.

Golden flaxseed hulls extruded at 12% feed moisture had the highest expansion ratio of all extrudates (Fig. 8), and produced the highest head pressure, motor load (%), and SME of all the hull blends (Table IX). High mechanical stress on the extruded golden hulls caused a released free oil (Fig.5B) at the extruder head (Camire, 2001), thus decreasing the oil content of the material in the extruder barrel. The high crude protein content of the golden flaxseed hull blends (13, 14, and 15%) and its extrudates (Table XII) shows a possible reason for the increased expansion ratio. Fig.11 displays the crude protein compared to the expansion ratio of brown and golden flaxseed hull extrudates. Camire and King (1991) reported extrudates containing soy protein isolate added to corn meal had higher expansion than corn meal extrudates.

Texture

Golden flaxseed hull extrudates extruded at 15% feed moisture had a higher shear force (harder) than brown flaxseed hull extrudates at the same feed moisture (Fig. 12). As previously mentioned extrudates of golden and brown hulls had decreased expansion. However the decreased expansion of golden hulls extrudates was due to increased oil percentage from pieces of cotyledons. Expansion phenomenon depends on viscoelastic melt properties. Colonna et al. (1989) reported semi-crystalline amylose-lipid complex formation generates rigid zones and produced a more rigid matrix that is less elastic.

The golden flaxseed hull extrudates at 15% feed moisture were more compact and dense which contributes to the higher shear force needed. However the brown flaxseed hull extrudates at 15% feed moisture required significantly less shear force (softer) (Fig. 12). There was increase in shear force in extrudates as the percentage of brown hulls increased. This would indicate that reduction in expansion was not due to disruption of cell formation by fiber. The expansion was longitudinal, and cell walls were thin thus requiring less shear force.

Golden hull extrudates with 12% feed moisture required more shear force than brown flaxseed hull extrudates at the same feed moisture. Shear force increased as the percentage of hulls increased for extrudates with 12% feed moisture. Extrudates processed at the lower feed moisture have been reported to require less shear force (Lue et al., 1990, Camire, 2001). Results in the experiment showed higher shear force was required for the brown hull extrudates at 12% feed moisture compared to the 15% feed moisture. The extrudates at 12% feed moisture had lower bulk densities than at 15% feed moisture. The brown hull extrudates extruded at 12% feed moisture had a sponge like internal structure (Fig. 13 D) which required more compression before shearing occurred.

Table XII
Crude protein (db%) of brown and golden hull extrudates extruded at 12 and 15% feed moisture

% [c]FM	Extrudates	Crude Protein (N x 6.25)
13	[a]CM (Control)	9.3
16	CM (Control)	8.7
15	15% Brown [b]FH + 85% CM	10.1
15	20% Brown FH + 80% CM	10.6
15	25% Brown FH + 75% CM	11.0
12	15% Brown FH + 85% CM	10.7
12	20% Brown FH + 80% CM	11.1
12	25% Brown FH + 75% CM	11.6
15	15% Golden FH + 85% CM	11.4
15	20% Golden FH + 80% CM	11.9
15	25% Golden FH + 75% CM	13.1
12	15% Golden FH + 85% CM	12.2
12	20% Golden FH + 80% CM	12.9
12	25% Golden FH + 75% CM	13.9

[b]**CM**= Corn meal, [c]**FH** = Flaxseed hulls, [d]**FH** = Feed Moisture

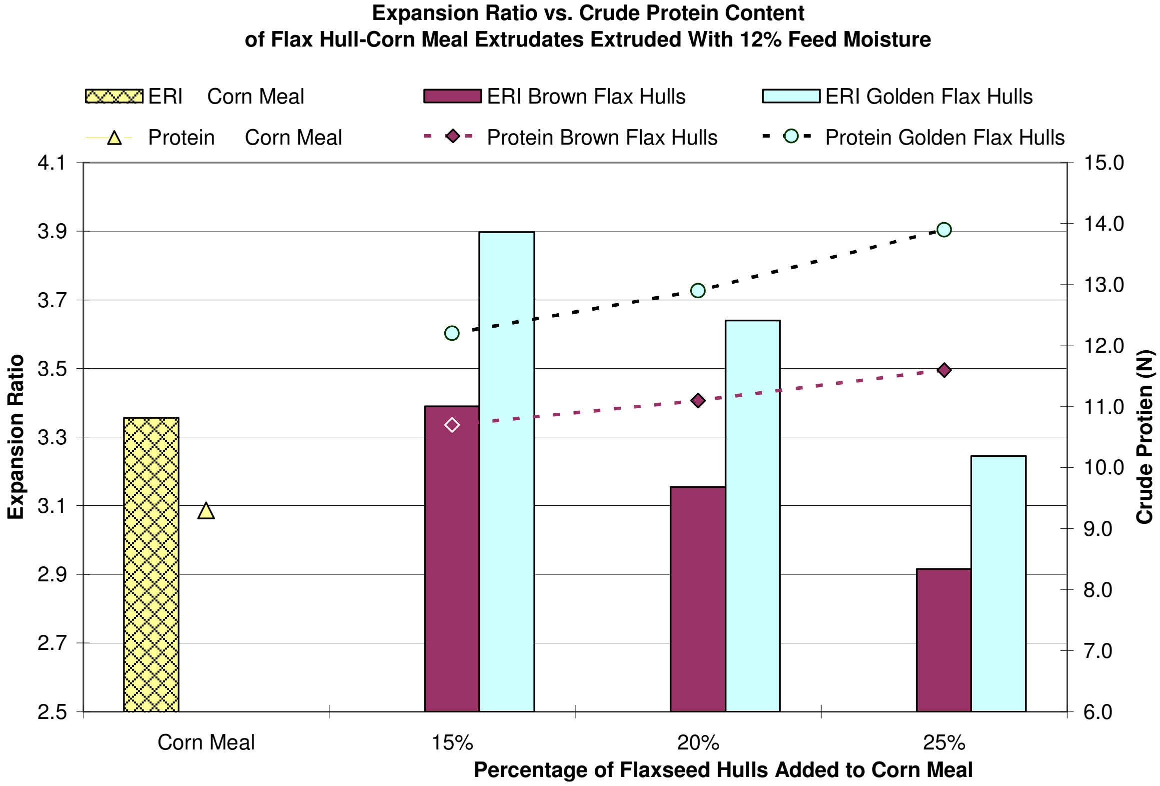


Fig. 11. Expansion Ratio vs. Crude Protein content brown and golden flaxseed hull extrudates at 12% feed moistures.

BH-EX= brown flaxseed hull extrudates, **GH-EX**= golden flaxseed hull extrudates.

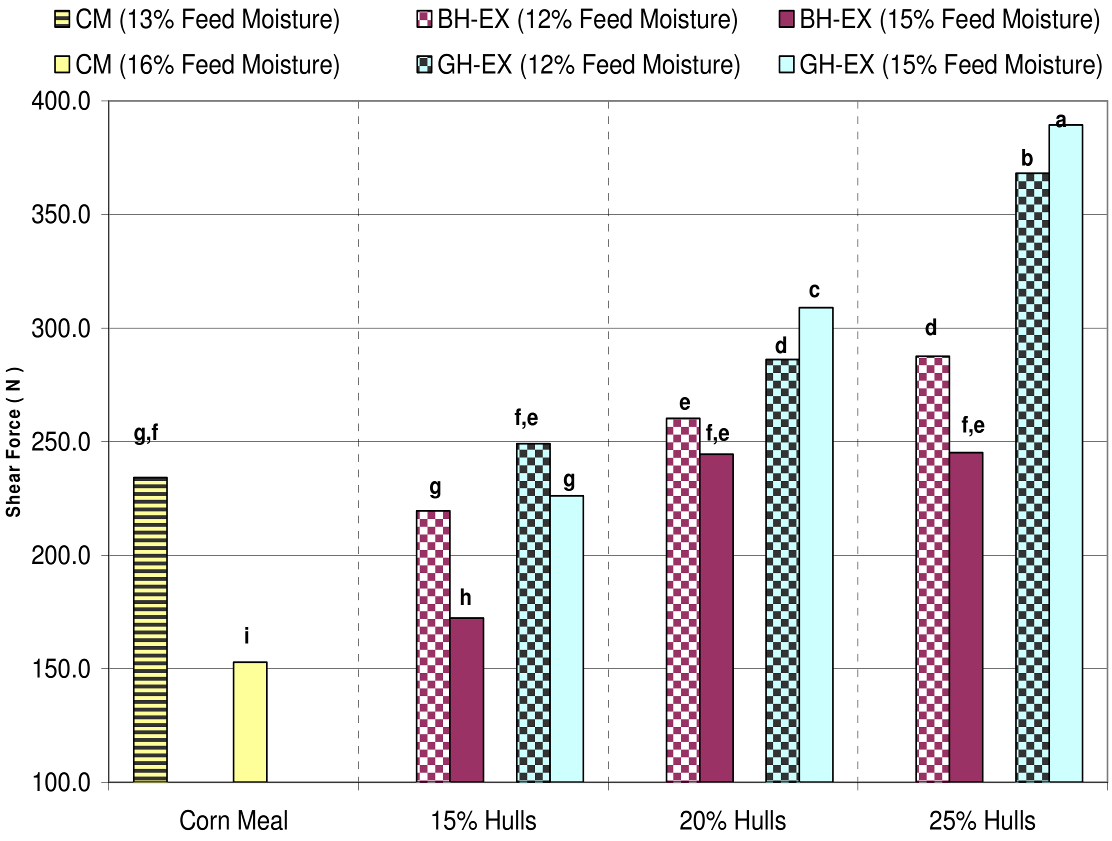


Fig. 12. Shear force (N) of brown and golden flaxseed hull/corn meal extrudates extruded at 12% and 15% feed moistures.

[a]Values with same letter are not significantly different ($p< 0.05$)

BH-EX= brown flaxseed hull extrudates, **GH-EX**= golden flaxseed hull extrudates.

Macrostructure

Blends extruded at 15% feed moisture produced extrudates with larger air cells (Fig. 13 A,B) compared to blends extruded at 12% feed moisture which had sponge like internal structure (Fig. 13 C,D).The decreased feed moisture helped increase shear producing smaller air cells. The degree of expansion of extrudates is closely related to the size, number, and distribution of the air cell surrounded by the cooked matrix (Lue et al. 1990). Larger air cells indicate greater expansion. The size of the air cells in the brown hull extrudates was correlated with expansion; extrudate in Fig.13B had greater expansion than the extrudate in Fig. 13D. However the opposite was true for the golden hull extrudates as extrudate in Fig. 13A was less expanded than the extrudate in Fig. 13C. As previously mentioned cotyledon pieces contributed to disruption air cell formulation causing a decrease in expansion.

Microstructure

Extrudates produced at 15% feed moisture had larger air cells than at 12% feed moisture (Fig. 14A & 15A). The brown hull extrudates had thinner cell walls compared to the golden hull extrudates at 15% feed moisture. The thick cell walls of the golden hull extrudate contributed to their hard structure. Extrudates extruded at 12% feed moisture had smaller air cells (Fig. 14B & 15B), this could be explained by the increased shear and SME the material was subjected to in the extruder. The increase in feed moisture helps make the extruded material more elastic promoting greater expansion in the 15% feed moisture extrudates.

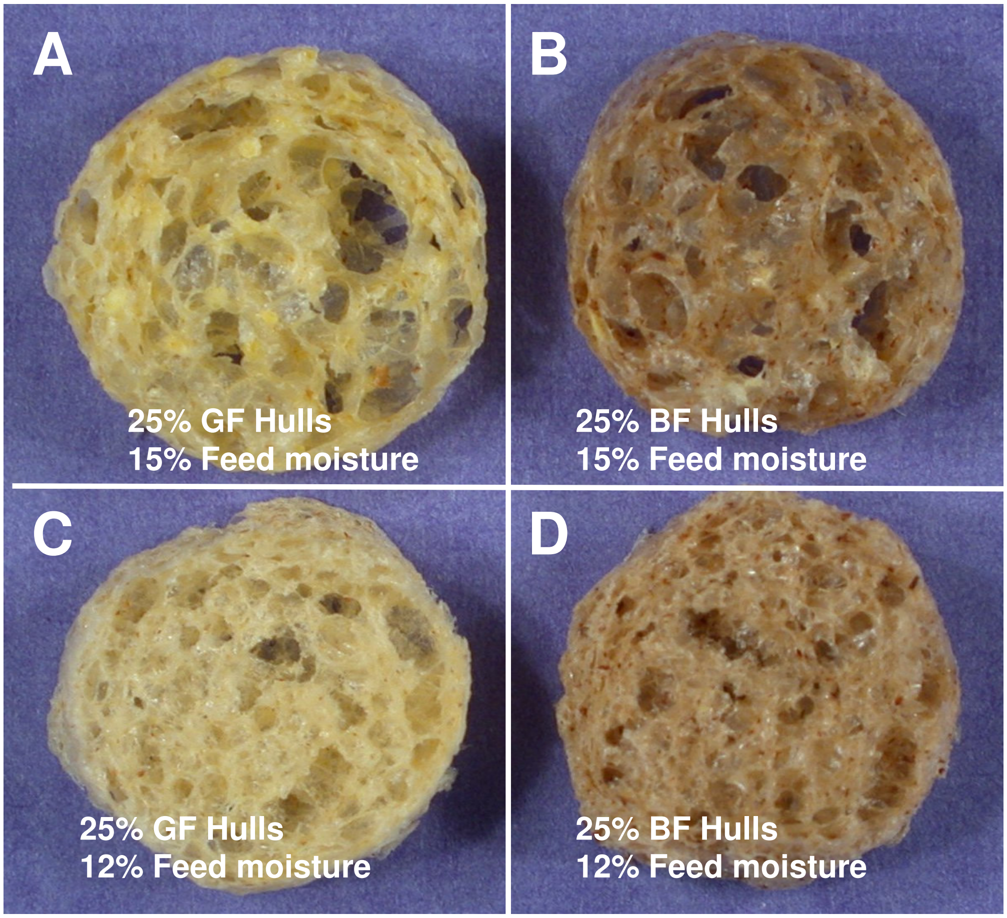


Fig. 13. Cross section of extrudates extruded at 12 or 15% feed moisture with 25% golden or brown flaxseed hulls **A)** 25% Golden flaxseed hull extrudate, 15% feed moisture, **B)** 25% Brown flaxseed hull extrudate, 15% feed moisture **C)** 25% Golden flaxseed hull extrudate, 12% feed moisture, **D)** whole 25% Brown flaxseed hull extrudate, 12% feed moisture.

GF=Golden flaxseed, **BF**=Brown Flaxseed.

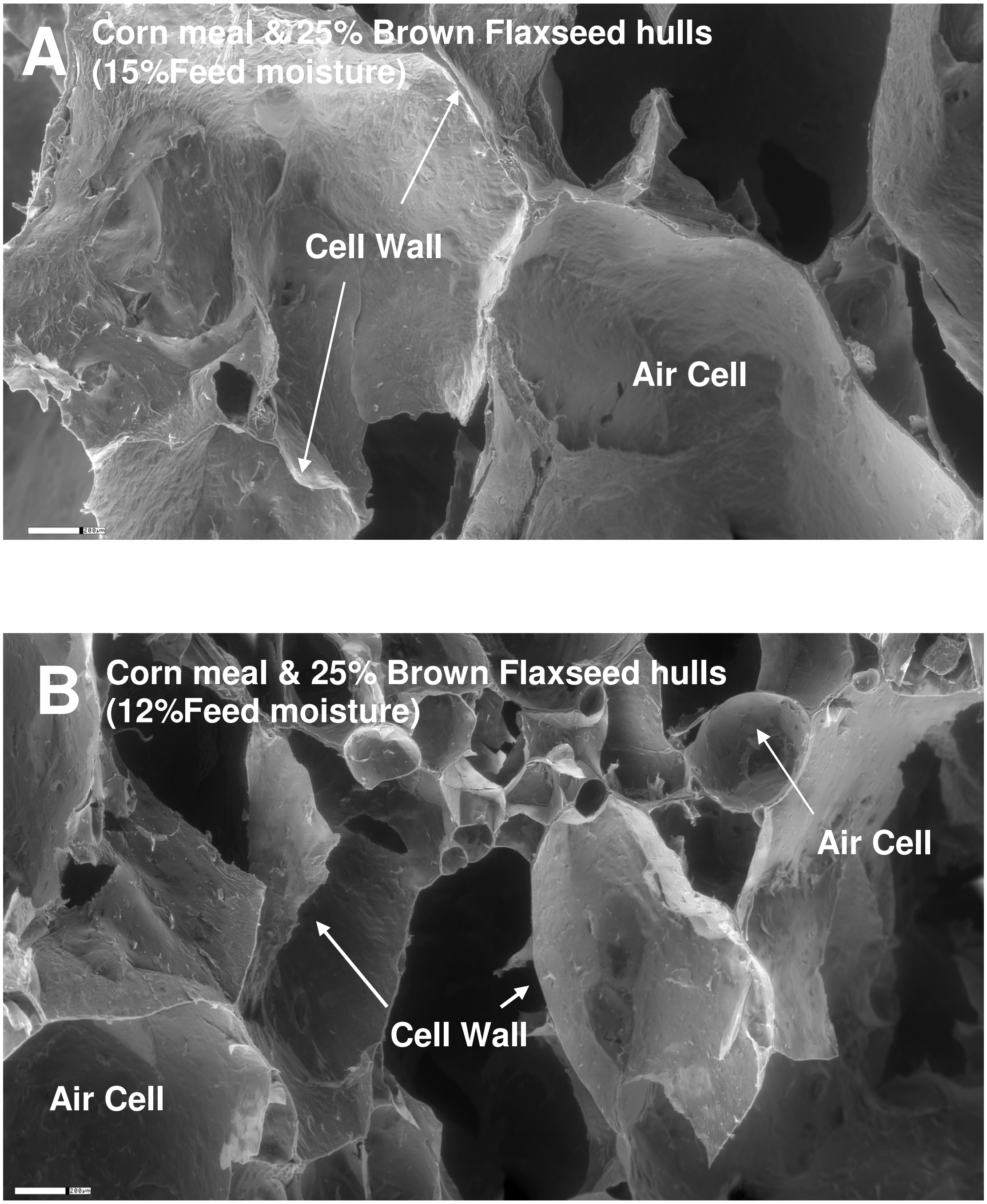


Fig. 14. Environmental Scanning Electron Microscope images of extrudates containing brown flaxseed hulls. **A)** 25% Brown flaxseed hulls (15% feed moisture); **B).** 25% Brown flaxseed hulls (12% feed moisture)

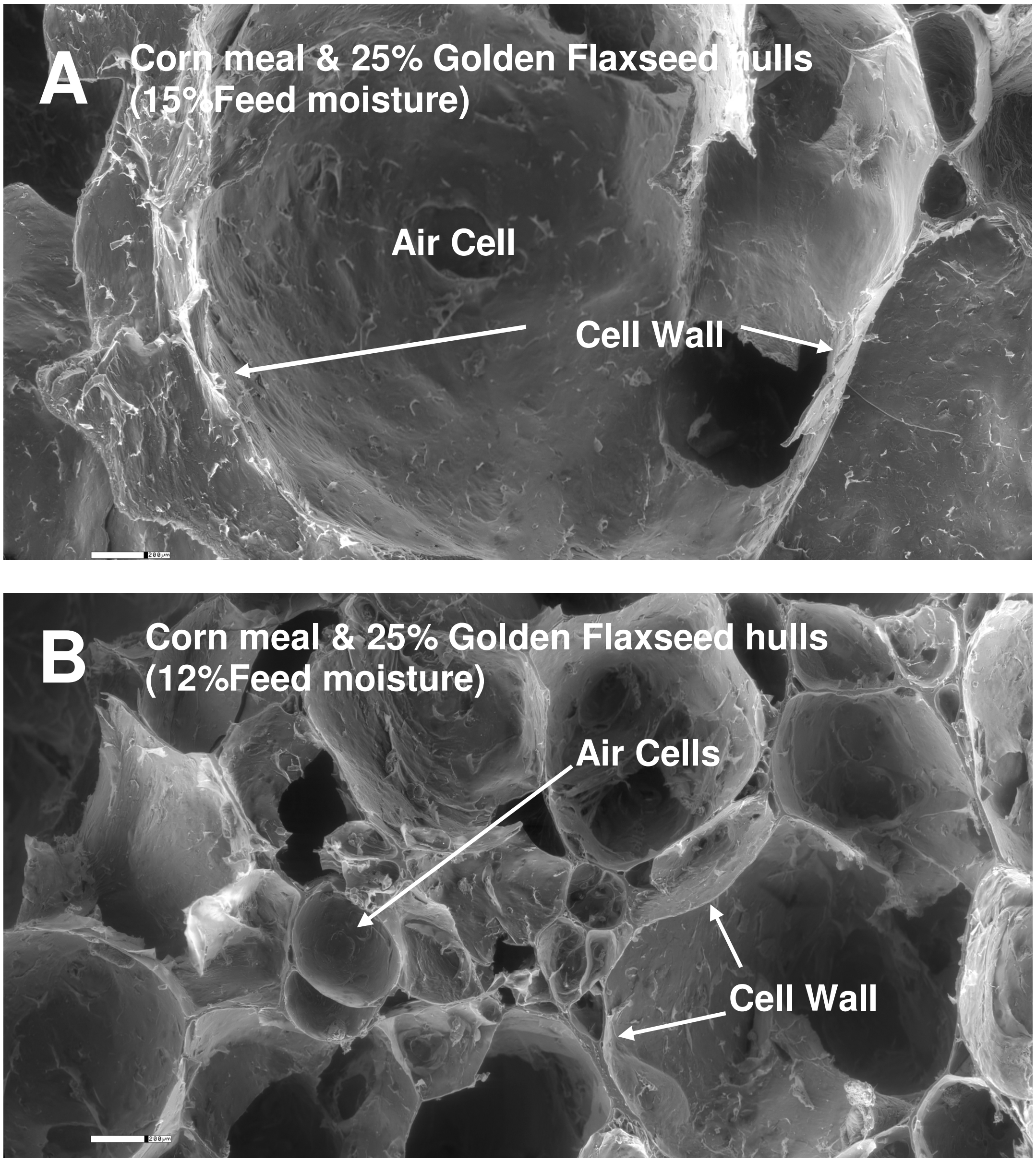


Fig.15. Environmental Scanning Electron Microscope images of extrudates containing Golden flaxseed hulls. **A)** 25% Golden flaxseed hulls (15% feed moisture); **B).** 25% Golden flaxseed hulls (12% feed moisture)

Informal Subjective Taste and Texture Evaluation

Subjective Taste Evaluation

Extrudates were dried to < 3% moisture before being subjectively evaluated for taste and texture. The control corn meal extrudates (at both feed moistures) had a distinct corn flavor, however extrudates with added flaxseed hulls, even at the lowest addition percentage, did not have a noticeable corn flavor. There was a noticeable difference in taste between extrudates with added brown or golden flaxseed hulls.

Extrudates containing brown flaxseed hulls possessed a cardboard like flavor. The cardboard flavor became more pronounced as the percentage of brown hulls as increased from 15 to 25% at both 12 and 15% feed moistures. The cardboard like flavor was stronger in extrudates processed at 15% feed moisture compared to 12% indicating that the feed moistures used during processing may play a part in the intensity of the flavor. It may be concluded that at 12% feed moisture more shear and friction caused the breakdown of large fiber pieces thus reducing the intensity of the cardboard like flavor compared to extrudates processed at 15% feed moisture. Cardboard like flavor is commonly correlated with oxidative rancidity; however in this case it is more likely due to the fiber contained in the extrudates which increased as the amount of brown flax hulls was increased in each blend.

Extrudates with added golden flaxseed hulls did not give a cardboard like flavor. However similar to brown hull extrudates feed moisture during processing and percentage of added golden flaxseed hulls influenced flavor. Extrudates processed at 12% feed moisture had a bland flavor, but as the percentage of golden flaxseed hulls increased a very slight nutty flavor was evident. At 15% feed moisture all the extrudates gave a nutty flavor that was more noticeable at 25% than 15% added golden flaxseed hulls. Whole golden flaxseed has nutty flavor and is commonly added to products such as breads to give this type of flavor. As previously mentioned the golden hulls used in this experiment where contaminated with pieces of cotyledons. The high percentage of cotyledons in the golden hull fractions was most likely the cause of the nutty flavor in the extrudates. A pure golden flaxseed hull fraction free of cotyledons may not produce a nutty flavor in the extrudates.

Subjective Texture Evaluation

All extrudates with added brown or golden flaxseed had acceptable textures. The feed moisture at which the extrudates were processed (12% or 15%) was the biggest contributor to textural differences. Brown or golden flaxseed hull extrudates extruded at 12% feed moisture had a soft texture, and packed in the teeth during chewing. As the percentage of hulls increased from 15 to 25% for both types of hulls there was no noticeable difference in the texture of the extrudates processed at 12% feed moisture.

Extruding at the 15% feed moisture produced extrudates with a crunchy texture and produced significantly less packing around the teeth during chewing compared to extrudates processed at 12% feed moisture. Brown flaxseed hull extrudates had an initial crunch in the first bite however following bites there was a decrease in the crunchy texture. The increase in brown hulls to 25% had no effect on the crunchiness of the texture.

Golden hull extrudates processed at 15% feed moisture had a hard crunchy texture that was still evident after the initial bite. The golden flaxseed hull extrudates did become harder to the bite as the percentage of hull increased. As the percentage of golden flaxseed hulls increased extrudates became dense and compact due to piece of the cotyledons disrupting the cell structure of the extrudates making them harder and crunchier. Also noticed in the golden flaxseed hull extrudates processed at 15% feed moisture was a slimy mouth feel that became more noticeable as the golden hulls increased. The slimy mouth feel was similar to that found in okra. Mucilage is probably contributing the slimy mouth feel found in the extrudates.

Antioxidant Activity of Extrudates

Extrudates with added brown flaxseed hulls were evaluated for antioxidant activity and phenols. Extrudates containing 15 and 20% brown flaxseed hulls were significantly higher in antioxidant activity and phenols than the corn meal extrudates. This was expected since lignans are concentrated in flaxseed hulls and have antioxidant activity (Prasad, 1997). Increasing the level of brown flaxseed hulls caused increased phenol levels and antioxidant activity (Fig. 17 & 18). A high correlation (r^2=1.0) (Fig. 18) was obtained for phenols and antioxidant activity. Extrudates containing golden flaxseed hulls were not tested due to the low initial phenols and antioxidant activity in the golden flaxseed hulls.

Extrudates containing 20% brown flaxseed hull with feed moistures 12 and 15% were evaluated. The extrudates at 12% feed moisture were higher in total phenols and antioxidant activity then extrudates at 15% feed moisture (Fig. 13 & 14). The lower feed moisture may have reduced the chemical interactions of phenolic compounds with other components such as starch and proteins. The extrudates at 12% feed moisture had higher total phenols and antioxidant activity which might have been caused by the extrusion which freed phenolic acids bound in the cell walls. The increased shear and mechanical energy due to the decrease in feed moisture may have released bound phenols. Adom and Liu (2002) found that corn had higher level of phenolic compounds than wheat, oats, and rice; 85% of the phenolics in corn existed in the bound form.

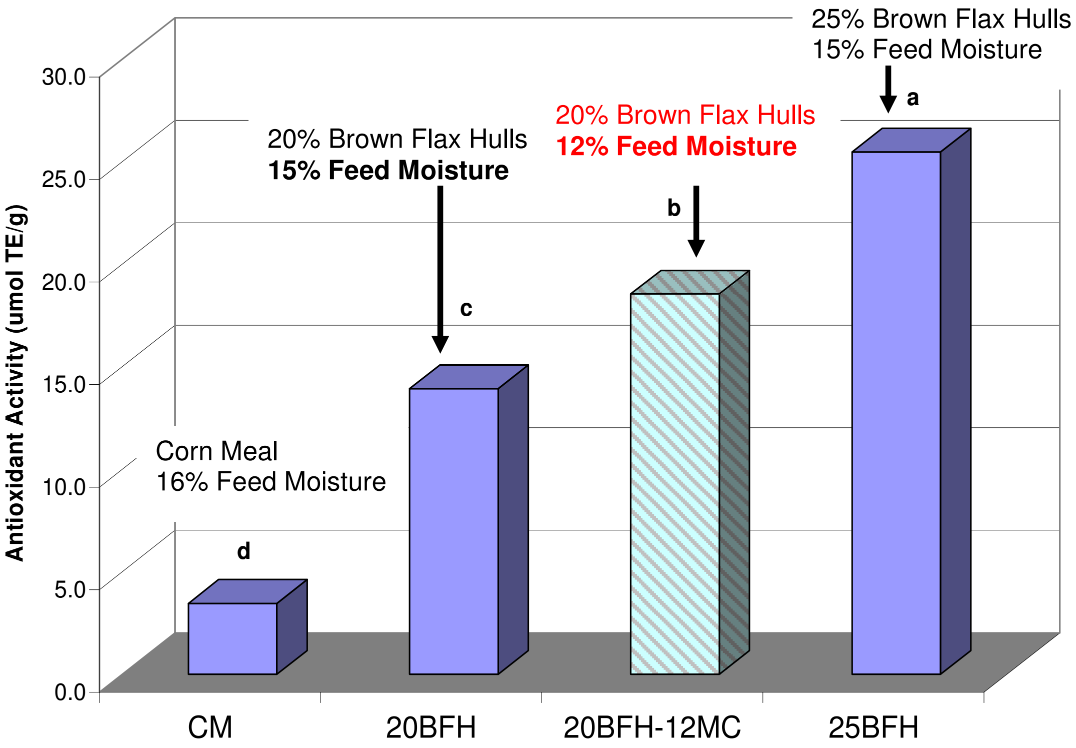


Fig. 16. ABTS antioxidant activity (µmol TE/g) of extrudates containing brown flaxseed hulls. **TE=** Trolox equivalents.

[a]Values with same letter are not significantly different ($p< 0.05$)

CM= Corn meal (16% feed moisture), **20BFH=** extrudates with 20% brown flaxseed hulls (15% feed moisture), **20BFH-12MC=** extrudates with 20% brown flaxseed hulls extruded with 12% feed moisture, **25BFH=** extrudates with 25% brown flaxseed hulls (15% feed moisture)

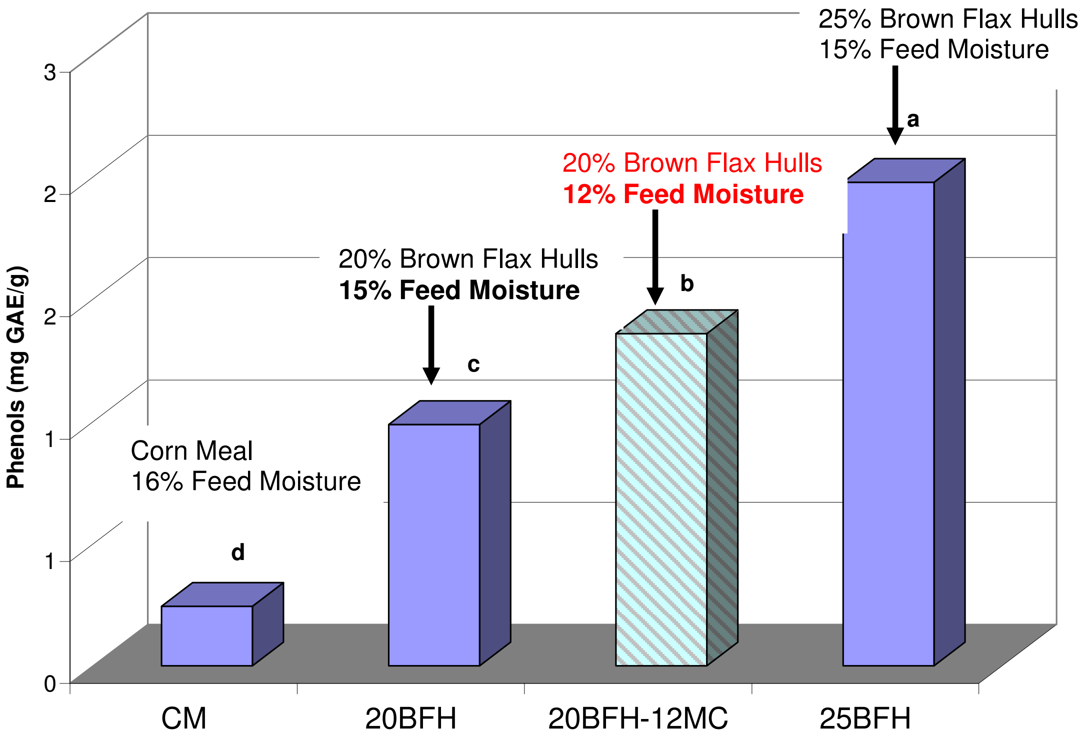


Fig. 17. Total Phenol level (mg GAE/g) of extrudates containing brown flaxseed hulls. **GAE=** Gallic acid equivalents.

^{a}Values with same letter are not significantly different ($p < 0.05$)

CM= Corn meal (16% feed moisture), **20BFH=** extrudates with 20% brown flaxseed hulls (15% feed moisture), **20BFH-12MC=** extrudates with 20% brown flaxseed hulls extruded with 12% feed moisture, **25BFH=** extrudates with 25% brown flaxseed hulls (15% feed moisture)

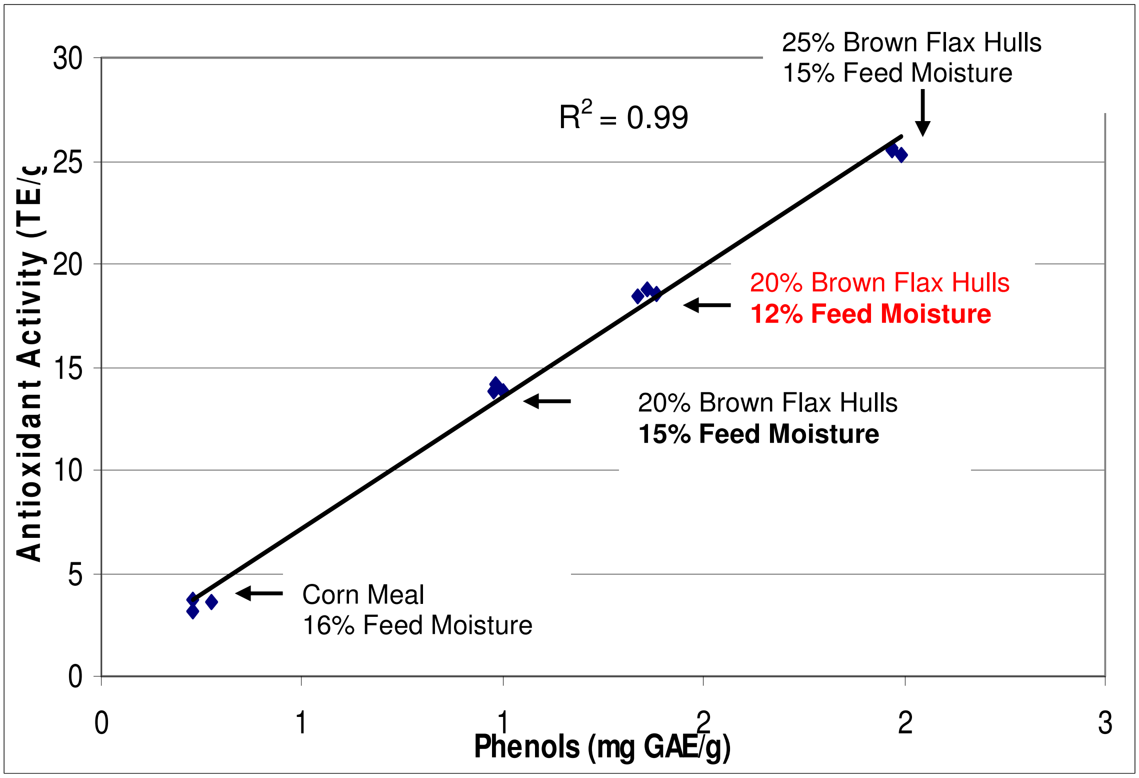


Fig. 18. Correlation between ABTS antioxidant activity and total phenols in extrudates containing brown flaxseed hulls. **TE=** Trolox equivalents. **GAE=** Gallic acid equivalents

Summary

Using a twin screw extruder hulls from brown and golden flaxseed were mixed at percentages of 15 to 25% with de-germed corn meal and extruded to produce expanded snacks with varying composition and properties. The composition of the flaxseed hulls and feed moistures used during extrusion were the major contributors to the composition and property differences. The brown flaxseed hulls used were dark brown with high levels of antioxidant activity and were relatively free of contamination of oil containing pieces of cotyledons. In contrast the golden flaxseeds had a very light color but were contaminated with a significant amount of cotyledon pieces that affected extrudates properties significantly.

Extrudates containing brown flaxseed hulls were dark brown in color and though the hulls were high in dietary fiber they had little negative impact on extrudate expansion. Mucilage, a water-soluble hydrocolloid found in flaxseed, had a positive effect on expansion. Extrudates with 15% brown hulls had expansion and bulk density properties similar to that of the corn meal control. Although as the percentage of browns hulls increased expansion decreased, however the decrease did not affect texture negatively.

The addition of brown flaxseed had positive effect on the nutritional benefits of extrudates. A 50 g serving size of extrudates with 25% brown flaxseed hulls provides 7.2g of dietary fiber and 0.9 g of alpha linolenic acid. This serving size would provide 19% of Dietary reference intakes (DRI) for dietary fiber for men and 29% of DRI for women. In addition to dietary fiber, the extrudates would provide 56.3% of DRI for alpha linolenic acid for men and 81% of DRI for women. A negative to the use of hulls at percentages greater than 15% is extrudates may have a cardboard like flavor due to the fiber content, and will be more acceptable to rancidity due to the amount of alpha linolenic acids.

Golden flaxseed hulls produced extrudates with a lighter color which may be desirable in some applications, but the contamination by cotyledons affected the extrusion properties negatively plus the hulls were low in dietary fiber, antioxidant levels and tannin content. Thus, the health benefits of the golden flaxseed are significantly less than those of brown flaxseed hulls.

Hulls from flaxseed display promise for use in expanded product if the cotyledons are efficiently removed to decrease oil content which have a negative impact on expansion. Flaxseed hulls add nutrition benefits such as dietary fiber, antioxidants, and alpha linolenic acids with out greatly affecting extrudate quality. We need to determine the stability of expanded products containing alpha linolenic acids.

CHAPTER IV

EXTRUSION OF TANNIN SORGHUM WITH BROWN FLAXSEED HULLS

Justification

Brown flax seed hulls contain unsaturated lipids that are subject to oxidation in extruded food or feeds. Although brown flaxseed hulls possess a high concentration of lignans (secoisolariciresinol diglycoside) (Oomah et al. 1998), which have high antioxidant activity extrusion processing can decrease these endogenous antioxidants (Wu, 2004). To delay the oxidation of lipids in a direct expanded extruded product it may be beneficial to incorporate a phenolic rich cereal grain as a natural source of antioxidants.

Extrusion of white food grade and tannin sorghums has produced extrudates with acceptable characteristics (Acosta, 2003; Perez, 2005; Turner, 2004). Awika (2003) found the antioxidant activity of brans from tannin sorghums exceed that of blueberries, strawberries, and red wine on a dry basis. Awika (2003) reported high tannin sorghum extrudates retained 21% of their original assayable tannin content, and 89% of their original antioxidant activity. Thus extrusion of brown flaxseed hulls in combination with tannin sorghum may produce an acceptable extrudate with increased nutritional benefits and antioxidant activity delaying lipid oxidation. Therefore the objective of this experiment was to produce tannin sorghum and brown flaxseed hull extrudates to determine antioxidant activity and lipid oxidation.

Materials and Methods

Raw Materials

Ingredients used were brown flaxseed hulls (Fortigrad™, Pizzey's Milling, Angusville, MS, Canada, 2005), yellow corn snack meal (Cargill), white sorghum (ATX 631 x RTX 436, College Station, 2001) and tannin sorghum (Sumac variety, West Texas, 2004).

Sorghum Characterization

Test weight was determined with a Winchester Bushel Meter. Density was determined using a gas comparison pycnometer (Multipycnometer, Quantachrome, Syosset, NY). Thousand kernel weight (TKW) was determined by weighing 100 kernels and multiplying by ten. Hardness was evaluated with a tangential abrasive dehulling device (TADD) with 20 g sample and 3.5 min abrasion time. A single kernel hardness test (SKHT, model SKCS 4100, Perten Instruments, Reno, NV) was also utilized to determine hardness. Grain color was determined with a colorimeter (model CR-310, Minolta Co., LTD Ramsey, NJ) using CIE L*a*b* color scale. The Clorox bleach test was used to determine the presence of a pigmented testa.

Proximate Analysis of Raw Materials and Extrudates

Moisture content of raw materials and extrudates was determined using air oven AACC method 44-19 (AACC 2000). Samples were dried in a forced air draft oven for 2 hr at 135^{o}C. Moisture was determined by weight lost.

Crude fat of raw materials was determined using AACC method 30-26 (AACC 2000). Oil was extracted using petroleum ether with a butt type apparatus for 5 hr.

Preparation of Brown Flaxseed Hull and Sorghum Blends

White sorghum (ATX 631 x RTX 436, College Station, 2001) and tannin sorghum (Sumac variety West Texas, 2004) were ground using a Fitzmill (Fitzpatrick Co., Elmhurst, IL) first through a 3 mm screen, then through a 1 mm screen. Brown flaxseed hulls (Fortigrad™, Pizzey's Milling, Angusville, MS, Canada, 2005) were added at 20% to the ground sorghum and yellow corn meal. Ground white and tannin sorghums, along with corn meal were extruded without added brown flaxseed hulls; yellow corn meal was used as the control (Fig.19).

Extrusion Processing

Blends were extruded using a Wenger TX-52 twin screw extruder, with 6 zones, and a length/diameter ratio of 16.5/1. The screw configuration was typical for expanded snacks and was supplied by Wenger Manufacturing (Sabetha, KS., USA). A 2 to 1 back flow plate was placed prior to the die plate. A three hole die, with 4 mm (0.16 in.) openings and 2 cutting blades was used. Extrudates were cut at a fixed speed.

Blends were fed into the extruder inlet using an Accurate Feeder at a feed rate of 72 kg/hr. Screw speed was set at 325 rpm, and temperatures for zones 4, 5, and 6 were set at 80, 90, and 110°C for all blends. Water was injected directly into the extruder barrel at 0.062 kg/min. Independent variables such as feed rate, screw speed and zone temperatures were kept constant, however changes in dependent variables such as motor load (%) and head pressure (psi) were recorded.

After extrusion the extrudates were dried at 100°C for 15 min. and then cooled in a Wenger One Pass Dryer. Dried samples (2-3% moisture) were placed in a plastic bag until they were analyzed.

Analysis of Extrudates

The methods of analysis were the same as those described in chapter III.

Storage Stability of Sorghum-Flax Hull Extrudates

After drying the extrudates (sorghum and corn meal with 20% brown flaxseed hulls) were placed in 1 L glass jars with lids. The glass jars were then placed in an oven (Reed Oven Co.) at 54°C. Jars for each sample were taken out of the oven at 12 hr. intervals and smelled for rancidity odor (Schall Oven Test) then bagged and placed in a freezer until ready for oil extraction. This process was repeated every 12 hr until the 96 hr. passed.

Lipid Extraction from Sorghum-Flax Hull Extrudates

The removal of lipids from extrudates for analysis was performed at room temperature to prevent any thermal degradation. Approximately 175-200 g. of extrudates were ground and placed in a 500 ml beaker and mixed at a 1:3 ratio of hexane for an hour. The mixture was stirred every 30 min. to prevent clumping. After an hour the mixture was passed through a filter flask vacuum filter using Whatman #1 paper. The process was done in triplicate (3 hrs.) for each sample to insure the maximum lipid extraction. The hexane solvent was removed using a roto-evaporator at 40°C. The flask was flushed with nitrogen to remove air during the evaporation process (Camire and Dougherty, 1998). The oil samples were stored at 4°C until needed for analysis.

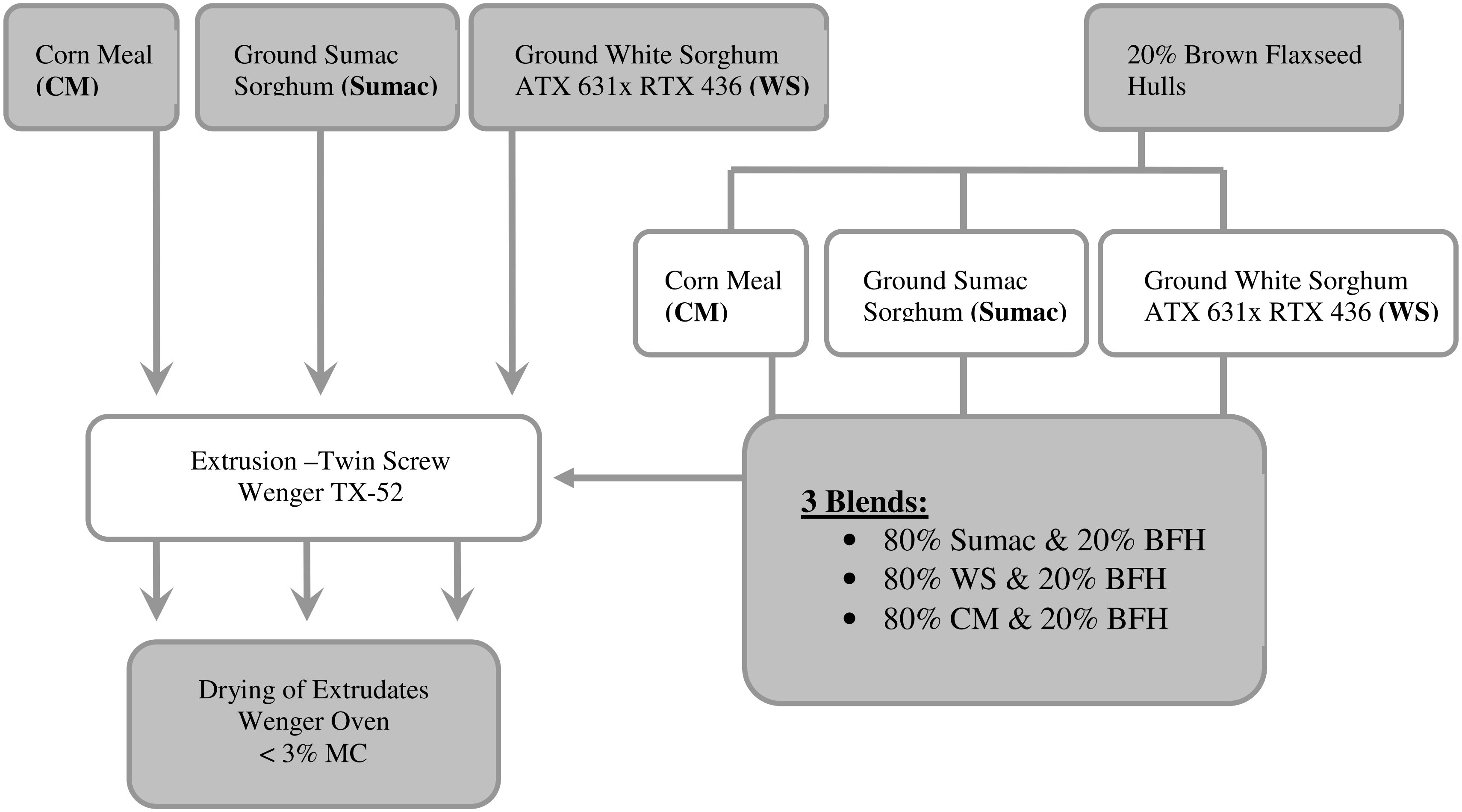


Fig. 19. Flow chart of preparation and extrusion processing of flaxseed hull-sorghum and hull-corn meal blend.

Analysis for Lipid Oxidation

Extracted oil samples from the dried sorghum-flax hull and corn meal-flax hull extrudates were analyzed for oxidation. Secondary changes, generally due to odor activation were completed by determining the p-Anisidine Value (AOCS, 1998).

Statistical Analysis

Analysis of variance (ANOVA) was performed using SPSS v11.5 for Windows (SPSS Inc.). Differences were analyzed with Duncan's test. A confidence level of 95% was used.

Results and Discussion

Approach or Rationale

To determine if sorghum tannins delay the oxidation of flaxseed hull lipids in an extruded product, two sorghums were chosen that were similar in composition; one contained tannins and the other was tannin free (Table XIII).

Sorghum Characterization

The sumac tannin sorghum had smaller kernels and contained a softer floury endosperm compared to the white sorghum (ATX 631x RTX 436). This is evident by the low yield obtained by TADD dehulling and low hardness index from the SKHT (Table XIII) for sumac. White sorghum (ATX 631x RTX 436) had large kernels and contained more hard endosperm compared to sumac. The white sorghum was higher in starch but lower in protein than sumac. The Clorox bleach test was positive for tannins in the sumac sorghum. Sumac grain had lower L* values and higher a* (red hue) values than the white (ATX 631x RTX 436) sorghum.

Particle Size Distribution of Raw Materials

The whole ground sorghums had similar amounts of particles smaller than 250µm (thru #60 sieve) (Table XIV). The ground sumac (tannin) sorghum had larger particles (600µm and 425µm) retained on #30 and 40 sieves. Sumac had thick pericarp and floury endosperm (Perez, 2005) compared to the white sorghum (ATX 631x RTX 436).

Table XIII
Physical characteristics of the White and Tannin sorghums

	ATX 631x RTX 436 White sorghum	Sumac sorghum
Protein (% d.b.)	8.4	11.5
Starch (% d.b.)	76.7	69.8
TADD, % decorticated grain yield	86.0	79.3
Hardness index (SKHT)	84.5	64.3
Average kernel diameter (mm)	2.5	1.8
Thousand kernel weight (g)	30.7	15.6
Density (g/cm^3)	1.38	1.30
Test weight (lb/bu)	62.5	60.8
Color		
L	61.9	36.9
a	3.5	9.3
b	19.3	8.3
Clorox bleach test	Negative (tannin free)	Positive
Tannins (mg CE/g dry matter)*	-	13.7
Phenols (mg GAE/g d.m.)*	-	19.6
Anthocyanins (mg LE/g d.m.)*	-	2.9

*From Awika (2003).

Table XIV

Particle size distribution (%) of corn meal, whole ground sorghums and blends[a]

	Sieve US#20 (850µm)	Sieve US#30 (600µm)	Sieve US#40 (425µm)	Sieve US#60 (250µm)	Sieve US#80 (180µm)	Sieve US#100 (150µm)	Bottom Pan (<150µm)
Raw materials							
Brown flaxseed hulls	79.6 a	10.4 c	4.0 e	3.5 e	2.0 d	0.4 d	0.3 d
[b]CM (Control)	0.0 d	45.9 a	52.7 a	1.1 f	0.3 e	0.0 d	0.1 d
Ground (whole) Tannin sorghum	0.0 d	7.2 d	12.4 c	28.9 c	17.5 c	8.3 b	25.8 a
Ground (whole) White sorghum	0.0 d	0.5 f	10.7 d	38.7 a	17.1 c	8.4 b	24.9 a
Blends							
80% CM + 20% BFH	15.4 c	39.0 b	43.1 b	1.7 f	0.7 e	0.1 d	0.0 d
Ground (whole) Tannin sorghum + 20% BFH	18.4 b	7.9 d	11.8 d	25.8 a	18.9 b	9.2 a	8.0 b
Ground (whole) White sorghum + 20% BFH	18.7 b	2.9 e	12.4 c	32.1 b	20.2 a	7.0 c	6.6 c

[a] Values followed by the same letter within a column are not significantly different ($p< 0.05$)
[b] CM = De-germed corn meal; [c] BFH = Brown flaxseed hulls
Values are the percent overs of each sieve

Whole Ground ATX631xRTX436

Whole Ground Sumac (Tannin)

Corn Meal

Whole Ground ATX631xRTX436 with 20% Brown Flaxseed Hulls

Whole Ground Sumac (Tannin) with 20% Brown Flaxseed Hulls

Corn Meal with 20% Brown Flaxseed Hulls

Fig. 20. Extrudates A)White sorghum extrudates B) Sumac (tannin) sorghum extrudates, C) corm meal extrudates D) White sorghum extrudates with 20% brown flax hulls E) Sumac (tannin)extrudates with 20% brown flax hulls, F) Corn meal extrudates with 20% brown flax hulls

Extrudate Appearance

Whole ground sorghums with and with out added brown flaxseed hulls produce extrudates with acceptable appearance (Fig. 20 A, B, D, & E). Both the white and tannin whole ground sorghum extrudates with 20% added brown flaxseed hulls were (Fig. 20D, E) visibly larger and have a distinct form. Typically the addition of fiber negatively impacts extrudate quality, which was not true for these extrudates (Mendonca et al., 2000; Jin et al. 1994). Extrudates containing 20% brown flaxseed hulls were darker and had lower L* values in both sorghum and corn meal extrudates (Table XV). Sumac (tannin) sorghum extrudates had the highest a* values (red hue).

Table XV

Color of sorghum extrudates[a]

% Feed Moisture	Extrudates	L*	Color a*	b*
16	[b]CM (Control)	83.4 a	-0.5 e	39.8 a
15	20% Brown FH + 80% [b]CM	61.4 c	4.2 d	18.1 b
18	Sumac (Tannin)	48.6 e	10.1 a	10.4 e
17	Sumac (Tannin) +20% Brown FH	46.7 f	8.6 b	9.8 f
18	ATX631xRTX436 (white)	65.3 b	4.9 c	17.0 c
17	ATX631xRTX436 + 20%BFH (white)	57.4 d	4.8 c	14.2 d

[a] Values followed by the same letter within a column are not significantly different ($p < 0.05$)
[b] CM = Corn meal; [c] FH = flaxseed hulls;
L* indicates lightness, a* indicates hue on a green (-) to red (+) axis, and b* indicates hue on a blue (-) to yellow (+) axis

Extrusion Processing

There was an increase in SME for both sorghum extrudates when brown flaxseed hulls were added (Table XVI). The opposite was seen in the corn meal with added brown flax hulls where a decrease in SME was observed. An increase in motor load (%) and head pressure was also observed during the processing of the whole ground sorghum with added flaxseed hulls. This would be the opposite of what would be expected due to the soluble fiber contained in the hull. Lue et al (1991) reported an increase in head pressure when extruding corn meal with 0.1% CMC (Sodium carboxymethylcellulose) and attributed it to a higher melt viscosity.

Table XVI

Twin screw extrusion processing parameters for sorghum extrudates containing 20% brown flaxseed hulls

Extrudates	[a]FM	Motor Load (%)	Head Pressure (psi)	SME kJ/kg
Corn Meal (Control)	16	52	1100	443.7
20% [b]BFH + 80 %CM	15	49	950	316.9
Sorghum extrudates				
ATX631xRTX436 (white)	18	29	500	262.6
ATX631xRTX436 + 20%BFH (white)	18	30	600	271.6
Sumac (tannin)	18	27	400	244.5
Sumac (tannin) + 20% BFH	18	29	500	258.1

[a] FM: Feed Moisture Content, [b] BFH: Brown Flax Hulls

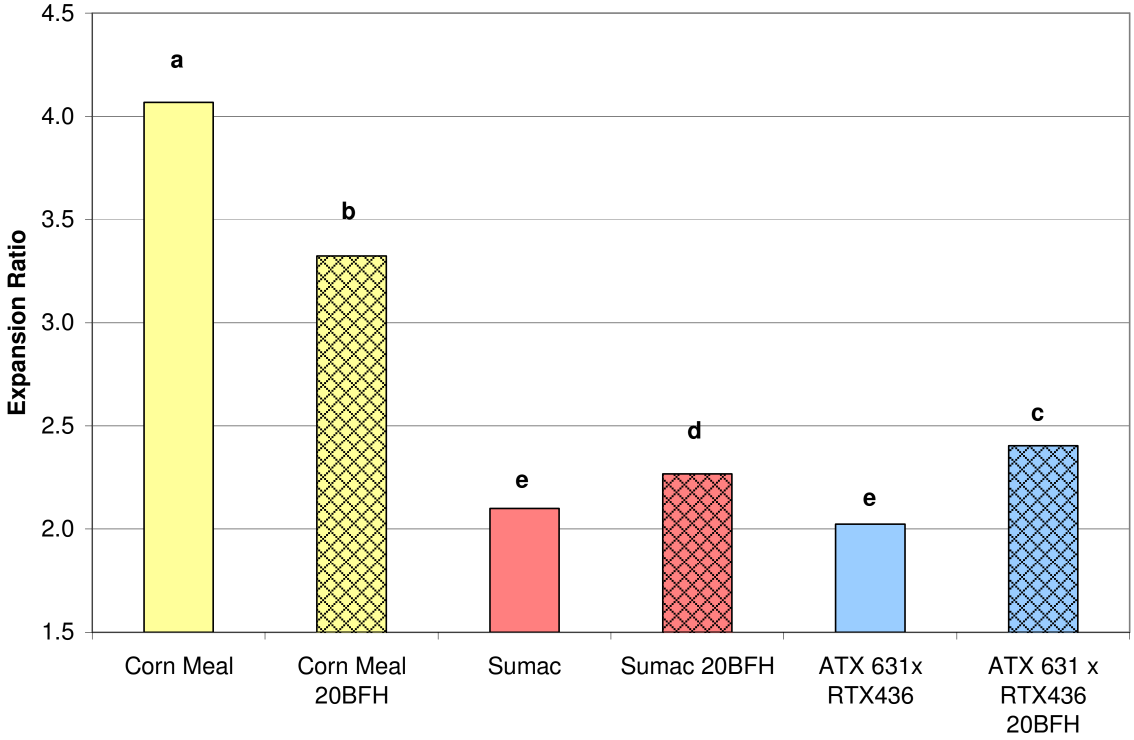


Fig. 21. Expansion ratio of white (ATX631xRTX436), Sumac (tannin), and corn meal extrudates with and without 20% brown flaxseed hulls.

[a]Values with same letter are not significantly different ($p < 0.05$)

20BFH= 20% added brown flaxseed hulls

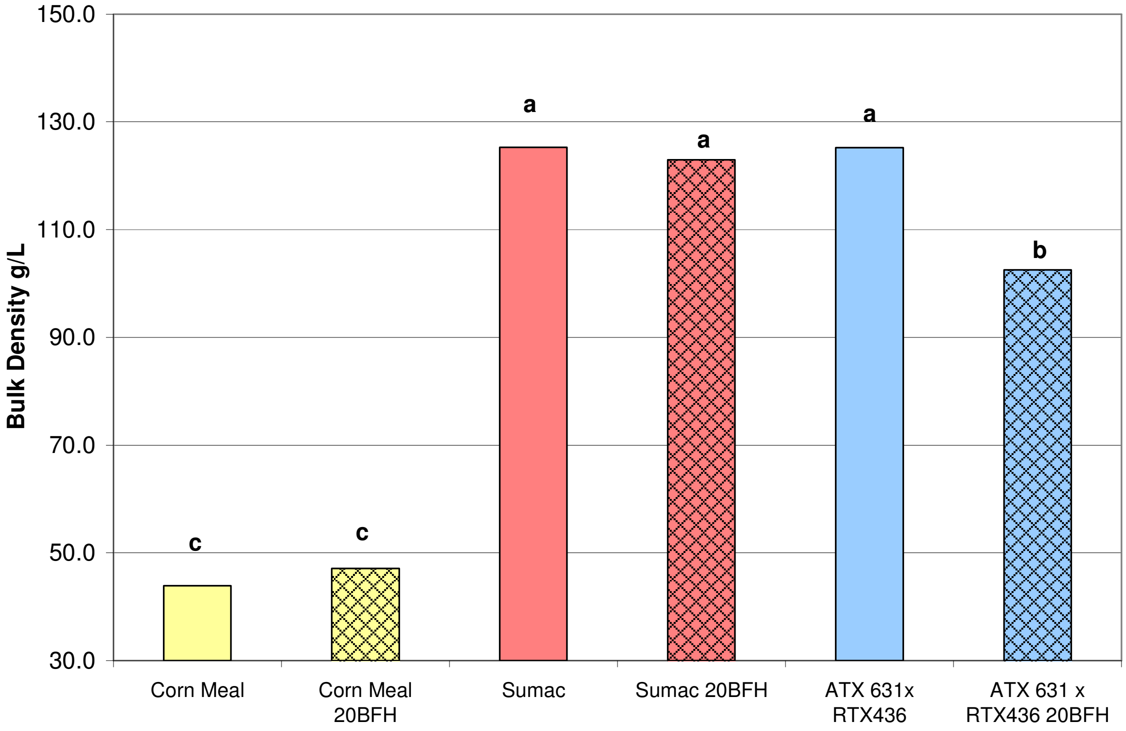


Fig. 22. Bulk density (g/L) of white (ATX631xRTX436), Sumac (tannin), and corn meal extrudates with and without 20% brown flaxseed hulls.

[a]Values with same letter are not significantly different ($p < 0.05$)
20BFH= 20% added brown flaxseed hull

Expansion Ratio and Bulk Density

Extrudates produced from corn meal and corn meal with 20% brown flaxseed hulls had the highest expansion ratio due to its high starch content and low fiber and protein contents compared to the whole ground sorghums (Fig. 21). Addition of 20% brown flaxseed hulls to the whole ground (sumac) tannin sorghum and white sorghums significantly increased expansion ratio compared to sorghum extrudates with out added flaxseed hulls (Fig. 21). The mucilage, a water soluble hydrocolloid, contained in the brown flaxseed hulls had an emulsifying effect during extrusion of the ground sorghum. Mucilage, a water soluble hydrocolloid found in the flaxseed hulls, counters the negative effect of the sorghum bran particles by preventing them from disrupting air cell formation, thus reducing expansion.

There was no significant difference in bulk density between the corn meal and corn meal with 20% added brown flaxseed hulls (Fig. 22). There was a significant decrease in bulk density in the (ATX 631x RTX 436) sorghum extrudates containing 20% brown flaxseed hulls. This was expected since there was an increase in expansion in the white sorghum extrudates when 20% brown flaxseed hulls were added. There was no significant difference for sumac extrudates containing 20% brown flaxseed hulls.

Texture

The corn meal extrudates were the softest with the lowest shear force (N) (Fig. 23). The addition of 20% flaxseed hull to corn meal increased the shear force. There was no significant difference in shear force for sumac (tannin) and white extrudates with out added brown flaxseed hulls. Although the addition of brown flaxseed hulls increased expansion it was not enough to produce a soft extrudate.

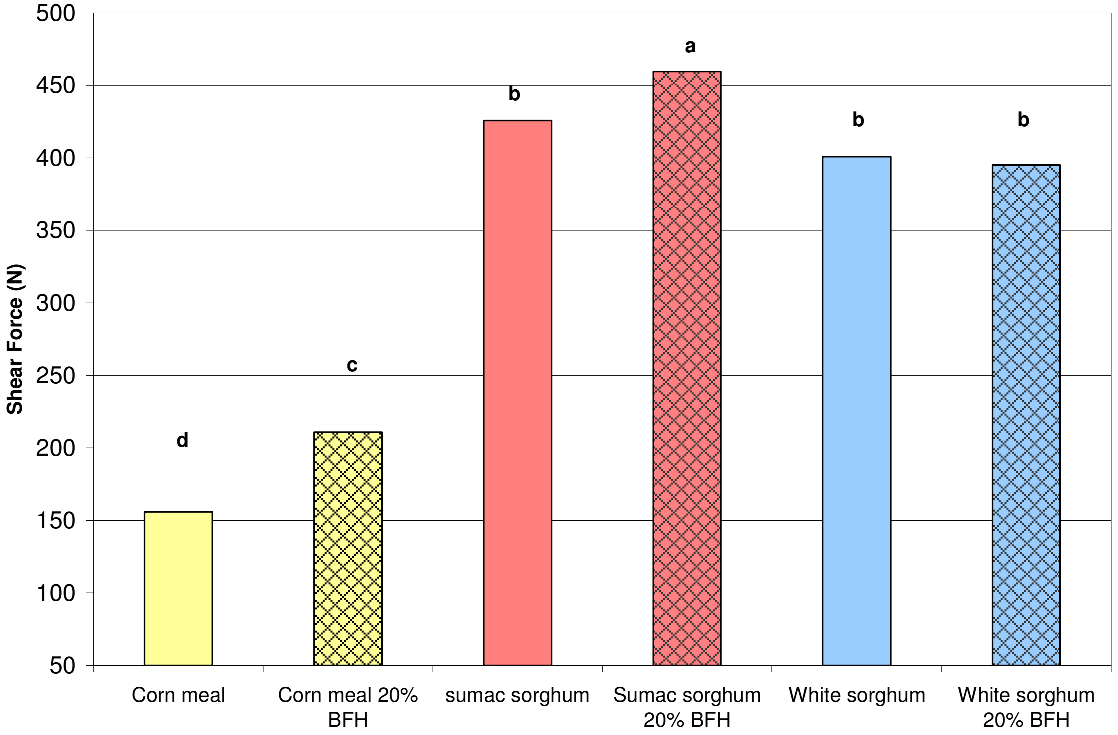


Fig. 23. Shear force (N) of white (ATX631xRTX436), Sumac (tannin), and corm meal extrudates with 20% brown flaxseed hulls and without brown flaxseed hulls.

[a]Values with same letter are not significantly different ($p< 0.05$)
20BFH= 20% added brown flaxseed hulls

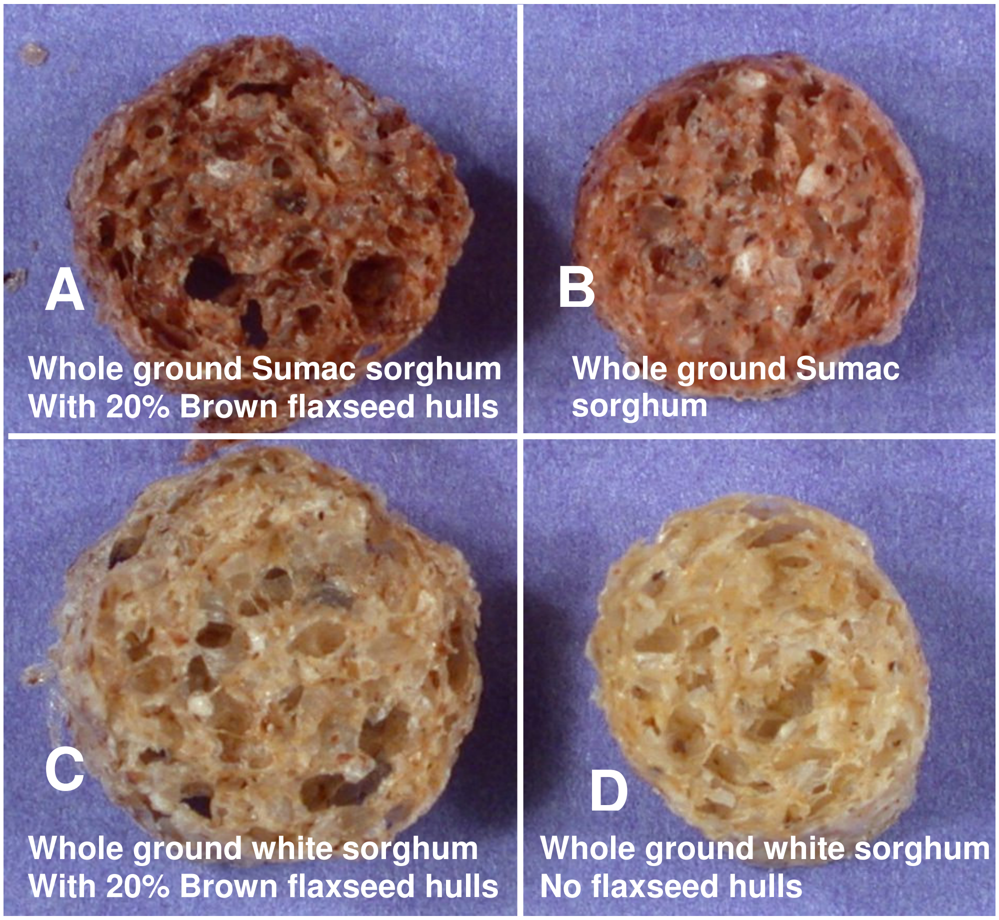


Fig. 24. Cross section of whole ground sorghum extrudates with and without 20% brown flaxseed hull A) whole ground sumac (tannin) with 20% brown flaxseed hulls, B) whole ground sumac (tannin) C) whole ground white (ATX631xRTX436) with 20% brown flaxseed hulls, D) whole ground white (ATX631xRTX436)

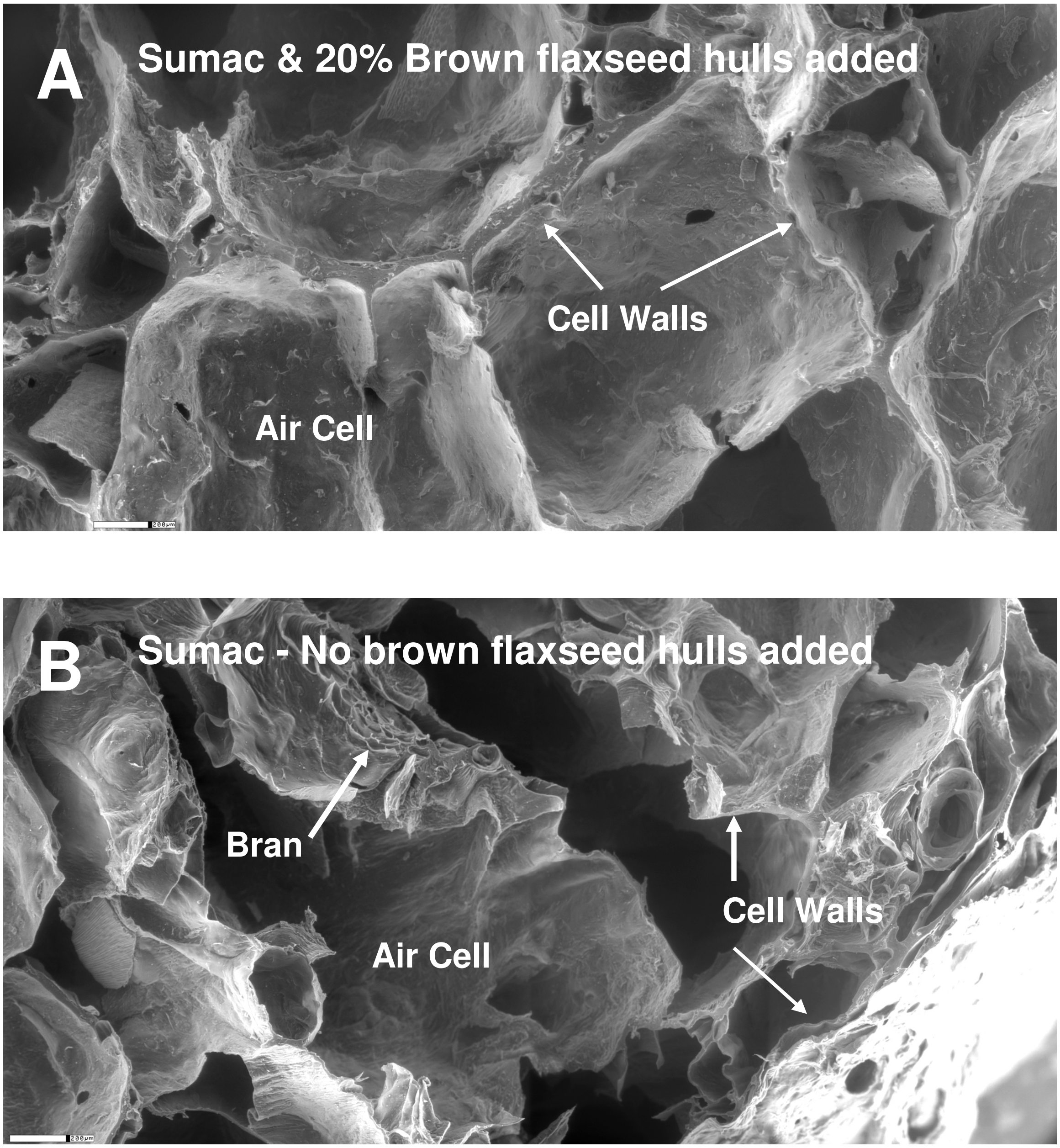


Fig. 25. Environmental Scanning Electron Microscope images of Sumac extruadates with and with out brown flaxseed hulls. A) Extrudate with 80% Sumac and 20% Brown flaxseed hulls; B).Extrudate of 100% Sumac

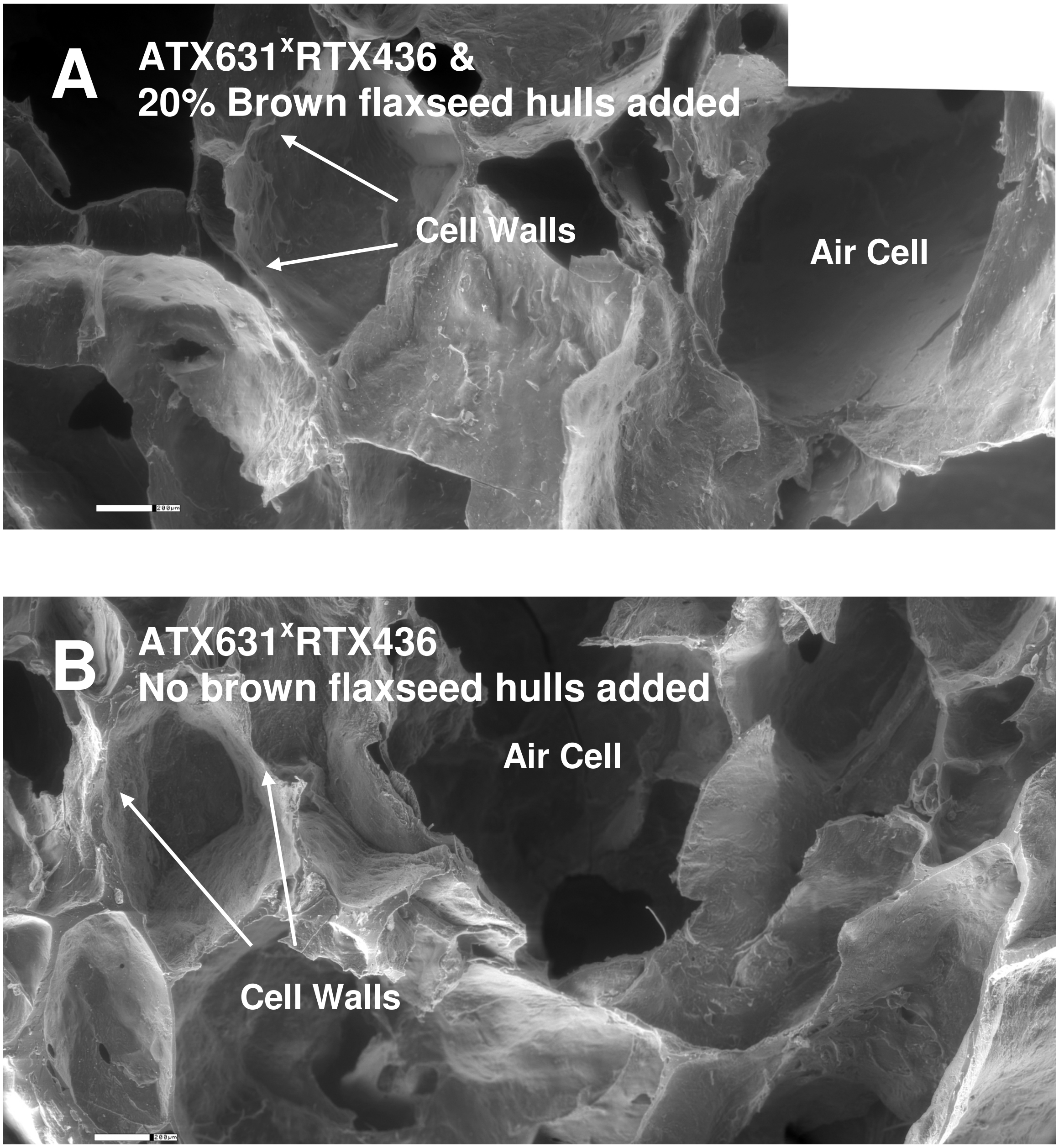


Fig. 26. Environmental Scanning Electron Microscope images of Sumac extruadates with and with out brown flaxseed hulls. A) Extrudate with 80% ATX631^{x}RTX436 and 20% Brown flaxseed hulls; B).Extrudate of 100% ATX631^{x}RTX436

Macrostructure

Viewing a cross section of the whole ground extrudates containing 20% brown flaxseed hulls larger air cells are visible compared to extrudates with no added hulls (Fig. 24). The whole ground white (ATX631xRTX436) extrudates containing 20% brown flaxseed had visibly higher expansion which could be due to higher starch content and fewer large pieces of sorghum bran.

Microstructure

Fig. 25B shows the environmental scanning electron microscope view of sumac extrudate without brown flaxseed hulls. It is dense with small air cell structure and pieces of bran in the cell walls. Fig. 25A shows extrudates with 20% brown flaxseed hulls added; there are larger air cells though the cell walls are still thick. The larger air cells in the tannin (sumac) extrudates with added brown flaxseed hulls back up the data on increased expansion ratio for sumac (tannin) extrudates.

Fig. 26B shows the environmental scanning electron microscope view of white (ATX 631x RTX 436) sorghum extrudates without brown flaxseed hulls. It has smaller air cell structures compared to sumac (tannin) extrudates. There was less bran visible in the cell structure. Fig. 26A shows white (ATX 631x RTX 436) sorghum extrudates with 20% brown flaxseed hulls where the air cells where larger and more dispersed than the extrudates with out added hulls (Fig. 26B).

Table XVII
Phenol levels (mg GAE/g), ABTS antioxidant activity (µmol TE/g), Tannins (mg CE/g) of defatted brown and golden flaxseed, and their hulls[a]. Values are means of 3 replicates

	Tannins mg [d]CE/g	Antioxidant Activity ABTS µmol [c]TE/g	Total Phenols mg [e]GAE/g
Corn Meal (Control)	0.0 d	3.5 f	0.2 f
20% [b]BFH + 80 %CM	0.1d	13.9 d	1.0 e
Sorghum extrudates			
Sumac (tannin)	5.8 b	134.0 b	7.41 b
Sumac (tannin) + 20% [b]BFH	6.6 a	138.7 a	8.4 a
ATX631xRTX436 (white)	0.2 c	10.8 e	1.1 d
ATX631xRTX436 + 20% [b]BFH (white)	0.2 c	22.2 c	2.4 c

[a]Values followed by the same letter within a column are not significantly different ($p< 0.05$)
[b]BFH= Brown flaxseed hulls, [c]TE = Trolox equivalent, [d]CE = Catechin equivalent, and [e]GAE = Gallic acid equivalent

Antioxidant Activity of Extrudates

The addition of 20% brown flaxseed hulls significantly increased antioxidant activity and total phenols in corn meal and both sorghum extrudates (Table XVII). As previously reported the sumac (tannin) sorghum extrudates had the highest content of tannins and total phenols (Awika, 2003) of all extrudates.

There was a significant increase in tannin content in sumac extrudates when 20% brown flaxseed hulls were added. The greatest increase in antioxidant activity with the addition of brown flaxseed hull was in the corn meal and white sorghum extrudates. Whole white sorghum extrudates contained a similar antioxidant activity as the corn meal extrudates with 20% added brown flaxseed.

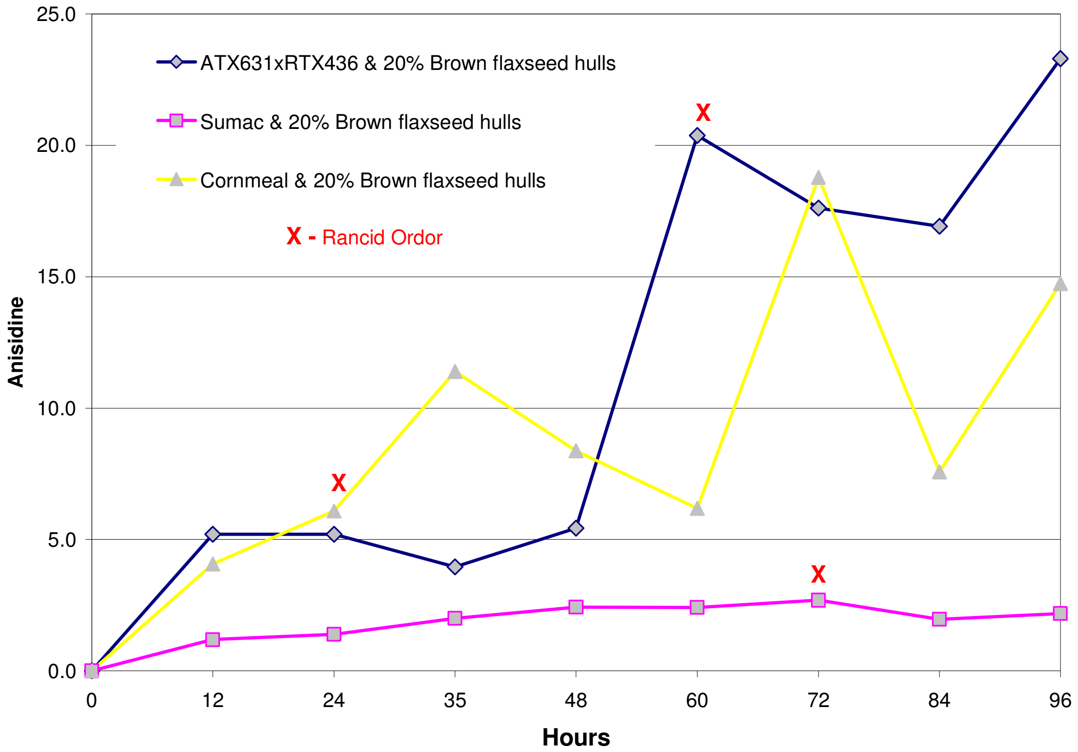


Fig. 27. The p-Anisidine value of extrudates containing 20% brown flaxseed hulls, X indicates when the samples became rancid by the Schall Oven test.

Lipid Oxidation Analysis of Extrudates

The p-Anisidine value measured the presence of secondary products of lipid oxidation, such as aldehydes. The low oil content of direct expanded products caused difficulty in conducting the test. The experimental variation was high. The trends indicated that there was possibly a delay in rancidity when the tannin sorghum was in the extrudate.

The Schall Oven Test was used to subjectively test for rancid odor and flavor which is an indicator of volatile secondary products. At 24 hrs the corn meal extrudates with 20% brown flax hull produced a noticeable rancid (paint like) odor (Fig. 27) which was expected since the extrudates were highly expanded possessing large air cells with increased surface area. Lin et al. (1998) reported pet food extrudates containing different sources of fats became rancid faster as the expansion increased.

White sorghum extrudates containing 20% brown flax hulls produced noticeable rancid (paint like) odors after 60 hr (Fig. 27) storage in the oven. This was 2 ½ times longer than the corn meal-flax hull extrudates. The structure and composition of the white sorghum extrudates may have contributed to delayed oxidation or an undetermined factor was present. As previously mentioned the white sorghum extrudates (Fig. 21 & 22) containing 20% brown flax hulls were less expanded and denser than the corn meal extrudates with the same percentage of flax hulls. Thus, the smaller, more compact structure of the air cells in the extrudate might protect lipids from air thus delaying the onset of oxidation. Another possible contributor to the delayed of oxidation may be form complexes lipids formed with starches and proteins in the white sorghum rendering them less susceptible to oxidation (Youngs et al., 1970, Kobrehel and Sauvaire, 1990). However the most reasonable factor that delayed oxidation is the compact structure of the extrudates, due to the fact both the whole white sorghum and corn meal contained proteins and starches.

Sumac sorghum (tannin) extrudates containing 20% brown flax hulls produced rancid odors at 72 hr. The sumac extrudates were similar in structure to the white sorghum extrudates which may explain the delay in noticeable rancid odor. The tannins of sumac sorghum likely caused part of the delay in the noticeable rancid (paint like) odors. Tannin sorghum possesses high levels of antioxidant activity which make it a good ingredient for retarding oxidation (Table XVI) (Hagerman et al., 1998)(Awika, 2003).

The p-Anisidine values were the lowest for the sumac extrudates compared to the corn meal and white sorghum extrudates (Fig. 27). The p-Anisidine values for the sorghum and corn meal containing flax hulls were similar during the first 24 hr, however the cornmeal produced rancid odor earlier than the white sorghum extrudates. The higher values produced from the white sorghum extrudates may be due to contamination in the oil samples tested. Cloudiness in the oil samples from the white extrudates may have contributed the higher values. For future research in this area the peroxide value of the samples would be useful as a secondary test to confirm the onset of lipid oxidation.

Informal Subjective Taste and Texture Evaluation of Sorghum Extrudates

Whole Ground Sorghum Extrudates

Sorghum extrudates were dried to < 3% moisture before being subjectively evaluated for taste and texture. Extrudates made from whole ground white and tannin sorghum was similar in texture, both were crunchy. Extrudates were more dense than corn meal extrudates. The hard outer surface and compact inner structure of both white and tannin sorghum extrudates was the major contributor to the noticeable crunchy texture.

Although texturally both sorghum extrudates were similar they differed in flavor. The white sorghum extrudates gave a slight earthy flavor. As previously mentioned earlier in this chapter the white sorghum has some contamination from glumes which adhered to the kernel surface and were not removed during cleaning. The glumes are probably the reason for the earthy flavor noticed. Previous work done with whole ground white extrudates did not note any earthy flavor (Acosta, 2003).

Extrudates processed with whole ground tannin sorghum gave a noticeable astringent after taste. During the initial chewing of the extrudate the astringent flavor was not noticed however after continued chewing the astringency became more intense. The use of a flavor coating, such a cheese flavor, may be use to mask the initial astringency however if extrudates adhere to the teeth the astringent flavor will still be noticeable. Using a sweet coating flavor or added to the formula may help mask the astringent taste.

Sorghum Extrudates With 20% Brown Flaxseed Hulls

Whole ground white and tannin sorghum extrudates containing 20% brown flaxseed hulls had similar crunchy texture as extrudates with no added hulls. Their structures were similar with the extrudates containing hulls being slightly more expanded with is discussed in more detailed later in this chapter.

The taste of the sorghum extrudates with 20% brown flaxseed hulls was similar to the corresponding extrudates with no added hulls. However extrudates with brown flaxseed hulls did have a noticeable slimy feel after chewing which can be comparable to the slimy mouth feel one may get from eating okra. Mucilage, the water soluble hydrocolloid found in the hulls, may be contributing to the slimy mouth feel. The slimy texture may not be significant negative by consumers. Reducing the percentage of hull used and the use of flavor coatings may help mask or decrease the slimy mouth feel.

Nutritional Content of Extrudates

The combination of high tannin sorghum and flax hull has the potential to produce an extruded product with good expansion properties that provides increased nutritional value with high levels of dietary fiber, α-linolenic acids, and antioxidants. A 50g serving of extrudates containing 80% whole tannin sorghum with 20% brown flaxseed hulls would contain 6.68 g. dietary fiber, which would represent 17.6% of the dietary reference intake (DRI) for dietary fiber for adult men and 26% of the DRI for adult women. In addition, the 50 g serving would provide 0.700 g. α-linolenic acids or 43% DRI for adult men and 63% DRI for adult women. There are no RDI's for antioxidants but test have shown that flax lignans (Prasad, 1997) and sorghums tannins (Awika, 2003) display high antioxidant properties.

Summary

Quality extrudates were produced using whole sorghum with the addition of 20% brown flaxseed hulls. The particle size and moisture content of the ground whole sorghum affects the expansion characteristics. The addition of flaxseed hulls increased expansion of sorghum extrudates compared to extrudates without added flaxseed hulls. The sorghum flax hull extrudates had a dense and compact structure which made them harder than the corn meal extrudates.

An informal evaluation of the taste of the sorghum extrudates showed that the tannin sorghum produced extrudates that had a noticeable astringent after taste, and with added brown flaxseed hulls gave a slimy mouth feel. The possibility of the use of a flavored coating or an ingredient additive to reduce the astringency could be tested in with future research.

Also in addition to the nutritional benefits that a whole grain sorghum extrudate provides, increased fiber and antioxidants (found sorghum containing tannins); the addition of brown flaxseed hulls has a positive effect on the nutritional benefits. The brown flaxseed hulls add α-linolenic acids which can be highly oxidative have been shown to have nutritional benefits.

Tannin sorghum with added brown flaxseed hulls delayed lipid oxidation, compared to white sorghum and corn meal extrudates with the same percentage of brown flaxseed hulls. Due to the low levels of oil extracted for oxidation testing the data was not conclusive. Further research is needed to test for lipid oxidation and stability. Data obtain from this experiment will need to be replicated. Also a formal taste panel needs to be done to detect the production of rancid flavors in these extrudates. This research has shown that the extrudates are prone to oxidations which may be a serious deterrent to use of flax seed in extrusion processing. The role of antioxidants from sorghum was not determined although the preliminary information suggests there is a positive effect.

CHAPTER V
SUMMARY AND CONCLUSIONS

Corn Meal-Flaxseed Hull Extrudates

Extrusion of flaxseed hulls from brown and golden flax with a twin screw extruder produced snacks with varying composition and properties. The brown flaxseed hulls were dark brown in color with high levels of antioxidant activity and were relatively free of contamination from cotyledons. In contrast the golden flax hulls had a very light color, but were highly contaminated with a significant amount of cotyledon pieces which negatively affected extrusion processing.

Extrudates containing brown flaxseed hulls had good expansion and bulk density characteristics; this was mainly due to the removal of excess cotyledon pieces. Brown flaxseed hull extrudates however did produce a card board like flavor that was noticeable during tasting. Extrudates containing golden flaxseed hulls were acceptable; however the extrudates were dense and compact making them harder than brown flaxseed hulls extrudates. The presence of the cotyledon pieces disrupted cell formation during expansion causing the compact extrudate characteristics. The golden hull extrudates did have a nutty like flavor that was not noticed in the brown flaxseed hull extrudates.

Quality direct expanded snacks can be produced with the addition of flaxseed hulls. The hulls used for expanded snack production will need to be free cotyledon pieces to ensure good expansion properties. Snacks produced will have good nutritional properties such as dietary fiber, antioxidant activity, and alpha linolenic acids. Further work will be need to done to determine product stability.

Sorghum-Brown Flaxseed Hull Extrudates

Extruding whole ground sorghum with 20% brown flaxseed hulls produce good quality extrudates. Particle size of the ground sorghum had an affect on expansion characteristics. Sorghum extrudates with 20% added brown flaxseed hulls were more expanded than extrudates without added brown flaxseed hulls. The mucilage, a water soluble hydrocolloid, found in the flaxseed hulls may have a positive affect on the expansion of the extrudates.

Tannin sorghum with added brown flaxseed hulls delayed lipid oxidation, compared to white sorghum and corn meal extrudates with the same percenatage of brown flaxseed hulls. However future work will need to done to verify the results due to low levels of oil in the extrudates the data was not conclusive.

The use of tannin sorghums in extrudates containing brown flaxseed hulls produces quality extrudates. Extrudates containing tannin sorghum and brown flaxseed hulls did have an astringent flavor, however flavor coatings or additional ingredients added to mix prior to extruding could reduce the astringent flavor. Extrudates containing whole ground tannin sorghum with the addition of brown flaxseed hulls will have excellent nutritional benefits such a high antioxidant activity, dietary fiber, and alpha linolenic acids. To verify the use of sorghum containing tannins to delay oxidation in an extrudate with added flaxseed hulls will need further research.

LITERATURE CITED

AACC, 2000. Approved Methods, 10th edition. American Association of Cereal Chemists: St. Paul, MN.

Acosta, D. 2003. White food type sorghum in direct expansion extrusion applications. M.S. Thesis. Texas A&M University: College Station, TX.

ADA Reports. 2004. Journal of American Dietetic Association. Position of the American Dietetic Association: Functional Foods. 104(5):814-826

Adams, N.R., 1995. Detection of the effects of phytoestrogens on sheep and cattle. J. Anim Sci. 73:1509-1515.

Adlercreutz, H., 2002. Phyto-oestrogens and cancer. Lancet Oncol. 3:331-337.

Agriculture and Agri-Food Canada, 2002 Bi-weekly Agri-Industries Bulletin. August. Vol. 15:17

Alpers, L., and Sawyer-Morse, M.K. 1996. Eating quality of banana nut muffins and oatmeal cookies made with ground flaxseed. Journal of the American Dietetic Association. 96:794-796.

Anderson, J.W., Deakins, D.A., Floore, T.L., Smith, B.M., and Whitis, S.E., 1990. Dietary fiber and coronary heart disease. Food Science and Nutrition. 29:95-97.

Anderson, Y., Hedlund, B., Jonsson, L., and Svensson, S. 1981. Extrusion cooking of a high fiber cereal product with crisp bread character. Cereal Chem. 58:380-374.

Artz, W.E., Rao, S.K., and Sauer, R.M. 1992. Lipid oxidation in extruded products during storage as affected by extrusion temperature and selected antioxidants. In: Food Extrusion Science and Technology. Kokini, J.L., Ho, C.T., and Karwe, M.V. eds. Marcel Dekker, Inc.: New York, pp. 449-461.

Awika, J.M. 2003. Antioxidant properties of sorghum assessed by three methods. Ph.D. Dissertation. Texas A&M University: College Station, TX.

Awika, J.M., Dykes, L., Rooney, L.W., and Prior, R.L. 2003a. Processing of sorghum (sorghum bicolor) and sorghum products alters procyanidin oligmer and polymer distribution and content. J. Agric. Food Chem. 51:5516-5521.

Beare-Rogers, J. 1988. Nutritional attributes of fatty acids. Fat Science Technology. 90:85-88.

Beecher, E. D., and Starer, M.S. 1998. Direct expanded cereals produce on high-speed, high-torque twin screw extruders. Cereal Food World 43(10):753-757.

Bhatty, R.S., and Cherdkiatgumchai, P. 1990. Compositional analysis of laboratory-preparedand commercial samples of linseed and of hulls isolated from flax. Journal of American Oil Chemistry Society. 67:79-84

Blumenthal, M., 2003. Industry need to rethink Dietary Supplement Health and Education Act. HerbalGram. 58:59-61.

Burtea, O., 2001. Snack foods from formers and high shear extruders. In: Snack Food Processing. Lusas, E.W. and Rooney, L.W. eds., CRC Press. Baca Raton, FL, pp. 281-314.

Camire, M.E., and King, C.C. 1991. Protein and fiber supplementation effects on extruded cornmeal snack quality. Journal of Food Science. 56(3):760-763.

Camire, M.E., and Dougherty, M. P. 1998. Added phenolic compounds enhance lipid stability in extruded corn. Journal of Food Science. 63:516-518.

Camire, M.E, 2000. Chemical and nutritional changes in food during extrusion. In: Extruders in Food Applications. M.N.Riaz. ed. Technomic Publishing Company, Inc. Lancaster, PA.: Ch 7.

Carter, J.F. 1993. Potential of flaxseed and flaxseed oil in baked goods and other products in human nutrition. Cereal Foods World. 38:753-759.

Chen, F., Cole, P., Mi, Z.B. and Xing, L.Y. 1993. Corn and wheat flour consumption and mortality from esophageal cancer in Shanxi, China. Int. J. of Cancer. 53:902-906.

Chen, Z-Y., Ratnayake, W.M.N., and Cunnane, S.C. 1994. Oxidative stability of flaxseed lipids during baking. Journal of Oil Chemistry Society. 71: 629-632.

Chinnaswamy, R., 1993. Basis of cereal starch expansion. Carbohydrate Polymers. 21:157-167.

Chinnaswamy, R., and Hanna, M.A. 1988a. Relationship between amylase content and extrusion-properties of corn starches. Cereal Chemistry. 65(2):138-43.

Chinnaswamy, R., and Hanna, M.A. 1988b. Optimum expansion-cooking conditions for maximum expansion of corn starch. Journal of Food Science. 53 (3): 834-6, 840.

Colonna, P., Tayeb, J., and Mercier, C. 1989. Extrusion cooking of starch and starchy products. In: Extrusion Cooking. C. Mercier, P. Linko, and J.M. Harper. eds. American Association of Cereal Chemists: St. Paul, MN, pp. 247-320.

Coward, L., Barnes, NC, Setchell, KDR, Barnes, S. 1993. Genistein, daidzein, and their β-glycoside conjugates: antitumor isoflavones in soybean foods from American and Asian diets. Journal of Agriculture Food Chemistry. 41:1961-67.

Cunnane, S.C., Ganguli, S., Menard, C., Liede, A.C., Hamadeh, M.J., Chen, Z.Y., Wolever, T.M.S. and Jenkins, D.J.A. 1993. High alpha linolenic acid flaxseed: Some nutritional properties in humans. Br. J. Nutr. 69:443-453.

Daun, J.K., Barthet, V.J., Chornick, T.L., and Duguid, S., 2003. Structure, composition, and variety development of flaxseed. In: Flaxseed in Human Nutrition. Thompson, L.U., and Cunnane, S.C. eds. AOCS Press: Champaign, IL, Ch. 1.

Desrumaux, A., Bouvier, J.M., and Burri, J., 1998. Corn grits particle size and distribution effects on the characteristics of expanded extrudates. Journal of Food Science. 63(5):857-863.

Dev, D. K. and Quensel, E. 1989. Functional properties of linseed protein products containing different levels of mucilage in selected food systems. J. Food. Sci. 54:183-186.

2002. Dietary Reference Intakes (DRI's) for energy, carbohydrate, fiber, fat fatty acids, cholesterol, protein, and amino acids. The National Academies: Washington, D.C.

Draughon, F.A. 2004. Use of botanicals as biopreservatives in foods. Food Technology. 58:20-28.

Faubion, J.M., and Hoseney, R.C. 1982. High temperature short time extrusion cooking of wheat starch and flour.II Effect of protein and lipid on extrudate properties. Cereal Chem. 59:533-537.

Franke, A.A., Custer, L.J., Cerna, C.M., Narala, K.N. 1995. Rapid HPLC analysis of dietary phytoestrogens from legumes and from human urine. Proc. Soc. Exp. Biol. Med. 208:18-26.

Fredeniuk, R.W., and Biliaderis, C.G., 1994. Compostition and physicochemical properties of linseed (Linum usitatissimum L.) mucilage. J. Agric. Food Chem. 42:240-247.

Gomez, M., Waniska, R.D., Rooney, L.W., and Lusas, E.W. 1988. Extrusion cooking of sorghum containing different amounts of amylase. J. Food Sci. 52 (6):1818-1822.

Gray, J., Armstrong, G., and Farley, H. 2003. Opportunities and constrains in the functional food market. Nutrition and Food Science. 33:213-218.

Green, A.G., 1986. Effect of temperature during seed maturation on the oil composition of low-linolenic genotypes of flax. Crop Sci. 26:961.

Gubbels, G.H., Bonner, D.M., and Kenaschuk, E.O., 1993. Effect of time of swathing and desiccation on plant drying, seed color and germination of flax. Can. J. Plant Sci. 73:1001-1007.

Guy, R. 2001. Raw materials for extrusion cooking. In: Extrusion Cooking: Technologies and Applications. Guy, R. ed. Woodhead Publishing. Cambridge, UK, pp. 5-28.

Hadley, M. 1996. Stability of flaxseed oil used in cooking/stir frying. In: Proceedings of the 56th Flax Institute of the United States, Flax Institute: Fargo, ND, pp. 55-59.

Hagerman, A.E., Riedl, K.M., Jones, G.A., Souik, K.N., Ritchard, N.T., Hartzfeld, P.W., and Riechel, T.K. 1998. High molecular weight plant polyphenolics (tannins) as biological antioxidants. Journal Agric. Food Chem. 46:1887-1893.

Haggans, C.J., Hutchins, A.M., Olsen, B.A., Thomas, W., Martini, M.C., and Slavin, J.L., 1999. Effect of flaxseed consumption on urinary estrogen metabolites in post menopausal women. Nutrition and Cancer. 33:188-195.

Haumann, B.F. 1997. Nutritional aspects of n-3 fatty acids. Inform. 8:428-447.

Heinonen, S., Nurmi, T., Liukkonen, K., Poutanen, K., Wahala, K. Deyama, T., Nishibe, S. and Adlercreutz, H., 2001. In vitro metabolism of plant lignans: New precursors of mammalian lignans enterolactone and enterodiol., J. Agric. Food Chem. 49:3178-3186.

Hernandez, E., 2004. Battle of the Omega-3s: Marine vs. veggie sources. Nutrition Science News (3):12-16.

Hsieh, F., Grenus, K.M., Hu, L., and Huff, H.E.. 1993. Twin screw extrusion of rice flour with salt and sugar. Cereal Chem. 70(5):493-498.

Huber, G. 2001. Snack foods from cooking extruders. In: Snack Food Processing. Lusas, E.W. and Rooney, L.W. eds., CRC Press: Baca Raton, FL, pp. 315-367.

Ibarreta, D., Daxenberger, A., and Meyer, H.H.D., 2001. Possible health impact of phytoestrogens and xenoestrogens in food. APMIS. 109:161-184.

Jin, Z., Hsieh, F., and Huff, H.E. 1994. Extrusion cooking of corn meal with soy fiber, salt, and sugar. Cereal Chemistry 71(3):227-229.

Johnson, J.B., and Jimmerson, J. 2003. Agricultural Marketing Policy Center. Briefing No. 56. December. Montana State University. Bozeman, MT.

Kitts, D.D., Yua, Y.V., Wijewickreme, A.N., and Thompson, L.U., 1999. Antioxidant activity of the flaxseed lignan secoisolariciresinol diglycoside and its mammalian lignan metabolites enterodiol and enterolactone. Molecular and Cellular Biochemistry. 202:91-100.

Kobrehel, K., and Sauvaire, Y. 1990. Particular lipid composition in isolated proteins of durum wheat flour. Journal Agric. Food Chemistry. 38:1164-1171.

Kurzer, M.S. and Xu, X. 1997. Dietary phytoestrogens. Annu. Rev. Nutr. 17:353-81.

Lee, R.E. 2004. Content and stability of hexane extractable lipid at various steps of producing macaroni containing ground flaxseed. Journal of Food Processing Preservation. 28:133-144.

Lin, S., Hsieh, F., and Huff, H.E. 1998. Effects of lipids and processing conditions on lipid oxidation of extruded dry pet food during storage. Animal Feed Science and Technology. 71:283-294.

Lue, S., Hsieh, F., and Huff, H.E. 1991. Extrusion cooking of corn meal and sugar beet fiber: Effects on expansion properties, starch gelatinization, and dietary fiber content. Cereal Chem. 68:227-239.

Maga, J.A., and Fapojumo, O.O., 1986. Extrusion of corn grits containing various levels of hydrocolloids. J. Food Prot. 21:61-65.

Malcolmson, L.J., Przybylski, R. and Daun, J.K., 2000. Storage stability of milled flaxseed. Journal of American Oil Chemist Society (77) 235-238.

Manthey, F.A., Lee, R.E., and Hall III, C.A. 2002. Processing and cooking effects on lipid content and stability of alpha-linolenic acid in spaghetti containing ground flaxseed. Journal of Agriculture and Food Chemistry. 50:1668-1671.

Mark-Herbert, C. 2004. Innovation of a new product category: Functional foods. Technovation. 24:713-719.

Marlett, J. A., McBurney, M.I., and Slavin, J. L., 2002. Position of the American Dietetic Assoication: Health implications of dietary fiber. Journal of the American Dietetic Association. 102:993-1000.

Matthews, K.R., 2003. Effects of feeding flaxseed to pigs. In: Flaxseed in Human Nutrition. Thompson, L.U., and Cunnane, S.C. eds. AOCS Pres: Champaign, IL, Ch. 24.

Mazza, G. and Biliaderis, C.G., 1989. Functional properties of flax mucilage. J. Food Sci. Technol. 16:25-31.

Meagher, L.P., and Beecher, G.B. 2000. Assessment of data on the lignan content of foods. Journal of Food Composition and Analysis. 13:935-947.

Mendonca, S., Grossmann, V.E., and Verhe, R., 2000. Corn bran as a fibre source in expanded snacks. Lebensm.-Wiss. U.-Technol. 33:2-8.

Mercier. C. and Feillet, P. 1975. Modifications of carbohydrates components by extrusion-cooking of cereal products. Cereal Chemistry. 52(3):283-97.

Metcalf, R.G., James, M.J., Mantzioris, E., and Cleland, L.G. 2003. A practical approach to increasing intakes on n-3 polyunsaturated fatty acids: use of novel foods enriched with n-3 fats. European Journal of Clinical Nutrition. 57:1605-1612.

Milo Ohr, L. 2004. Nutraceuticals & functional food. Food Technology. 58: 71-75.

Minker, E., Bogdanova, S.V., and Penovak, I., 1973. Linseed mucilage as a water oil-type emulsifier. Farmatsiya (Soyfa) 23:13.

Miraglio, A.M. 2003. Fiber in the morning. Food Product Design. 6:131-144.

Morris, D. H. and Vaisey-Genser, M. 2003. Availability and labeling of flaxseed food products and supplements. In: Flaxseed in Human Nutrition. Thompson, L.U., and Cunnane, S.C. eds. AOCS Press: Champaign, IL, pp. 404-422.

Morris, D. H., 2003. A backgrounder on Omega 3 fatty Acids. In: Flax: A Health and Nutrition Primer. Morris, D.H. ed. Flaxseed Council of Canada. Winnipeg, Manitoba, Canada, Ch. 3.

Namiki, M. 1990. Antioxidants/antimutagens in food. Crit. Rev. Food Science Nutrition. 29:273-300.

Nelson, A. 2001. Defining high fiber ingredients terminology. In: High Fiber Ingredients. Eagan Press: St. Paul, MN, pp 1-14.

Noonan, W.P. and Noonan, C., 2003. Legal requirements for “functional food” claims. Toxicology Letters. 150:19-24.

Oomah, B.D. 2001. Flaxseed as a functional food source. Journal of the Science of Food and Agriculture 81: 889-894.

Oomah, B.D., 2003. Processing of flaxseed fiber, oil, protein, and lignan. In: Flaxseed in Human Nutrition. Thompson, L.U., and Cunnane, S.C. ed. AOCS Press: Champaign, IL, Ch. 20.

Oomah, B.D., and Mazza, G., 1993. Flaxseed proteins – a review. Food Chemistry. 48:109-114.

Oomah, B.D., and Mazza, G., 1994. Optimization of protein extraction from flaxseed meal. Food Research International. 27:355-361.

Oomah, B.D., Mazza, G., and Kenaschuk, E.O. 1998. Dehulling Characteristics of Flaxseed. Lebensm Wiss U-Technololgy. Fractionation of flaxseed with a batch dehuller. Industrial Crops and Products 9: 19-27.

Ososki, A.L. and Kennelly, E.J. 2003. Phytoestrogens: A review of the present state of research. Phytotherapy Research. 17:845-869.

Perez, A.J. 2005. Specialty sorghums in direct expansion extrusion. M.S. Thesis. Texas A&M University: College Station, TX.

Pizzey, G., 2004. Personal communication. Institute of Food Technologists (IFT) Expo. Las Vegas, NV.

Prasad, K., 1997. Hydroxyl radical-scavenging property of secoisolariciresinol diglucoside (SDG) isolated from flaxseed. Molecular and Cellular Biochemistry. 168:117-123.

Price, K.R., and Fenwick, R.W. 1985. Naturally occurring oestrogens in foods-a review. Food Addit. Contam. 2:73-106.

Prosky, L., Asp, N.G., Schweitzer, T.F., Devries, W.S., and Furda, I. 1988. Determination of insoluble, soluble, and total dietary fiber in foods and food products: Interlaboratory study. Journal Assoc. Official Analytical Chemistry. 71: 1017-1024.

Rao, S.K., and Artz, W.E., 1989. Effect of extrusion on lipid oxidation. Journal of Food Science. 54:1580-1583

Riaz, M.N. 2000. Introduction to extruders and their principles. In: Extruders in Food Applications. M.N.Riaz. ed. Technomic Publishing Company, Inc: Lancaster, PA, pp. 2-24.

Rokey, G.J. 2000. Single-screw extruders. In: Extruders in Food Applications. M.N.Riaz. ed. Technomic Publishing Company, Inc: Lancaster, PA, pp. 25-50.

Serna-Saldivar, S.O. and Rooney, L.W. 1995. Structure and chemistry of sorghum and millets. In: Sorghum and Millets Chemistry and Technology. D.A.V. Dendy, ed. AACC., Inc: St. Paul, MN, pp. 69-82.

Setchell, K.D.R. 1998. Phytoestrogens: The biochemistry, physiology, and implications for human health of soy isoflavones. Am. Journal Clin. Nutr. 68:1333S-1146S.

Setchell, K.D.R. and Adlercreutz, H., 1988. Mammalian lignans and phyto-oestrogens recent studies on their formation, metabolism, and biological role in health and disease. In: Role of the Gut Flora in Toxicity and Cancer. Rowland, I.R. ed. Academic Press: San Diego, CA, pp. 315-345.

Shin, H.S. and Gray, J.I. 1983. Physico-chemical assessment of quality characteristics of extruded barely under varied storage conditions. Korean J. Food Sci. Technol. 15:189-193.

Slavin, J. 2003. Impact of the proposed definition of dietary fiber on nutrient databases. Journal of Food Composition and Analysis. 16:287-291.

Suzuki, H., Chung, B.S., Isobe, S., Hayakawa, S., and Wada, S. 1988. Changes in omega-3 polyunsaturated fatty acids in the chum salmon muscle during spawning migration and extrusion cooking. Journal of Food Science. 53(6):1659-1661.

Thompson, L.U. 2003. Analysis and bioavailability of lignans. In: Flaxseed in Human Nutrition. Thompson, L.U., and Cunnane, S.C. eds. AOCS Press: Champaign, IL, Ch. 21.

Thompson, L.U., Robb, P., Serraino, M., and Cheung, F. 1991. Mammalian lignan production from various foods. Nutr. Cancer. 16:43-52.

Turner, D.L. 2004. The use of specialty sorghums for expanded snack food processing. M.S. Thesis. Texas A&M University: College Station, TX.

Tzen, J.T.C., Cao, Y.L.P., Ratnayake, C., and Huang, A.H.C. 1993. Lipids, proteins, and structure of the seed oil bodies from diverse species. Plant Physiol. 101:267-276.

Vaisey-Genser, M., and Morris, D. 1997. Description and Composition of Flaxseed. Pages 10-17 in: Flaxseed Health, Nutrition and Functionality Edition. Vaisey-Genser, M., and Morris, D. eds. Flaxseed Council of Canada, Winnipeg, Manitoba.

Van Rensbury, S.J. 1981. Epidemiological and dietary evidence for a specific nutritional predisposition to esophageal cancer. Journal of the National Cancer Institute. 67:243-251.

Van Soest, P.J., and McQueen, R.W. 1973. The chemistry and estimation of fibre. Proc. Nutr. Soc. 32:123-30.

Viscidi, K.A., Dougherty, M.P., Briggs, J. and Camire, M.E., 2004. Complex phenolic compounds reduce lipid oxidation in extruded oat cereals. Lebensm. Wiss. U.-Technol. 37:789-796.

Wanasundra, J.P.D., and Shahidi, F. 1994. Functional properties and amino acid composition of solvent extracted flaxseed meals. Food Chem. 4: 45-51.

Wang, H.J., and Murphy, P.A. 1994. Isoflavone content in commercial soybean foods. J. Agric. Food Chem. 42:1666-73.

Ward, W.E., and Thompson, L.U., 2001. Dietary estrogens of plant and fungal origin: Occurrence and exposure, in endocrine disruptors, Part 1. In: The Handbook of Environmental Chemistry. Metzler, M. ed. Springer-Verlag : Berlin/Heidelberg, Germany, pp. 101-128.

Watkins, S.M., and German, J. B., 1998. Omega fatty acids. In: Food Lipids: Chemistry, Nutrition, and Biotechnology. Akoh, C.C. and Min, D.B. ed. Marcel Dekker, Inc: New York, Ch. 18.

Wirck, K. L. 1993. Functional foods: Cereal products at the food drug interface. Cereal Foods World. 38:205-214.

Youngs, V.L., Metcalf, D.G., and Gilles, K.A. 1970. The distribution of lipids in fractioned wheat flour. Cereal Chemistry. 38:640-649.

Yu Wu, W., Hsieh, F.H., and Huff, H. 2004. Processing and properties of extruded flaxseed-corn puffs. Poster. Institute of Food Technologist Expo: Las Vegas, NV.

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