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# Addition of Three Dietary Fibers in an Extruded Whey and Cornstarch Expanded Snack Food

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# ADDITION OF THREE DIETARY FIBERS IN AN EXTRUDED WHEY AND CORNSTARCH EXPANDED SNACK FOOD

by

Alisha M. Wood

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# ABSTRACT

Addition of Three Dietary Fibers in an Extruded Whey and

Cornstarch Expanded Snack Food

by

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Different fiber types were incorporated in an extruded expanded high-protein snack food. Three dietary fibers (powdered cellulose, wheat fiber, and oat fiber) were selected based on ease of extrusion, percent total dietary fiber, visible expansion, and commercial availability. A high-fiber, high-protein snack food containing whey protein, normal cornstarch, and pregelatinized waxy cornstarch was extruded using the three selected fibers. The fibers replaced the normal cornstarch at 30, 60, and 80% yielding extrudates with three fiber levels (18, 36, and 48%). Each treatment or combination of fiber type and extrudate fiber level was extruded in triplicate. A control with no fiber added was also extruded in triplicate.

Extrudate characteristics were evaluated on physical (expansion ratio, air cell size, density, and breaking force) and chemical (moisture content, water absorption index, water solubility index, water and total soluble protein, and water soluble carbohydrate)

parameters. The physical and chemical characteristics of the extrudates were found to be greatly affected by combined interaction of the fiber type and level of fiber in the extrudate. As the amount of fiber in the extrudate increased, moisture content increased ($p < 0.0001$) associated with a decrease in expansion ratio ($p < 0.0001$), air cell size ($p < 0.0001$), and water solubility index ($p = 0.0013$) and increased extrudate density ($p < 0.0001$), breaking force ($p < 0.0001$), and water absorption index ($p < 0.0001$). Dependent extrusion parameters (pressure, motor torque, barrel and die temperature of the mix, barrel and die temperatures, residence time, and product flow rate) were recorded and analyzed. All dependent extrusion parameters were influenced by the level of fiber incorporation in the extrudates ($p < 0.0001$). The temperature at the die was also significantly influenced by the type of fiber used, and the level of fiber and fiber type interaction ($p< 0.0001$). Differences were deemed statistically significant at $p < 0.05$. The possibility exists to incorporate dietary fiber at levels >30% in extruded whey and cornstarch products.

(108 pages)

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Alisha M. Wood

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**Abbreviation Key**

| | |
|---|---|
| ANOVA | analysis of variance |
| BME | beta mercaptoethanol |
| C | (degrees) Celsius |
| cm | centimeter |
| CS | cross-section(al) |
| df | degrees of freedom |
| g | gram |
| kD | kilodaltons |
| kg | kilograms |
| kPa | kilopascal |
| M | molar (moles per liter) |
| ml | milliliter |
| mm | millimeter |
| min | minute |
| n | number of observations |
| N | Newtons |
| NaOH | sodium hydroxide |
| pH | potential of hydrogen |
| pI | isoelectric point |
| rpm | revolutions per minute |

| | |
|---|---|
| SDS | sodium dodecyl sulfate |
| sec | second |
| SWS | sweet whey solids |
| TDF | total dietary fiber |
| TOM | temperature of mix (in extruder) |
| µl | microliter |
| x g | times gravity |
| WAI | water absorption index |
| WHC | water holding capacity |
| WPC | whey protein concentrate (if followed by a number, denotes % protein) |
| WPI | whey protein isolate |
| WSI | water solubility index |

# INTRODUCTION AND OBJECTIVES

## Introduction

The U.S. snack food market has reached sales of $21.8 billion for 2001 (Moraru and Kokini 2003). Popular health diets include snacks as part of the weight management program. To name a few, the Atkins and South Beach diets stress inclusion of high-fiber, high-protein, low-fat, low-sugar and low carbohydrate snacks (Agatson 2003). Consumers are aware of the overall connection between diet and health. This has lead to the growth of the functional and fortified food and beverage market which grew from $18.4 billion in 2001 to $23.4 billion in 2004 (Anon 2005b). The appeal of functional foods is in the ability of a food product or added component if eaten as part of a varied diet, to provide health benefits beyond basic nutrition (Deis 2003). Dairy whey and plant fiber are very nutritional and relatively inexpensive functional food ingredients that are incorporated into a variety of nutritional snack foods. Currently, no high-fiber, high-protein, low-carbohydrate, and low-fat extruded snack foods are commercially available. There is not a snack or functional food product touting both whey protein and dietary fiber as the main ingredients.

Whey, a by-product of cheese manufacturing, retains 50% of the original nutrients in milk; largely lactose, vitamins, minerals, and soluble protein (Bylund 1995). Whey is an inexpensive, highly nutritional value-added commodity (Bylund 1995; Martinez-Serna and Villota 1992). The protein from whey is a complete protein source containing all essential amino acids requisite for healthy body maintenance and growth. Whey protein in the form of whey protein concentrate (WPC), and whey protein isolate (WPI) has been

successfully incorporated in infant formulas, power bars, muscle gain powders, and extruded expanded products.

Dietary fiber is defined by American Association of Cereal Chemists (2001) as the edible part of plants or analogous carbohydrates that are resistant to digestion and absorption in the human small intestine with complete or partial fermentation in the large intestine. American Association of Cereal Chemists (2001) further defined dietary fibers as promoting beneficial physiological effects including laxation, and/or blood cholesterol attenuation, and/or blood glucose attenuation. Consumers recognize the need for increased dietary fiber, however, are only consuming half of the current recommended consumption of dietary fiber (Deis 1999; Butrum and others 1988; Harland and Narula 2001). Dietary fiber is used as a functional food ingredient to help consumers increase dietary fiber consumption, thus, providing positive health benefits ranging from offsetting chronic diseases and cardiovascular disease to increasing fecal bulk and reducing the severity of constipation (Crosby 2005).

Dietary fiber and whey products, such as whey protein concentrate (WPC), have been incorporated into extruded expanded snack products with varying levels of success. Extrusion technology employs the continuous mixing, kneading, and expulsion of moistened, starchy, and/or proteinaceous materials through an orifice or die thereby allowing formation of the extrudate (Burtea 2001; Harper 1981). A variety of products can be made with extrusion technology. Extrusion of whey protein eliminates a waste disposal issue of the cheese industry while providing consumers with high quality protein in a convenient form of a snack food. Dietary fiber inclusion in expanded snack foods has also been researched. Whey protein and dietary fiber both tend to have detrimental

effects on extrudate characteristics such as decreased expansion ratio, air cell size, and increased hardness, and density (Cudy and Zall 1982; Moore and others 1990; Camire and King 1991; Martinez-Serna and Villota 1992; Jin and others 1995; Kim and Maga 1987; Onwulata and others 1998, 2001; Huber 2001; Allen 2004). As extrusion is an art all of its own, the possibility to extrude both dietary fiber and WPC in a snack food exists. The success or acceptability of the extrudate will depend on the ability to manipulate extrusion conditions, material selection (fiber type), product formulation and the intended use of the extrudate.

**Hypothesis**

Dietary fiber type and level influence the physical and chemical characteristics of extruded expanded snack products containing whey protein concentrate (WPC80) and cornstarch.

**Objectives**

Twelve fiber samples were extruded with WPC 80 (Lomira, WI) and normal cornstarch (Agro, Memphis, TN) at a composition of approximately 30% whey protein, 15 to 30% dietary fiber, and the remainder normal cornstarch. Extrudates were evaluated and three dietary fibers were selected for extrusion in a high-fiber, high-protein extruded snack food. Selection of three fibers was based on ease of extrusion, visible expansion, percentage of total dietary fiber in the sample and availability of dietary fiber source.

The three selected fibers were incorporated in an expanded snack food product containing 32% whey protein, 30% normal cornstarch and 10% pregelatinized waxy cornstarch (National Starch and Chemical, Bridgewater, NJ) and extruded. Normal cornstarch was substituted with 3 different dietary fibers at 4 levels (0, 30, 60, and 100 % wt/wt) yielding 0, 18, 36, and 48% total dietary fiber. Independent extrusion parameters of dry feed rate, screw speed and extrusion temperature zones throughout the extruded barrel and die exit were optimized and set for each fiber level. Dependent extrusion parameters of pressure, motor torque, observed barrel and die exit temperatures, temperature of the mix in the barrel and at the die, as well as residence time were recorded and analyzed. Extrudates were analyzed for physical (extrudate breaking, extrudate density, air cell diameter, and expansion ratio) and chemical (water adsorption index and water solubility index, moisture, water and total soluble protein, and water soluble carbohydrate) characteristics.

# LITERATURE REVIEW

## Whey

Whey is a by-product of cheese production (Bylund 1995). In the cheese manufacturing process, butter-fat and casein are precipitated from milk to make cheese curd leaving a liquid solution known as whey. This greenish-yellow, aromatic liquid is a major waste disposal issue for the food industry. Whey comprises 80-90% of the total volume of milk used for the production of cheese (Bylund 1995). Thus, from every 100 pounds of milk used for the manufacturing of cheese, only 10 pounds of cheese is produced with the subsequent generation of 90 pounds of whey. Traditionally, whey was viewed solely as waste having no intrinsic value and not effectively utilized. Whey disposal methods varied from dumping onto fields and usage as pig feed. Companies are trying to find new usages for whey, due to environmental concerns and economical issues.

Whey is an inexpensive, highly nutritional value-added commodity, retaining 50% of the original nutrients in milk; largely lactose, vitamins, minerals, and soluble protein (Bylund 1995; Martinez-Serna and Villota 1992). In addition to a high nutritional profile, whey has a broad range of functional properties such as solubility, viscosity, gelation, water-binding, foaming stability and emulsifying capacity. These attributes allow whey to be included in a myriad of products including beverages, sport bars, snack foods, pasta, meat products and analogs (Kilara 1994). Nonetheless, with only 50% utilization, whey remains one of the largest reservoirs of high quality protein residing

outside of daily human consumption (Bylund 1995). The high whey supply and low demand, allows for the innovative usage of whey ingredients.

*Whey composition*

Whey is primarily water (Bylund 1995). Composition of whey varies depending on the type of whey and the milk used to make cheese. Sweet whey has a pH of 5.9-6.6 and is the by-product of hard, semi-hard or soft cheeses (acid-set cheeses). Mineral-acid set cheeses yield acid whey with a pH of 4.3-4.6 (Bylund 1995). Generally speaking, whey is 93% water, 6.3% solids, 4.9% lactose, 0.9% protein, 0.5% minerals, and 0.05% fat (Mittal and Usborne 1985).

Whey contains 20% of the total milk proteins. Whey protein is very nutritional as it has a high protein efficiency ratio (PER) between 3.2-3.4 (Cuddy and Zall 1982). PER represents the amount of weight gained (grams) relative to the amount of protein consumed (grams) and is used to determine protein quality. The biological value (BV) measures the amount of nitrogen retained by the body in comparison to the amount of nitrogen absorbed and is also used to determine protein quality (Pasin and Miller 2000). Whey protein has a high BV of 104 (Haines 2005). Therefore, the body is able to efficiently digest and use whey protein to improve health.

Whey protein is a complete protein containing all essential amino acids required for healthy body maintenance and growth. The two main groups of proteins in milk are casein and whey proteins. Casein proteins precipitate at a pH 4.6 and account for 80% of the total protein in milk. Whey proteins are soluble at pH 4.6 and are the remaining 20% of milk protein (Bylund 1995; Huffman and Harper 1999). The groups of whey proteins

present in high concentrations are beta-lactoglobulin (25%), alpha-lactalbumin (55%), and serum albumin (12%) (Morr 1992). Beta-lactoglobulin and alpha-lactalbumin compose the majority of total protein in whey (80-90%).

Lactoferrin, lactoperoxidase, lysozyme and lipoprotein are also categorized as whey proteins (Walsh and others 2000). These make up the remaining 20% of whey proteins. Whey protein is a popular protein supplement for its complete amino acid content and high levels of branched chained amino acids-leucine, isoleucine, and valine. The non-immune protection of lactoferrin and lactoperoxidase against infection add to the acceptability of whey ingredients as a functional food ingredient (Wade 1994)

*Whey processing*

Liquid whey is processed after cheese manufacturing to retard microbial growth, remove leftover cheese fines and provided an ingredient for further usage in other products. There are many ways to process liquid whey into whey protein ingredients. However, any form of heat treatment is detrimental to the proteins. Heating denatures the proteins and limit whey protein.

Different processing methods result in different compositions of whey products and ingredients. The unreliability of whey ingredients and inconsistent product frustrate the efficient incorporation of whey into food products (Hugunin 1987). These are two reasons for low whey usage. Whey protein concentrate (WPC), whey protein isolate (WPI), and whey permeate (WP) are among the most common whey ingredients (Table 1).

Whey powder or sweet whey solids (SWS) are liquid whey with the water

:emoved through reverse osmosis and evaporation techniques. This yields a :oncentrated protein product with levels of 13% protein, 76% lactose, 10% ash, and 1% fat. Ice cream and bakery products often include SWS.

Table 1. Composition of various whey products

| | **Whey Protein Concentrate** | **Whey Protein Isolate** | **Whey Permeate** |
|---|---|---|---|
| Water | 4-5% | 4.5% | 5 % |
| Protein | 35-80% | > 90 % | 0 .05 % |
| Lactose | 53-7% | 1 % | 81.7 % |
| Fat | 4-7% | 1 % | 0.2 % |
| Ash | 4-7% | 3 % | 8.3 % |

(Huffman 1996; Hale 2000; Bylund 1995; Inglet 2004).

Whey protein concentrate is a powder obtained through drying the retentates from ultrafiltration of liquid whey (Bylund 1995). Protein levels range from 35-80% with lactose and fat increasing as the protein level decreases (Table 1). Whey protein concentrate can be tailor-made for any desired specification. The product WPC80 has 80% protein, 4-7% lactose, and 4-7% fat. The food industry uses WPC80 quite extensively in products ranging from meat extenders to fruit beverages to fat replacers.

Whey protein isolate (WPI) is furthered processed with ion exchange or membrane processes to remove the fat and lactose and increase the protein concentration to greater than 90% (Huffman and Harper 1999). Infant formulas and sport drinks incorporate WPI. Whey permeate (WP) is considered a by-product of whey processing. It is liquid whey with the water, fat, and protein removed. Thus, all the minerals remain.

Research using WP as an inexpensive growth medium for mushroom mycelia has been successful (Inglet 2004).

*Whey protein functionality*

Whey ingredients have functional properties ideal for many food applications. The nutritional appeal of whey protein lends the status of being a functional food additive to promote increased nutrition. Sports drinks utilize whey ingredients because of low viscosity of whey proteins. This allows for a high concentration of protein without the need to consume large volumes of liquid. Upon heating, the viscosity and water-holding capacity of whey proteins increase. The partial unfolding of the proteins from heat denaturation liberates water-binding sites (Huffman 1996). The volume occupied by the protein expands as more water is trapped and viscosity increased. This attribute of increased viscosity and water-holding capacity upon heating gives whey proteins the ability to improve gelation in food systems. Various types of gels can be produced from heated whey proteins. An irreversible gel has inhibited syneresis because the water is held within the capillaries of the gel matrix. Whey proteins begin gelation when heated to 65° C and at concentrations of 7% in aqueous solutions (Huffman 1996). The type of gel formed depends on processing conditions, pH, protein concentrations, and other food ingredients. Gelation can improve textural characteristics of hardness, elasticity, and cohesiveness of food products. Thus, the quality of yogurt, meats and cakes can be modified with inclusion of whey protein ingredients.

Whey proteins have a wide range of solubility. Denatured proteins have reduced solubility between pH 3-5 because the isoelectric point of some whey proteins is reached

between pH 4.5-5.3. Thus, isoelectric precipitation occurs. However, most whey proteins (80%) remain soluble unless heated above 70° C (Huffman 1996). The addition of sugar can increase solubility in heated whey products. Salad dressings benefit from the solubility range of whey proteins. The acidic environment of salad dressings does not hinder the emulsification functional properties of whey ingredients. The hydrophobic and hydrophilic regions of whey proteins allow oil or water droplets to be encapsulated by the formation of an interfacial membrane. The same holds true with the stabilizing of foams but with an interfacial membrane foaming around air. Whey protein can be used to prevent creaming in dairy products and oil/water separation in salad dressings (Huffman 1996).

**Dietary Fiber**

Nutritionally, dietary fiber is defined by the American Association of Cereal Chemists (2001) as the edible parts of plants or analogous carbohydrates resistant to digestion and absorption in the human small intestine with complete or partial fermentation in the large intestine. Thus, dietary fiber includes polysaccharides, oligosaccharides, lignin, and associated plant substances. Dietary fibers promote beneficial physiological effects including laxation, and/or blood cholesterol and glucose attenuation (AACC 2001). Increased dietary fiber intake has been associated with improved heath through reduced incidence of coronary heart disease, obesity, diverticular disease, diabetes, and some cancers (Blaylock and others 1996). The National Cancer Institute of American, American Dietetics Association and the Dietary Guidelines for Americans (2000) all recommend consumption of 20-35 g/day of dietary fiber for a 2,000

calorie diet (Butrum and others 1988; Harland and Narula 2001). However, Americans are consuming only half of the recommended levels. The National Center for Health Statistics, Hyattsville, MD, reports that Americans consume on average only 14-15 grams of fiber intake per day (Deis 1999). The Surgeon General's Report on Nutrition and Health advises increase consumption of dietary fiber.

*Dietary fiber composition*

Dietary fiber is, therefore, an umbrella term enshrouding a complex mixture of plant components resistant to digestion by the alimentary enzymes of humans (Prosky and Devries 1991; Dreher 2001). Thus, all are non-digestible polymers (BeMiller and Whistler 1996). Dietary fiber is also used to describe the supporting structure of cell walls and the substances intimately associated with them (Dreher 2001). Primary components of dietary fiber are hydrogen-bonded saccharides such as cellulose, hemicelluloses, pectins, lignins, gums, and mucilages (Dreher 2001; BeMiller and Whistler 1996). Most human consumption of dietary fiber is obtained from the cell walls of fruits, vegetables, cereals, and other seeds (Selvendran and Verne 1988).

Dietary fiber is divided into two categories- insoluble and soluble. Insoluble fiber increases fecal bulk, renders softer feces, and shortens bowel transit time (Dreher 2001), all desirable heath benefits. Good dietary sources of insoluble fiber are dried beans, peas, vegetables, nuts, and whole grain cereals (Dreher 2001). Soluble fiber lowers serum cholesterol levels, slows gastric emptying, retards glucose absorption, and enhances immune function (Dreher 2001). Good dietary sources of soluble fiber include whole grain oats and barley, oat bran, some fruits, dried beans, and other legumes (Dreher

2001). In a typical diet, 75% of all dietary fibers are consumed in the insoluble form (Dreher 2001; Deis,1999).

*Insoluble dietary fiber*

Cellulose is the primary structure found in insoluble dietary fiber (Cho and others 1997). Ubiquitous in nature, cellulose is the most abundant source of insoluble fiber (Deis 1999). Cellulose is a linear polymer of up to 10,000 monomer units of beta 1-4 linked D-glucose. This polysaccharide has a degree of polymerization of 300-1500 (Dreher 1987). The insolubility of cellulose in water, dilute acids and hot dilute alkali solutions is largely due to the tight hydrogen bonding between polymer chains (Cho and others 1997). The high degree of intermolecular hydrogen bonding provides cellulose with strong tensile strength and shear (Cho and others 1997). Humans lack the enzyme necessary to break the beta 1-4 linkage (Dreher 1987). Cellulose can absorb 3.5 - 10 times its weight in water (Deis 1999). Water absorption increases with an increase in the length of cellulose fiber (Deis 1999). Cellulose can be purified into a vast array of cellulose derivatives. Such examples are methylcellulose and microcrystalline cellulose.

Hemicellulose, unlike cellulose, is soluble in dilute alkali solutions (Cho and others 1997; Prosky and Devries 1991). A heterogeneous group of saccharide polymers containing xylose, manose, glucose, and galactose compose hemicellulose. Side chains of glucose, arabinose, and glucuronic acid are present in hemicellulose (Prosky and Devries 1991). Hemicellulose is a mixture of soluble and insoluble fibers (Cho and others 1997).

Lignin is a highly cross-linked phenylpropane polymer included in the definition of dietary fiber (IOM 2001). The North American diet does not contain huge amounts of lignin. Poorly digested, lignin is a highly water-insoluble compound covalently bound to fibrous polysaccharides (IOM 2001). Lignin is found as a complex with either cellulose or hemicellulose within plant cell walls (Dintzis 1982). These lignin-carbohydrate complexes and the physiological effects on dietary fiber are the reasons lignin is included in the definition of dietary fiber (IOM 2001).

Resistant starches are escapees of starch digestion in the small intestine that are fermented in the large intestine (Deis 1999). This carbohydrate serving as "functional fiber" is classified into 3 categories RS1, RS2, RS3 (Cho and others 1997). RS1 is starch physically inaccessible to digestion. RS2 are ungelatinzed, intact starch granules. RS3 starches retrograde after processing (Deis 1999; Cho and others 1997). Commercial resistant starches are high amylose starches modified by biochemical and/or physical processing to maximize total dietary fiber. The largest source of naturally occurring resistant starch is legumes (IOM 2001).

*Soluble dietary fiber*

Soluble dietary fibers are composed mainly of gums and pectins (Prosky and Devries 1991). A number of gum varieties contribute to the total dietary fiber content of the food supply (Prosky and Devries 1991). Gums are hydrophilic colloids that easily dissolve in water and impart a thickening and gelling effect (Glicksman 1982). Agar, alginate, carrageenan, flax seed gum, modified celluloses, xantham gum, locust bean gum

and guar gum are common gums used in food products to improve food quality and serve as dietary fiber functional food ingredients (Prosky and Devries 1991).

Beta glucans are gums and an important source of soluble dietary fiber. Beta glucans are glucose polymers resistant to digestive hydrolysis. The glucose monomers are linked with beta 1-4 and beta 1-3 linkages (Prosky and Devries 1991). Beta glucans are largely found in barley (3.0%), oats (2.5% to 6.6%), and rye (1.9-2.9%) (Cho and others 1997; Deis 1999). Oat bran has half of the total dietary fiber in beta glucans allowing for FDA approval of health claims on food labels. As gums, beta glucans can form heat-irreversible gels when heated in an aqueous suspension (Dea 1982).

Pectins also constitute soluble dietary fiber and are widely found in fruits, vegetables, legumes, and roots. A water-soluble fiber, pectin is a polymer of D-galacturonic acid linked by alpha 1-4 linkages with side chains of arabinose, xylose, rhamnose, glucose and galactose (Dreher 1987; Prosky and Devries 1991). Pectins have a wide range of functional properties based on its water-binding abilities. Pectins, like gums, are soluble dietary fibers used to aid in the texture, gelling, thickening, and emulsification of food products.

*Functional characteristics of dietary fiber*

Dietary fiber can be obtained from various sources from fruits to seaweed. No matter the form, dietary fiber can provide a multitude of functionalities that may be utilized in many food products. As consumers become further educated with the role of dietary fiber and the protective effects against cardiovascular disease and various cancers, foods products listing added or enhanced fiber may find a larger consumer market. The

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I would like to thank Dr. Walsh for her bravery in taking me on as a graduate student. Her patience, advice, good-humor, and trust in me have been enduring and a tremendous support for allowing me to finish this endeavor. I appreciate Dr. Brian Nummer and Dr. Darren Cornforth for serving on my committee. I would also like to thank Dr. Donald McMahon for roping me into food science. I would like to especially thank Randall Bagley and Dave Campbell for their friendships and all they taught me. It has been a pleasure working with you both for all these years. A thousand thanks go to Karin Allen for being recipient of many questions. Without her training in the extruder, statistical tutoring, and endless time and empathy, this project would not have succeeded. I am especially grateful for the generosity of the Collins' family during my stay in Logan. I will be forever grateful for my parents for instilling in me the importance of education. And to my siblings, Malissa, Stacie, Tracie, Allison, Anthony, and Sharron, thanks for your faith, hugs, laughter, and crazy times throughout it all. Finally, I will be eternally grateful for the support of my husband, Jeremy, who has also sacrificed so I could finish this document.

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Viscosity, in a nutshell, is the resistance to flow (Dreher 1987). Water-soluble dietary fiber has the polysaccharide characteristic of producing viscous solutions (Oakenfull 2001). At low concentrations, dietary fiber exists as "random coils" (Cho and others 1997). Thus, as the concentration of dietary fiber increases the random coils are forced together and become entangled with other molecules (Oakenfull 2001). The result is an increased product viscosity. An increase in the rate of shear or stirring causes a decrease in viscosity (Oakenfull 2001). The molecular size and weight of the polysaccharide, pH, electrolytes, temperature and water-binding capacity variedly affect viscosity (Prosky and Devries 1991).

Water-Binding Capacity (WBC) or water holding capacity (WHC) is the ability of dietary fiber to hold water under specific conditions (Dreher 1987). Polysaccharides have numerous free hydroxyl groups allowing hydrogen bond formation with water. Thus, soluble and insoluble fibers entrap water through gelation. Insoluble fibers absorb water in a sponge like fashion. Factors influencing WBC or WBC are pH, ionic strength, and particle size (Dreher 1987).

Cation Exchange, or mineral binding, is seen with dietary fiber. The presence of free carboxyl groups on the sugar residues and the uronic acid content allows dietary fiber the functional capacity of cation exchange (Cho and others 1997). Dietary fiber can bind minerals such as calcium, iron, magnesium, and copper (Dreher 1987; Harland and Narula 2001; Cho and others 1997). Binding of metal ions by dietary fiber is pH dependent (Cho and others 1997). Mineral binding is lower at an acidic pH than at a neutral pH (Cho and others 1997).

*Dietary fiber in food*

Cereals are a common source for dietary fiber. Oat, wheat, barley, and corn are the most commonly used sources for dietary fiber. Oat bran, as defined in the United States, is not more than 50% of the original starting material and provides at least 5.5% on a dry weight basis beta-glucan soluble fiber and a total dietary fiber content of 16% on a dry weight bases (Malkki 2001). Soluble fiber must account for one-third of the total dietary fiber in oat bran (Malkki 2001). Wheat bran has 35-45% dietary fiber (Dreher 2001). The bran consists of the outer coats of the wheat grain, namely the pericarp, seed coat, and aleurone layer (Dreher 1987). The bran composes 12-15% of the wheat grain (Cho and Clark 2001). Barley fiber may serve as a great ingredient in many functional foods. An assortment of both soluble and insoluble fiber can be separated from barley grains. The soluble fraction of barley is high in beta-glucans (Fastnaught 2001). Dietary fiber content of barley varies with cultivars, growing conditions and processing methods (Fastnaught 2001). Corn bran can be refined or unrefined. Refined corn bran has 80-90% total dietary fiber. Products with corn bran have increased levels of dietary fiber, improved texture and increased water and fat absorption (Dreher 1987).

*Health benefits of dietary fiber*

Dietary fiber is a key factor in the holistic health of an individual. Decrease in dietary fiber intake is associated with an increase in obesity, colon-cancer, colitis, constipation, coronary heart disease, hyperlipidemia, and maturity-onset diabetes (Prosky and Devries 1991). On the flip side, short term and long term improvements to the health

status of an individual can be seen with increases in dietary fiber in the diet (Prosky and Devries 1991).

Soluble fiber aids in the control of diabetes. Blood sugar level swings are limited, as digestion and absorption of carbohydrates are slowed by soluble fiber (Prosky and Devries 1991). High-fiber foods slow stomach emptying promoting satiety. This leads to reduced food intake, thereby controlling obesity (Oakenfull 2001). Constipation and diverticulosis is lessened with insoluble fiber consumption. Fecal bulk is also increased and laxation and regularity are improved. Soluble fibers trap nutrients, and bile acids in a gel matrix (Oakenfull 2001). Thus, absorption of cholesterol and bile acids in the small intestines is inhibited as viscosity in the intestine is increased by dietary fiber (Cho and others 1997). The benefits of sufficient dietary fiber intake are varied. Numerous studies have been conducted on dietary fiber and the role in various health issues. Studies on cardiovascular disease (Anderson and others 2000), obesity (Miller and others 1994), satiety (Burley and others 1987), colon cancer (Lanza 1990), diverticular disease (Dreher 1987) and diabetes have shown a positive correlation with dietary fiber intake.

Dietary fiber in high doses (greater than 35 g daily) can have deleterious health effects (Dreher 1987). Noted side effects are negative mineral balance, bowel obstruction leading to constipation, increased abdominal pressure, and increased flatulence (Dreher 1987; Prosky and Devries 1991).

*Labeling of dietary fiber*

The definition of what constitutes dietary fiber has undergone much question and debate over the past years. Currently, dietary fiber is defined, as proposed by the Institute of Medicine (2001), as follows:

1. *Dietary Fiber* consists of non-digestible carbohydrates and lignin that are intrinsic and intact in plants.
2. *Added Fiber* consists of isolated, non-digestible carbohydrates that have beneficial physiological effects in humans. *Total Fiber* is the sum of *Dietary Fiber* and *Added Fiber.* (IOM 2001)

Thus, naturally occurring resistant starch, as in legumes and pasta, are considered dietary fiber.

The Food and Drug Administration has no written definition of dietary fiber for the purpose of food labeling and health claims (IOM 2001). The Nutrition Labeling and Education Act of 1990 (NLEA) require total dietary fiber to be included as part of total carbohydrates declared on the label. Dietary fiber labeling is required unless the product contains less than 1 gram of fiber per serving. Declaration of soluble and insoluble fiber is voluntary unless a health claim is reported regarding the content (Gelroth and Ranhotra 2001). Dietary fiber has 0 kcal/gram for insoluble fiber and 4 kcal/gram for soluble fiber.

FDA regulations for nutrient content claims on fiber-containing foods are as follows:

1. "good source of," "fiber fortified," or "contains" fiber require 10-19% of the recommended daily intake of fiber or 2.5 grams of fiber per serving.

2. "high fiber" or "rich in" fiber must contribute a minimum of 5 grams per serving or 20% or more of the recommended daily intake of fiber per serving (Deis 1999; Gelroth and Ranhotra 2001).

The FDA has 4 approved health claims for foods pertaining to fiber.

1. Fiber-containing grain products, fruits, and vegetables help reduce the risk of cancer and cardiovascular disease.
2. "Fiber food" health claim is permitted for foods containing fiber "without fortification."
3. Oats and psyllium are rich in soluble fiber, which reduces the risk of coronary heart disease. Thus, food products must contain 0.75 grams of soluble fiber from oat or 1.7 grams of soluble fiber from psyllium husk per serving in order to tout claims of reducing the risk of heart disease.
4. Whole grain foods with greater than 51% whole grain ingredients can make a claim to reduce in heart disease and certain types of diseases (Gelroth and Ranhotra 2001).

**Functional Foods**

American consumers are aware of the positive correlation between lifestyle and eating habits to health and well being (Hasler, 1998). As consumers learn to optimize health through diet, the market for foods with altered nutritional characteristics and unchanged sensory attributes widens (Riaz 1999). The functional and fortified food and beverage market grew from $18.4 billion in 2001 to $23.4 billion in 2004 (Anon 2005b). This growth is expected to continue. The United States food-fiber market was reported

by *Strategic Analysis of the United States Food Fiber Industry* to have earned a revenue of $193 million in 2004 (Pszczola 2006). A global growth consulting company, Frost & Sullivan, estimated the future of the United States of the food-fiber market to reach $495 million by 2011 (Pszczola 2006). The appeal of functional foods is in the ability of a food product or added component if eaten as part of a varied diet, to provide health benefits beyond basic nutrition (Deis 2003)

Dietary fiber is a functional food component that provides positive health benefits ranging from offsetting chronic diseases such as diabetes and cardiovascular disease to increasing fecal bulk and reducing the severity of constipation (Crosby 2005). Foods containing dietary fiber can be touted as a functional food with health benefits. In order to make a health claim for reduced risk of coronary heart disease, food products must contain at least 0.75 g of oat soluble fiber per serving (Gelroth and Ranhontra 2001). Foods must contain at least 2 g of dietary fiber per serving to be considered a good source of fiber (Gelroth and Ranhontra 2001).

Consumers respond positively to foods labeled a good source or high-fiber food (IFIC 2000). "Increased consumer interest in the potential biomedical or calorie reduction benefits of dietary fiber and the Food Drug Association's (FDA) reassessment of its policy for allowing health messages has created a demand for the development of high fiber foods" (Dreher 1987). This trend continues. Opinion Dynamics Corp found Americans are more likely to buy products based on health labeling such as "high-fiber," "low in fat," or "high in protein" (Anon 2005a). Consumers recognize the need for increased dietary fiber consumption. Dietary fiber can be incorporated into food products as a functional food in improve consumers health.

**Snack Foods**

The U.S. snack food market has reached sales of $21.8 billion for 2001 (Moraru and Kokini 2003). This growing industry caters to all generations from the walking toddler to the geriatric adult. Popular health diets include snacks as part of the weight management plan. To name a few the Atkins and South Beach diets stress snack inclusion, snacks of a high-fiber, high-protein, low-fat, low-sugar, and even low carbohydrate content (Agatson 2003). This urging, along with the increasing awareness of the connection between diet and overall health, increases the need for functional food snack products for health conscious consumers.

The snack food industry has three broad classes or generations. The highest selling snack products are the first-generation products of the baked and fried nature such as corn chips, crackers, and potato chips (reviewed in Allen 2004). Second-generation products are thermoplastic extruded collets (reviewed in Allen 2004). These are low moisture products (<15%) oven-dried for further crispiness (Huber and Rokey 1991). Products can also be extruded at higher moisture levels and deep- fried. The nature of these products is the result of direct expansion of the dough as it exits the extruder die. The degree of starch gelatinization and melting of the dough in the extruder will determine the internal structure of the product (Colonna and others 1989). The collets can be dusted with flavor. The cheese flavored puffed corn snacks are classic examples of popular second-generation snack products.

Third-generation snack products or pellets are extruded snacks puffed by additional methods such as frying, baking, secondary expansion extrusion, or micro-waving (Huber and Rokey 1991; Matz 1993). These half products or pellets are extruded

at high moisture levels resulting in extrudates with little or no expansion. The extrudates are dried to moisture levels less than 12% (Huber and Rokey 1991; Matz 1993). These pellets can be bagged and stored up to a year before the final cooking or puffing stages (Matz 1993). Before consumption, the pellets enter a final cooking stage and are puffed by frying, microwaving or baking. The pellets are transformed as the water vaporization inside the starch matrix causes the product to expand (reviewed in Allen 2004). The extruded pellets may also be flaked to produce ready-to-eat cereals and snack foods (reviewed in Allen 2004).

**Extrusion Technology**

Extrusion technology employs the continuous mixing, kneading, and expulsion of moistened, starchy, and/or proteinaceous materials through an orifice or die thereby allowing formation of the extrudate (Burtea 2001; Harper 1981). An extruder is basically a pump that produces enough pressure to force material through a die (Rauwendaal 1998). There are different kinds of extruders based on the desired type of extrudate. The single and twin screw cooking extruders represents the two most commonly utilized extruders in the food industry.

*Extrusion history*

For over seventy years, extrusion technology has been pivotal in the development of food product innovations in the food industry. The mid-1930's ushered in the first major commercial application of single-screw extruders in Italy with the production of pasta from semolina (Rokey 2000; Huber 2000). In the mid-1940's, single-screw extruders were used to produce the first extrusion-cooked, expanded corn snack (Huber

2000; Rokey 2000). The high temperature, short-time heat treatment within the extruder was sufficient to allow complete starch gelatinization (Huber 2000). Thus, as the extrudate leaves the die, pressure is be released, moisture is flashed off, and an exothermic post die expansion transpires making possible the "puffed" characteristic (Riaz 2000).

Expanded pet food was produced by single-screw extrusion technology in the 1950's. This led to the commercial development of the continuous cooking extruder, thereby, eliminating process steps, increasing efficiency and reducing production costs (Riaz 2000). Today, extruded cooked expanded pet food accounts for the largest volume of extrusion-cooked products in the United States (Rokey 2000).

Textured vegetable protein production through extrusion cooking was used in the 1970's giving rise to meat extenders and meat analogs. The application of extrusion technology continues as its versatility, high productivity, minimal cost and improved energy efficiency is attractive to food manufacturers. Extrusion technology spawns high quality products. In 1998, 3.7 million tons of extruded products were produced in the United States, representing a retail value of $3.62 billion (Bregenzer 1998). The development and application of twin-screw extruders is widening the extruded product market. Research in extrusion technology continues especially in the application of healthy, functional snack foods.

*Extrusion process*

An extruder is not limited in application. Thermoplastic extrusion technology is used particularly in the snack food industry to transform grains and high-protein materials

into a variety of palatable snack foods through a series of complex physical processes (Huber 2001; Camire 1991). Extrusion exposes food to heat and shear stress allowing for the interaction of starch and protein. Starch gelatinizes and proteins denature allowing for the molecules to realign and interact, forming matrices (Harper 1981). An extruder is composed of an Archimedean flighted helical screw that rotates within a fixed metal barrel or cylinder. Dry materials are added to the barrel via a feed hopper. The hopper allows for a constant and uniform introduction of materials to the extruder, thus preventing surging and providing product uniformity. Liquid such as water or sodium hydroxide may be added just after the hopper or inlet feed.

The material is conveyed forward through the barrel by the rotating force of the screw and the frictional force at the barrel (Rauwendaal 1998). The helical screw provides conveyance, heating, melting and mixing of the material throughout the barrel (Rauwendaal 1998). Screws allow for extrusion to be a continuous process. The screw design is important as paddles on the screw control the flow and mixing of the materials. Typical extruders have one or two screws. Twin-screw extruders offer advantages over single screw extruders. Twin-screw extruders vary in design by the different degrees of screw meshing and direction of rotation. This allows for a variety of materials to be extruded. Low moisture materials can be extruder and eliminates the need for a preconditioning stage. The twin-screw design provides self-swiping capabilities allowing positive forward transport of the material through the barrel to the die exit. The constant flow of material and pressure at the die will then allow for extrudate uniformity.

Heating zones line the extruder barrel. Barrel temperature is measured by thermocouples and can be monitored and controlled. Heat allows for melting of the

material to form a dough. Increased mixing and heating throughout the barrel generates pressure at the die end. Sufficient pressure must be generated to overcome resistance of the die and discharge the material. Formation of an expanded or "puffed" extrudate results from the sudden decrease of pressure leaving the die and the water vaporization of the extrudate (Rauwendaal 1998). Extrudate shape is dependent on the die design.

The extrusion process can indeed be considered its own form of art. The reproducibility of a desired product greatly resides on the ability of the operator to control extrusion process parameters (Huber 1991). Independent variables that directly control product quality attributes are formulation, material feed rate, liquid feed rate, screw speed, screw design and paddle configuration, die configuration, and barrel temperatures (Huber 1991). Product temperature within the barrel and at the die, residence time, barrel pressure, and specific mechanical energy are among the dependent variables. Final product quality can be measured through final moisture content, extrudate expansion (i.e. bulk density, size, and shape), solubility, texture, color and flavor (Huber 1991).

**Extrusion research**

Traditionally snack foods have inferior nutritional qualities. Many efforts to add nutritional value to extruded snacks have been attempted with the inclusion of soy, whey, and meat proteins with varying results. Incorporation of whey proteins not only utilizes the excess supply of whey protein, but also adds high quality protein, thereby, increasing the nutrient density of the snack food. Fiber has also been investigated as a value-added

ingredient to many types of snack foods. As with any snack food, the success of an extrudate depends largely on consumer acceptance and the application of the extrudate.

*Whey in extruded products*

Whey proteins have been manipulated over the years through various technologies to yield ingredients with usage potential in an array of food applications. Thermoplastic extrusion of whey proteins is a continuous process with little waste. Process parameters are easily controlled and cost is limited. Whey protein extrusion promotes protein aggregation through the breaking and reforming of disulfide bonds as a result of protein denaturation. Whey protein extrusion is feasible. However, success is limited by the acceptability of the extrudates.

Hale (2000) successfully extruded textured whey protein for use in a meat patty. Acceptability of extrudate was dependent on the texture of the product, which contained whey protein concentrate, cornstarch and sodium hydroxide. Her work was later followed by Allen (2004) who extruded whey protein concentrate at varying levels with different types of starches. It was found that starch type had the greatest impact on extrudate characteristics. Normal cornstarch with 32% protein had higher sensory scores despite smaller expansion and higher bulk density. Pregelatinized waxy cornstarch at each protein level (32 and 40%) yielded extrudates with greater expansion and lower bulk densities than those with normal cornstarch. However, tooth pack was greater yielding lower sensory scores.

Many other researchers have incorporated whey proteins into extruded starch blends with limited success due to the detrimental effects on extrudate properties

(Martinez-Serna and Villota 1992; Kim and Maga 1987; Onwulata and others 1998). The main problems inherent with whey addition are reduced cross-sectional expansion, increased hardness, heightened non-enzymatic browning, and difficulty in extrusion (Cuddy and Zall 1982; Martinez-Serna and Villota 1992).

*Dietary fiber in extruded products*

Huber and Rokey (1991) state that fiber, cellulose, bran, and fruit-derived pectins can successfully be blended with cereal grains or protein blends. Expanded snacks can have addition of 20% fiber and protein with little effect on flavor and expansion. More soluble fibers and proteins, however, can be added in higher levels. High levels of fiber yield soft-textured snacks. This is due to the fact that fiber absorbs water. Water retention inhibits water loss at the die and reduces expansion (Camire and King 1991). Artz and others (1990) showed that the water-holding capacity of fiber decreased with increased extrusion temperature.

Fiber containing bran particles added to extruded products cause premature rupture of gas cells leading to reduced expansion (Moore and others 1990). Lue and others (1991) found reduced particle size of sugar beet fiber improved both radial and longitudinal expansion of extrudates.

High fiber decreases expansion and yields extrudates with high bulk densities (Burglund and others 1994; Huber 1991). Jin and others (1995) contributed reduced radial expansion to increased fiber content. Jin and others (1995) found fiber caused thickening of the cell walls and decreased air cell size in the microstructure of the extrudate. Purity of fiber directly influences expansion characteristics (Huber 2001).

Low levels of low-molecular weight starches will counter effects of fiber and protein additions (Huber and Rokey 1991; Huber 1991).

Onwulata and others (2000) conducted research extruding triticale and wheat products with 20 g and 40 g dietary fiber from wheat bran. It was found that starch expands better than flour. Only percent fiber and product flow rate affected product hardness. Extrudates with 20 g fiber and high flow rates were softer than higher fiber and slower flow rates. Increased fiber was associated with increased breaking strength of extrudates.

Azlyn and others (1989) found optimal fiber replacement in extruded products to be 20 g per 100 g of product. Huber (1991) reports beet, fruit, pea and soy fibers can be added up to 30% without significantly reducing expansion. Oat and rice fibers with high lipid and protein levels are not optimal fibers for extrusion (Huber 2001). High lipid and protein levels reduce extrudate expansion. Fibers with the lowest level of protein and lipid in conjunction with smallest particle size allow for the highest degree of expansion (Huber 2001).

Onwulata and others (2001) extruded a cornmeal snack with wheat bran fiber (12.5 and 50%) and milk proteins (25%). It was concluded that whey products with wheat bran fiber addition, even at levels higher than 12.5%, could improve extrudate expansion and other product characteristics of an extruded cornmeal snack.

Camire and King (1991) extruded cornmeal snacks with soy protein isolate and either cotton linter cellulose or soy cotyledon fiber. It was found that low levels of soy protein isolate increased expansion and low levels of cottonseed fiber decreased expansion. Higher soy protein levels altered sensory attributes of color, expansion, and

flavor. A blend of 10% fiber (either source) and 15% soy protein isolate was found acceptable through sensory testing.

Research on extrusion of dietary fiber has shown that processing affects the physiological effects of dietary fiber. However, the effects of extrusion on dietary fiber are unclear. The changes that can occur in dietary fiber from extrusion vary, largely depending on extrusion conditions, processing materials, and to some extent the method of fiber determination (Lue and others 1991; Wang and others 1993; Camire and Flint 1991; Gualberto and others 1997).

Rinaldi and others (2000) extruded wet okara and soft wheat flour. Wet okara contained > 20% protein and >50% dietary fiber and was added to a soft wheat flour blend at 33.3 % and 40%. Increased fiber content resulted in extrudates with decreased radial expansion and increased bulk density and breaking strength. Extrusion brought about a decrease in insoluble fiber and increased soluble fiber content. The greatest increase in soluble fiber content was apparent at higher extrusion temperatures. The blend with the higher fiber (40% wet okara) showed an increase in total dietary fiber (TDF), possibly due to the formation of enzyme-resistant starch.

Lue and others (1991) extruded sugar beet fiber and corn meal. Sugar beet fiber was extruded at 10, 20, and 30%. The insoluble, soluble, and total dietary fiber levels did not change significantly among the 30% sugar beet fiber extrudates. However, non-significant differences were observed from the raw and extruded materials. It was noted that changes in dietary fiber depended on extrusion conditions and processing materials.

Gualberto and others (1997) extruded wheat, oat, and rice bran at varying screw speeds. Total dietary fiber (TDF) was not affected in wheat bran at 148-180$^{o}$ C and

screw speeds of 200 rpm. Insoluble fiber decreased in wheat, oat and rice bran. Increase of soluble fiber was greatest at screw speeds of 225, 305 rpm for rice and oat bran, and at screw speeds of 305 and 450 rpm for wheat bran.

Lukesova and others (1996) found that extrusion of crisp bread in a twin-screw extruder brought a decrease in TDF in extrudates containing wheat flour. In extrusion with a single-screw extruder, the main differences were noted in the decrease of insoluble dietary fiber. Vegetable crisp bread extrudates had a decrease in soluble dietary fiber while non-vegetable extrudates had an increase in soluble dietary fiber. Single-screw extrusion only showed a significant decrease in TDF in one of the crisp bread extrudates

Extrusion of wheat bran was found to increase fiber digestibility in rats (Aoe and others 1989). Increased digestibility was the result of an increase of soluble fiber of the wheat bran extrudate. The soluble dietary fiber increased in wheat bran extruded at 136, and 160° C. Additionally, a decrease in insoluble fiber was attributed to solubilization of dietary fiber during processing and possible release of the soluble hemicellulose fraction from the dietary fiber in the wheat bran (Aoe and others 1989).

**Extrudate Analysis**

Common methods as cited in the literature for extrudate analysis, chemically and physically, employ a narrow range of tests (Jin and others 1995; Mohammed and others 2000; Onwulata and others 2000; Allen 2004; Hale 2000; Taylor and others 2006). Chemical tests include moisture determination, total and water soluble protein using the Lowry assay (Lowry and others 1951), soluble carbohydrate (Dubois and others 1956), water adsorption index (WAI) and water solubility index (WSI) as described by Jin and

others (1995). Physical tests often include extrudate breaking strength, density, expansion ratio, and air cell size.

Dietary fiber has much controversy as the definition of what constitutes dietary fiber is often not defined. The complexity of defining dietary fiber is due to the fact dietary fiber is a combination of chemical substances of distinct composition and structure and not a simple chemical compound (Rodriguez and others 2006). Therefore, there are many methods for fiber determination all focusing on different components or constituents of dietary fiber (Rodriquez and others 2006; Lukesova and others 1996). There is not a precise and accurate methodology for dietary fiber determination (Rodriguez and others 2006). However, generally speaking, dietary fiber analysis can be divided into 2 main groups: enzymatic-gravimetric methods and chemical methods. The enzymatic-gravimetric method quantitates fiber as the residue that remains after treatment to the sample with specific enzymes that degrade ash and protein (Rodriguez and others 2006, Lukesova and others 1996). The chemical method determines the non-starch polysaccharides (Rodriguez and others 2006; Lukesova and others 2006).

# MATERIALS AND METHODS

## Fiber Selection

An extruded snack food product was produced with 32% total whey protein (WPC 80, Grande Cheese, Lomira WI) and 60% normal cornstarch (Argo, Memphis, TN) as the standard control. Twelve dietary fiber samples with varying amounts of % total dietary fiber (%TDF) were obtained from different sources (Table 2).

Table 2. Dietary fiber sources and % total dietary fiber (TDF) composition

| **Fiber Type** | **%TDF** | **Source** |
|---|---|---|
| Orange fiber OF 400 | 60 | J.Rettenmaier USA LP, Schoolcraft, MI |
| Apple fiber AF401 | 55 | J.Rettenmaier USA LP, Schoolcraft, MI |
| Oat fiber HF 600 | 96 | J.Rettenmaier USA LP, Schoolcraft, MI |
| Oat fiber HF 401 | 90 | J.Rettenmaier USA LP, Schoolcraft, MI |
| Wheat Fiber WF 600 | 97 | J.Rettenmaier USA LP, Schoolcraft, MI |
| Powdered Cellulose L601 | 100 | J.Rettenmaier USA LP, Schoolcraft, MI |
| Oatvantage Oat fiber | 100 | Nuture Advanced Oat Technologies, Devon, PA |
| Cargill Maizewize 60 | 60 | Cargill, Indianapolis, IN |
| Cargill Maizewize 80 | 80 | Cargill, Indianapolis, IN |
| Fibersol-2 | 100 | ADM Specialty Ingredients Division, Decatur, IL |
| Litesse | 90 | Danisco Sweeteners, Ardsley, New York |
| Oat Fiber X | 100* | Roman Meal Milling Company, Tacoma, WA |

*%TDF was assumed to be 100%.

The twelve different sources of dietary fiber were separately blended with cornstarch and WPC80 to make 10 lb. dry blends (Table 3). Cornstarch and WPC 80 did not exceed 40 and 45% (wt/wt), respectively, of the dry blend. Final %TDF level of each dry blend varied based on %TDF content of sample and amount of sample available for extrusion. Each protein:starch:fiber blend was randomly extruded.

Table 3. Composition of 10 lb. dry blends used for fiber selection.

| Fiber Type | % Total Dietary Fiber (TDF) | % Protein (From WPC 80) | % Cornstarch |
|---|---|---|---|
| Orange fiber OF400 | 15.5 | 42 | 20 |
| Apple fiber AF 401 | 15 | 38 | 24 |
| Oat fiber HF 600 | 24 | 38 | 37 |
| Oat fiber HF 401 | 28 | 44 | 13 |
| Wheat Fiber WF 600 | 24 | 39 | 25 |
| Powdered Cellulose L601 FCC | 20 | 37 | 33 |
| Oatvantage Oat fiber | 36.5 | 38 | 16 |
| Cargill Corn fiber Maizewize 60 | 18 | 36 | 23 |
| Cargill Corn fiber Maizewize 80 | 40 | 32 | 16 |
| Fibersol-2 | 40 | 40 | 10 |
| Litesse | 38 | 40 | 8.3 |
| Oat Fiber X | 55* | 26 | 11 |

*%TDF in fiber sample was assumed to be 100%.

**Extrusion**

Fibers were extruded in random order employing a bench-top scale APV Baker MP-19TC twin-screw extruder (APV Maker, Inc., Grand Rapids, MI). Dry feed was added to the extruder and mixed with liquid feed (0.1 M NaOH) in the barrel (Allen 2004). Liquid feed rate was held constant at 5.6 g / min. Die temperature and temperature zones along the barrel and were controlled and monitored with CAL3200 Autotune temperature controllers (Cal Controllers, Inc., Libertyville, IL). The four barrel

temperature zones were set at 25, 25,115, 135° C for all extrusion runs. Die temperature or temperature of extrudate exiting the die was set for 145° C. Other independent extrusion conditions of dry feed rate and screw speed were initially set at a rate of 500 rpm for dry feed rate, and 200 rpm for screw speed. There were some minor variations in dry feed rate and screw speed to optimize extrusion of each dietary fiber sample (Appendix A Table A1). Optimized extrusion was defined as absence of product surging, indicating a state of equilibrium and minimal elastic recoil of exiting extrudate. Torque and pressure was measured using a NRC120 Safeguard Meter (Anders Electronics, London, UK) and an EPR3 3M-6M561 pressure transducer (Dynisco Instruments, Franklin, MA), respectively. The exit die was conical with a 2.5 mm diameter. The extruded was cleaned with water between extrusion runs. Extrudates were allowed to dry overnight at room temperature and then stored in plastic bags.

**Extrusion at Four Different Fiber Levels**

An extruded snack food product was produced containing 32% total protein and 50% normal cornstarch and 10 % pregelatinized waxy cornstarch (National Starch and Chemical, Bridgewater, NJ) as the standard control (0% fiber). Pregelatinized waxy cornstarch was used to help with expansion of the product (Allen 2004) and incorporated at a constant 10% (wt/wt) for each blend (Table 4). A 10 lb. mix was made for each dry blend. The three different fibers selected: Vitacel Powdered Cellulose L601 FCC (J. Rettenmaier USA LP, Schoolcraft, MI) Vitacel Oat fiber HF600 (J. Rettenmaier USA LP, Schoolcraft, MI) and Vitacel Wheat Fiber WF600 (J. Rettenmaier USA LP, Schoolcraft, MI) were separately blended with the normal cornstarch, pregelatinized waxy cornstarch

and WPC80 to form final %TDF levels of 18, 36 and 48% (wt/wt). Adjustments were made in formulations to account for different % TDF content of each fiber sample. The fiber content levels of extrudates were based on estimated 30, 60, and 80% replacement of the 60% starch (combined normal cornstarch and pregelatinized waxy cornstarch) in the 10 lb. dry blend of the control with each fiber type selected. The dry blend had a final total protein content of 32% using WPC80 (Table 4). Treatments were extruded in block form with each fiber type representing one block. Each fiber level was extruded in random order within each block. Each fiber type, fiber level and control was extruded in triplicate yielding 10 treatments (3 fiber types, 3 fiber levels and 1 control in triplicate) for a total of 30 samples. All samples were extruded as described previously. The extruded was cleaned between extrusion runs with water. Extrudates were allowed to dry overnight at room temperature and then stored in plastic bags.

Table 4. Composition of 10 lb. dry blends used for extrusion at different fiber levels.

| % Fiber Level | Sample | % Protein (From WPC80) | % Normal Cornstarch | % Pregelatinized Waxy Cornstarch |
|---|---|---|---|---|
| 0 | Control | 32 | 50 | 10 |
| 18 | Powdered Cellulose | 32 | 32 | 10 |
| 18 | Wheat Fiber WF 600 | 32 | 31.5 | 10 |
| 18 | Oat Fiber HF 600 | 32 | 31 | 10 |
| 36 | Powdered Cellulose | 32 | 14 | 10 |
| 36 | Wheat Fiber WF 600 | 32 | 12.9 | 10 |
| 36 | Oat Fiber HF 600 | 32 | 12.5 | 10 |
| 48 | Powdered Cellulose | 32 | 2 | 10 |
| 48 | Wheat Fiber WF 600 | 32 | 1 | 10 |
| 48 | Oat Fiber HF 600 | 32 | 0 | 10 |

Die temperature and temperature zones along the barrel were set and monitored with CAL3200 Autotune temperature controllers (Cal Controllers, Inc., Libertyville, IL). The four barrel temperature zones (25, 25,115, 125° C) were set for all extrusion runs. Die temperature or temperature of extrudate exiting the die was set for 135° C.

Independent extrusion parameters of dry feed rate and screw speed were determined for each fiber level and used to optimize product extrusion based on a constant liquid feed rate of 5.6 g/min (Table 5). In general, each fiber level had a unique extrusion condition varying only slightly between fiber types. Optimized extrusion was obtained with absence of product surging indicating a state of equilibrium and minimal elastic recoil of exiting extrudate. All set and observed independent extrusion parameters were recorded. Dependent extrusion parameters such as of residence time, torque, pressure, TOM of die and barrel, and barrel and die temperatures were recorded.

Table 5. Optimal extrusion parameter ranges for various fiber levels.

| **% Fiber level** | **Dry feed rate (rpm)** | **Screw speed (rpm)** | **Residence (sec)** | **Product Flow (g/s)** |
|---|---|---|---|---|
| 0 | 425 | 180-200 | 65-69 | 42.5 |
| 18 | 450-475 | 180-200 | 73-90 | 25.8-35.7 |
| 36 | 425-450 | 180-200 | 80-89 | 25.7-29.2 |
| 48 | 250-300 | 140-160 | 114-137 | 14.4-17.0 |

After all extrudate samples were collected, food coloring was added to the barrel with the dry feed. The time from food coloring addition in the barrel to the exiting of colored product from the die was recorded as residence time. Four extrudate samples

were randomly collected for 20 seconds and weighed. Product flow was then calculated for each extrusion run. The 4 collected samples were used for moisture determination. Extrudates were further analyzed for WAI, WSI, water and total soluble protein, water soluble carbohydrate, extrudate breaking strength, air cell diameter, expansion ratio and diameter. The samples were analyzed in triplicate unless otherwise noted. Comparison of extrudates was conducted using analysis of variance. Because the effects of dietary fiber addition to a high-protein extruded snack foods was the focus of this study, the effects of extrusion on dietary fiber were not evaluated and dietary fiber content of extrudates was not tested. It should also be noted that the exact composition of the fiber sources (i.e. dietary fiber components) were not known. Thus, selection of the appropriate method for dietary fiber determination would be difficult.

*Physical tests*

Samples were embedded in melted household wax (Parowax, Roswell, GA.) and allowed to cool. Amount of sample embedded in wax varied based on the diameter of the extrudate. Approximately 4-8 extrudates per sample were used. Embedded extrudates were cut lengthwise as close to the center as possible with a razor to expose the longitudinal cross section. Images of the cross section were taken using a stand-mounted Nikon Coolpix 5700 digital camera (Nikon USA, Melville, NY). Camera settings included a focal length of 15.7 mm, a Fine picture setting, F3.6 and a 2560 x 1920 pixel resolution. Paper squares with known areas of 1, 0.5 and 0.25 $cm^2$ area were placed along-side the extrudate and photographed with every extrudate cross sectional image.

Clear air cells (12) from the images of the cross sections were randomly selected and analyzed using Adobe PhotoShop (Adobe Systems Inc., San Jose, CA). Air cell surface area was outlined with the Magnetic Lasso tool generating a total pixel count within the outlined circumference. Pixel counts of the known paper squares areas were used to make a standard curve. Total pixel counts of the air cells were compared to the standard curved to determine air cell size.

A Salter 235 shear device with a Warner-Bratzler shear cell (GR Electric Manufacturing, Manhattan, KS) was used to provide shear values for extrudate breaking strength. Ten extrudates were randomly selected from each starch: fiber ratio and sheared. Extrudate length and diameters at point of shear where measured with calipers. Sheared, measured extrudate fragments were weighed. Breaking strength force was calculated using the following equation:

$$\text{Force (Pa)} = \frac{(9.7865\ \text{N/kg})\ (\text{breaking strength (kg)})}{\pi\ ((\text{extrudate diameter (mm)})/2)^2} \times 1000$$

The ratio of cross sectional area of each extrudate (CS) to the area of the die exit was used for expansion ratio calculation. Ten values were obtained for randomly selected extrudate samples.

A gravimetric displacement method was not used to determined extrudate density, due to concern of media entering the extrudate's air cells, thus, altering the volume measurements (Allen 2004). Instead, a simple mathematical formula was used:

$$\text{Density (g/cm}^3\text{)} = \frac{\text{segment weight (g)}}{\text{segment length (mm)}\ \pi\ (d_{ave}(\text{mm}))/2)^2}$$

where $d_{ave}$ is the average of the initial and final diameters of a given extrudate segment taken at point of shear. Length and weight measurements of each extrudate sample used for breaking strength determination were used for density calculation. A total of ten values per sample were obtained.

*Chemical tests*

Four 20-second samples randomly collected during each extrusion run were weighed to determine product flow rate and then used for moisture determination. The first and third samples were immediately dried overnight for at least 16 hours at 70° C in a drying oven while the second and third samples were them dried 24 hours later under the same conditions. Pans were allowed to cool and were weighed. Percent moisture content was calculated as the percent weight difference before and after drying. Data reports an average of 12 samples.

The water adsorption index (WAI) and water solubility index (WSI) were determined using minor modifications to procedures as described by Jin and others (1995). Samples were blended. The finely ground sample was then sifted through a #16 sieve and then through a #60 sieve. Particles that passed through both sieves were used for WAI and WSI determination. Into a tared centrifuge tube, approximately 0.5 g of ground sample was weighed and 5.0 ml of distilled water was added. The mixture was

sealed, immediately inverted, and allowed to hydrate for 15 minutes. The sealed tube was inverted every 5 minutes to ensure proper mixing. Samples were centrifuged for 15 minutes at 1000 x g using a Sorvall RC-5B fixed angle rotor (DuPont Instruments, Wilmington, DE). The resultant supernatant was decanted into a pre-weighed aluminum dish, allowed to dry overnight in a drying oven (70° C) and then re-weighed. Centrifuge tubes were reweighed after supernatant removal to determine the sediment weight. WAI and WSI values were calculated as described by Onwulata and others (1998). WAI values were reported as grams of water absorbed per 100 grams sample. However, WSI values are reported as grams of sample solubilized per 100 grams sample. WSI and WAI analysis was done in triplicate for each replicate.

Extrudate samples for protein measurements were prepared as described for WAI and WSI except sample portions that passed through a #16 sieve and retained in a #60 sieve were used for analysis. For each ground sample, 2 portions of approximately 0.2 g were added into a 15-ml centrifuge tube. Into one tube a 10-ml solution of 1% w/v sodium dodecyl sulfate and 1% v/v beta-mercaptoethanol (SDS/BME) was added. In the other tube, 10-ml of distilled water was added. The sealed tubes were rocked overnight on a laboratory rocker (Rocking Platform 200, VWR Scientific, Bristol, CT) on a rocker setting of 4. The samples were centrifuged for 15 min at 5000 x g, filtered through Whatman 4 glass fiber filters, and analyzed for water soluble and total soluble protein using a modified Lowry protein assay (Pierce, Rockford, IL) with bovine serum albumin as standard (Lowry and others 1951). SDS/BME filtrates were diluted 1:11 and 200 µl were assayed. Distilled water filtrates were not diluted and 200 µl were assayed. Analysis was in triplicate for each replicate. Values for distilled water filtrates were used

for water soluble protein determination and SDS/BME filtrates provided values for total soluble protein determination.

For water soluble carbohydrate, the distilled water filtrates were diluted 1:20 with 1 ml being assayed using a phenol/sulfuric acid method or the Dubois Assay (Dubois and others 1956). D-glucose was used as the reference standard. Each sample filtrate or replicate was analyzed in triplicate. Sample filtrates of SDS/BME solution were not used for water soluble carbohydrate analyze due to interference with the colorimetric glucose assay (Allen 2004).

**Statistical Analysis**

Treatment means for dependent extrusion parameters and physical and chemical results were calculated and analyzed using the proc glm function in Statistical Analysis Software (SAS) version 9.0 (SAS Institute, Inc., Cary, NC). Analysis of variance (ANOVA) was used to compare treatment means and identify statistically significant differences at the 95% confidence level. Fiber inclusion, fiber type and fiber type/fiber level interactions were set as fixed factors and were analyzed based on ANOVA results.

# RESULTS AND DISCUSSION

Various dietary fiber samples were extruded in a high-protein snack food. Three dietary fiber samples (powdered cellulose, wheat fiber and oat fiber) were selected for further application in the extrusion of a high-protein, high-fiber snack food. Dietary fiber selection was based on ease of extrusion, apparent radial expansion, percentage of total dietary fiber in the sample and availability of dietary fiber source.

The effects of the addition of the three chosen fiber types (powdered cellulose, wheat, and oat) on extrudate characteristics were analyzed. The fibers were added to the extrudate replacing the normal cornstarch in a 10 lb. dry blend at levels of 30, 60, and 80% corresponding to total dietary fiber levels of 18, 36, and 48%. Each fiber type/level and control (no fiber added) combination was extruded in triplicate. Independent parameters such as screw speed, dry feed rate, and extrusion temperatures were optimized for each fiber level and recorded (Table 5). Liquid feed was held constant at 5.6 g/min for each extrusion run. The extrudates were examined for the physical parameters of breaking force, density, expansion ratio, and air cell size. Chemical analysis was conducted on the extrudates for moisture content, WAI, WSI, water soluble protein, total soluble protein and water soluble carbohydrate. Dependent extrusion parameters of residence time, product flow rate, motor torque, pressure, observed die and barrel TOM, die and barrel temperatures were recorded. Extrudate measurements for all parameters (physical, chemical, and dependent extrusion) were analyzed for statistical differences and correlations and compared to each other and to a 0% fiber control.

**Fiber Selection**

Extrudates for all dietary fiber sources were compared and three dietary fibers were selected for further extrusion application. Selection was based on:

1) Ease of extrusion of each fiber sample. Could a product be successfully extruded?
2) Visible radial expansion. Was there a "puffed" appearance of the extrudate?
3) % Total dietary fiber content. Did the fiber sample have significant TDF?
4) Availability of fiber sample. Could sufficient amounts of sample be obtained?

The three fiber sources not successfully extruded under the aforementioned extrusion parameters (Appendix A Table A1) and dry blend compositions (Table 3) included Oat fiber X, Litesse, and Fibersol-2 fiber sources. Unsuccessful extrusion was determined by seizing of extruder before extrusion parameters could be obtained and/or inability to consistently form an extrudate.

Visible radial expansion was greatest in the extrudates from Vitacel Oat fiber HF600, Vitacel Apple fiber AF401, Cargill Corn fiber Maizewize 60, Vitacel Powdered Cellulose L601 FCC, and Vitacel Wheat fiber HF600 (Appendix B Fig. B1).

Samples with similar % TDF content were desired since this would allow for comparison of extrudates with similar compositions of % TDF, % protein and % cornstarch. Vitacel Apple fiber AF401 and Cargill Corn fiber Maizewize 60 contained 60% TDF. Vitacel Powdered Cellulose L601 FCC was assumed to be 100% TDF, and Vitacel Oat fiber HF600 and Vitacel Wheat fiber WF600 had 96 and 97% TDF, respectively. Therefore, Powdered Cellulose L601 FCC, Vitacel Oat fiber HF600, and

Vitacel Wheat fiber WF600 were the closest in % TDF and as already mentioned, better suited to continue research.

Cargill Corn fiber Maizewize 60 and Maizewize 80 were in the prototype stages and sufficient quantities of fiber sample could not be obtained. Vitacel Powdered Cellulose L601 FCC, Vitacel Oat fiber HF600 and Vitacel Wheat Fiber WF600 were then selected for extrusion at four different fiber levels.

**Extrusion at Four Different Fiber Levels**

Three different fiber types (powdered cellulose, wheat, and oat) were extruded with normal cornstarch, pregelatinized waxy cornstarch and WPC80 to form a high-protein, high-fiber snack food. The effects of dietary fiber addition on extrudate characteristics were examined. The physical, chemical and dependent extrusion parameters were analyzed for statistical differences and correlations.

**Physical Parameters**

Extrudate characteristics exhibited highly statistical differences based on the amount of fiber in the extrudate (18, 36, 48%) and to some degree by the type of fiber (powdered cellulose, wheat fiber and oat fiber) used (for more detailed statistics on physical parameters see Appendix D Tables D1-D8). Generally, as the amount of fiber in the extrudate increase, negative effects on physical parameters were observed. These findings were consistent with previous research (Onwulata and others 2000; Lue and others 1991; Rinaldi and others 2000). Expansion ratio was strongly influenced by fiber level ($p < 0.0001$) in the extrudate and the fiber level/fiber type interaction ($p < 0.0001$),

while air cell size was significantly influenced ($p < 0.0001$) only by fiber level (for more detailed statistics see Appendix D Table D1-D2).

Expansion ratio (Fig. 1) and air cell size (Fig. 2) both decreased with an increase of the amount of fiber present in the extrudate. Powdered cellulose had the lowest expansion and wheat fiber had the highest expansion ration with 18% fiber. However, as fiber increased to 36 or 48%, powdered cellulose had the highest expansion ratio. There was no difference between air cell size of the extrudates at all TDF levels. The 48% TDF level was significantly different from the other fiber levels for both expansion ratio and air cell size, except for wheat fiber. No expansion was observed at the 48% TDF level (Appendix C Fig. C1), nor were there any air cells present (Appendix C Fig. C2). There was more of a layered effect observed in the extrudate interior for all samples. Generally, as the amount of fiber increased in the extrudates, regardless of fiber type, extrudate air cells were smaller and more numerous. Fiber particle size has been shown to reduce air cell size and reduce extrudate expansion (Moore and others 1990; Lue and others 1991; Huber 2001). Powdered cellulose may have more air cells present than the other fiber types and less unexpanded material despite no differences in air cell size between fiber types. However, expansion ratio and air cell size is also influenced by moisture content of the extrudate, extrudate temperature, pressure during extrusion and the water absorption of the fiber and starch in the extrudate. These factors will be discussed below. All fiber types were significantly less than the control (0% TDF) for both expansion ratio and air cell size at every fiber level.

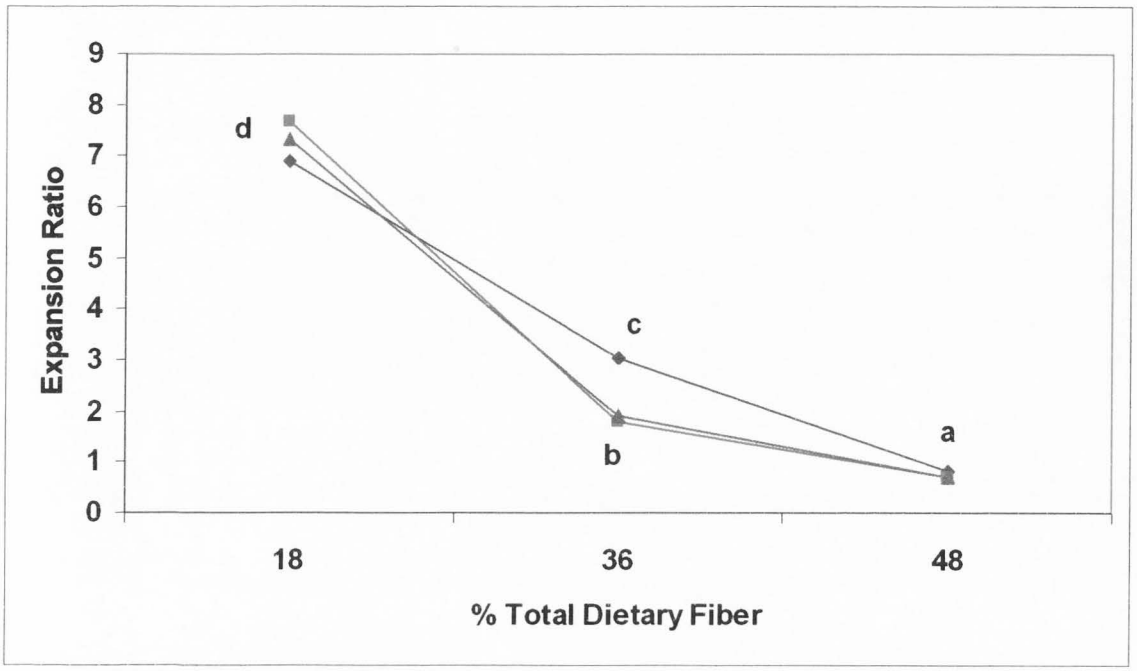


Fig. 1. Expansion ratio of extrudates (♦, Powdered Cellulose; ■, Wheat; ▲ Oat). Control (0% TDF), not shown, has a mean of 13.49 and letter sharing of 'e'. Points are means of all three extrusion blocks. Means sharing letter are not different at $p > 0.05$.

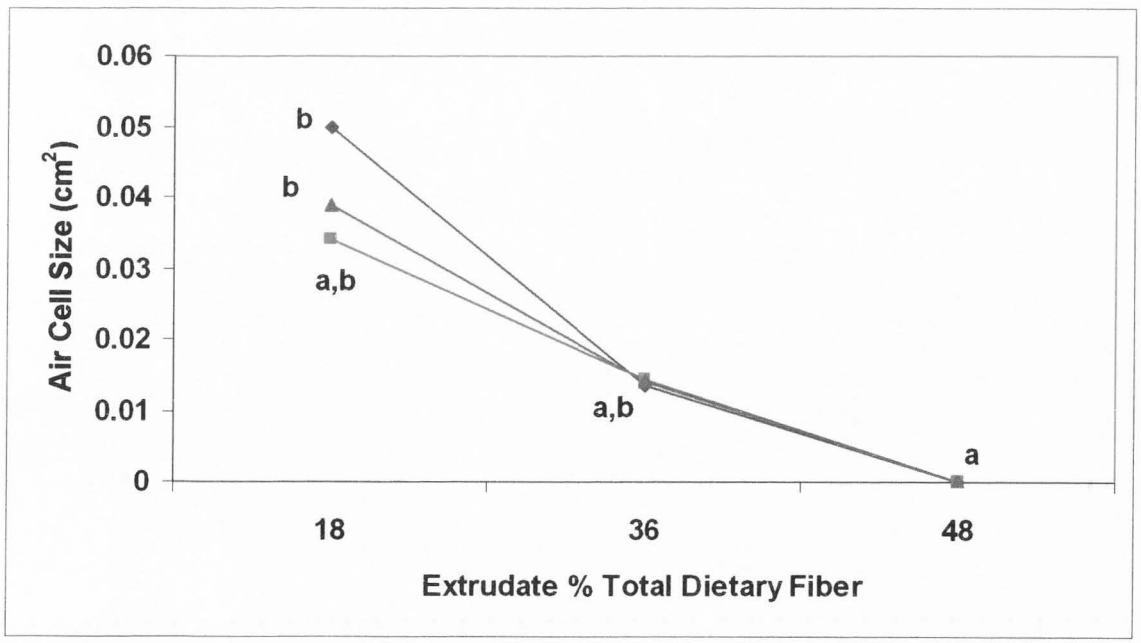


Fig. 2. Air cell size of extrudates (♦, Powdered Cellulose; ■, Wheat; ▲ Oat). Control (0% TDF), not shown, has a mean of 0.22195 and letter sharing of 'c'. Points are means of all three extrusion blocks. Means sharing letter are not different at $p > 0.05$.

Expansion ratio is attributed to the degree of starch gelatinization. As stated previously, dietary fibers binds water more tightly than starch (Harper 1981; Gomez and Aguilera 1984; Bhattacharya and Hanna 1987; Moraru and Kokini 2003). As more water is structurally bound by fiber, less water is made available for starch gelatinization and moisture flash-off as the extrudate leaves the die (Onwulata and others 1998; Lue and others 1991). This would result in decreased extrudate expansion as less steam would be available to act as a leavening agent (Camire 1991). Decreased expansion may be a result of insufficient starch in the extrudate and not just the presence of dietary fiber.

Extrudate density (Fig. 3) and breaking force (Fig. 4) where both influenced by fiber type, fiber level and the fiber type/fiber level interactions with $p < 0.0001$ for all parameters. The same trends were observed with density and breaking strength. Each fiber type at 48% TDF was significantly different than the other fiber levels. Each fiber type had an increase in extrudate density and breaking force as the fiber level increased. Thus, as breaking strength and density increased, extrudate expansion ratio and air cell size decreased. Powdered cellulose had the lowest density and breaking strength. Wheat usually had the highest density and breaking strength at all fiber levels. There was no difference between samples and the control for breaking force at 18% TDF. Powdered cellulose was not significantly different from the control at 18% TDF for density. Despite no differences between fiber types with air cell size at 36 and 48% TDF, and expansion ratio at 48% fiber levels, there were differences between fiber types with density and breaking strength at 36 and 48% TDF levels. Other parameters, such as WAI and moisture, may affect the expansion ratio and air cell formation in the extrudates.

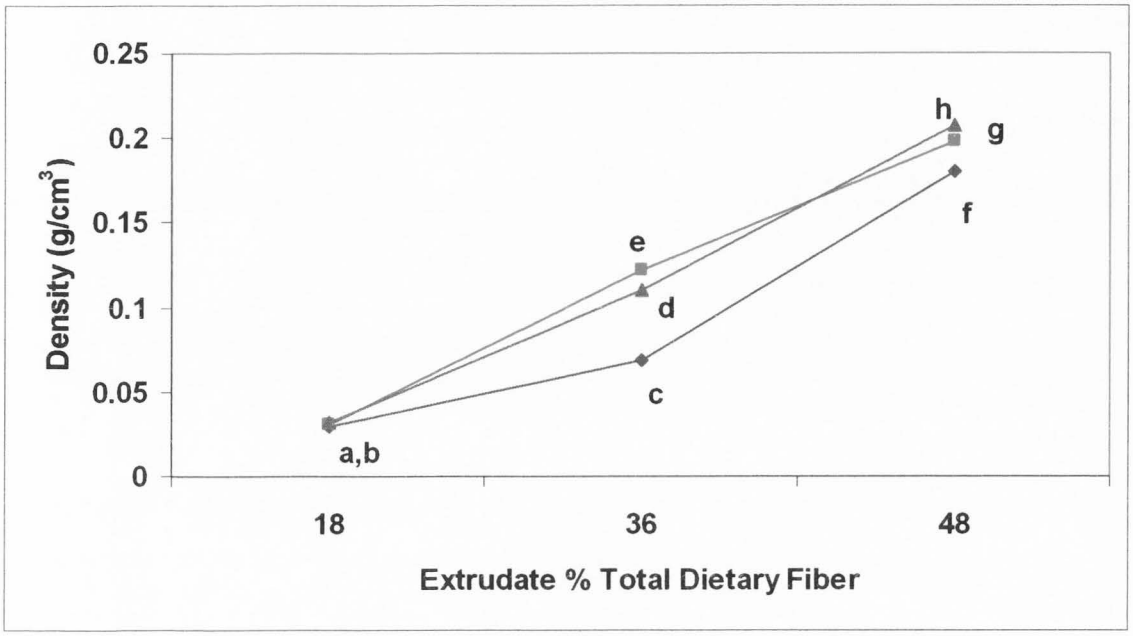


Fig. 3. Extrudate density (♦, Powdered Cellulose; ■, Wheat; ▲, Oat). Control (0% TDF), not shown, has a mean of 0.0225 and letter sharing of 'a'. Points are means of all three extrusion blocks. Means sharing letter are not different at $p > 0.05$.

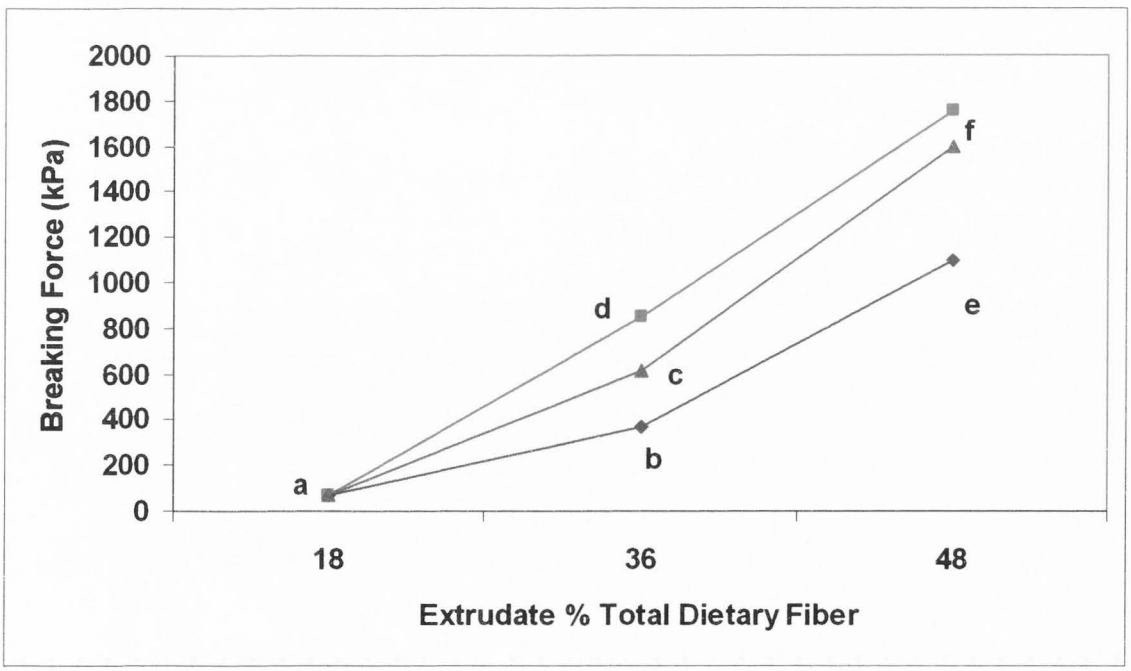


Fig. 4. Breaking force of extrudates (♦, Powdered Cellulose; ■, Wheat; ▲, Oat). Control (0% TDF), not shown, has a mean of 16.68 and letter sharing of 'a'. Points are means of all three extrusion blocks. Means sharing letter are not different at $p > 0.05$.

**Correlations of Physical Parameters**

All physical parameters were significantly correlated with each other (Table 6). Air cell size was negatively correlated with density and breaking force. Density and breaking force were positively correlated with one another. Cross-sectional images of extrudates support these relationships (Appendix C Fig. C2). As the fiber level increased, less expansion was seen, with a decrease in air cell size associated with a denser, harder extrudate. Expansion ratio was negatively correlated with density, breaking strength and positively correlated with air cell size (Table 6) as consistent with findings of Rinaldi and others (2000). Jin and others (1995) attributed decreased expansion to the thickening of the extrudate cell walls and decreased air cell size. Fiber has also been shown to cause premature rupture of air cells thereby reducing air cell size and expansion (Moore and others 1990). Moore and others (1990) found smaller air cell sizes would allow easy exit of steam, thereby limiting expansion of the dough matrix during the flashing process.

Table 6. Correlations among physical parameters. Bold text indicates significant ($p < 0.05$) coefficients

| | Expansion ratio | Air cell size | Density | Breaking force |
|---|---|---|---|---|
| Expansion ratio | 1.00 | | | |
| Air cell size | **0.83** | 1.00 | | |
| Density | **-0.83** | **-0.58** | 1.00 | |
| Breaking force | **-0.76** | **-0.53** | **0.97** | 1.00 |

Decreased expansion ratio will bring an increase in density and breaking strength. This is especially true when fiber level in the extrudates increased. This is a result of the fiber particles thickening the cell wall of the extrudates. The 48% TDF level yielded extrudates with no expansion and air cell size.

**Chemical Parameters**

Moisture content of extrudates was strongly influenced ($p < 0.0001$) by the level of fiber incorporated in the extrudate. Both WAI ($p < 0.0001$, $p = 0.0028$, $p < 0.0001$) and WSI ($P < 0.0001$, $p = 0.0371$, $p = 0.0013$) were strongly influenced by the fiber level, fiber type, and fiber level/fiber type interactions, respectively (for detailed statistics on chemical parameters see Appendix E Tables E1-E12).

Generally, moisture content (Fig. 5) and WAI (Fig. 6) increased with increasing fiber level of the extrudate. With moisture content, there was no difference between fiber types at each fiber level. The 48% TDF level was statistically different from the other fiber levels. Oat fiber at 18% TDF level was the only fiber type to not be statistically different from the control. The significant increase of moisture content at 48% TDF level can be attributed to increase fiber leading to more water being bound during extrusion (Moraru and Kokir, 2003; Onwulata and others 1998). Thus, as more water is structurally bound by fiber, less water may become available for moisture flash-off as the extrudate leaves the die (Onwulata and others 1998; Lue and others 1991), allowing for extrudates with higher moisture content.

The WAI is the amount of water an extrudate can absorb. WAI is usually dependent on the starch present in the extrudates. It was found that WAI generally exhibited an increase with an increase in fiber. There were no differences between fiber types at 18% TDF. However, at the 36% and 48% TDF levels, powdered cellulose was statistically different from the other fiber types. Powdered cellulose had no differences in WAI at all fiber levels. Both oat and wheat fibers were not statistically different from each other at all fiber levels. Oat and wheat fibers absorbed the most water, thus having

the highest WAI. Powdered cellulose at 48% TDF was significantly different from the control and oat and wheat fibers.

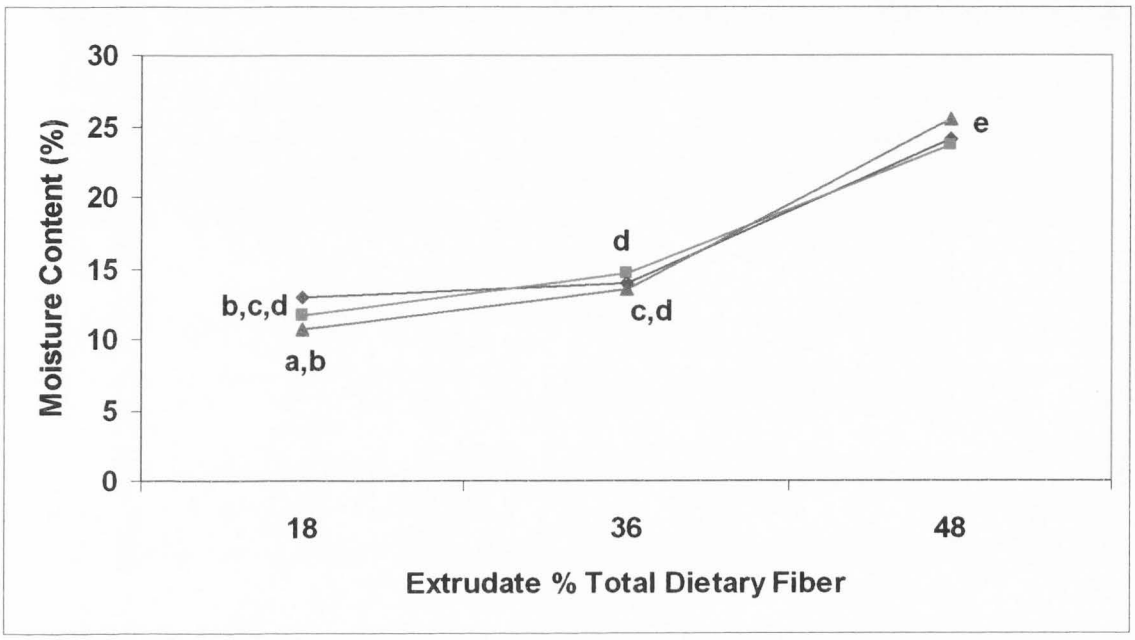


Fig. 5. Moisture content of extrudates (♦, Powdered Cellulose; ■, Wheat; ▲, Oat). Control (0% TDF), not shown, has a mean of 9.7325 and letter sharing of 'a'. Points are means of all three extrusion blocks. Means sharing letter are not different at $p > 0.05$.

Unlike moisture content and WAI, the ability of extrudates to be solublilized by water (WSI) was decreased with an increase of fiber (Fig. 7). This is consistent with the findings of Jin and others (1995) who reported an increase of fiber in extrudates from 20% up to 40% caused an increase in WAI and a decrease in WSI. All fibers had significantly less WSI values than the control at all fiber levels. Generally, there was no difference in WSI between fiber types at each fiber level. Oat and wheat extrudates were more likely to absorb water than dissolve in water with an increase of fiber. At each fiber level, regardless of fiber type, WSI and WAI values were statistically different.

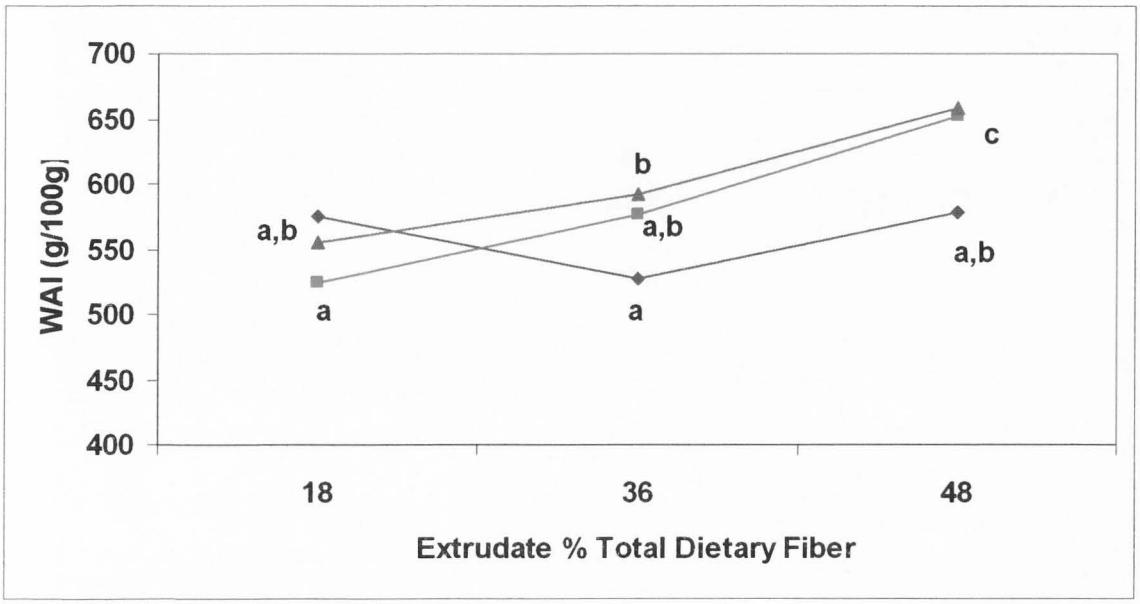


Fig. 6. WAI of extrudates (♦, Powdered Cellulose; ■, Wheat; ▲,Oat). Control (0% TDF), not shown, has a mean of 707.33 and letter sharing of 'c'. Points are means of all three extrusion blocks. Means sharing letter are not different at $p > 0.05$.

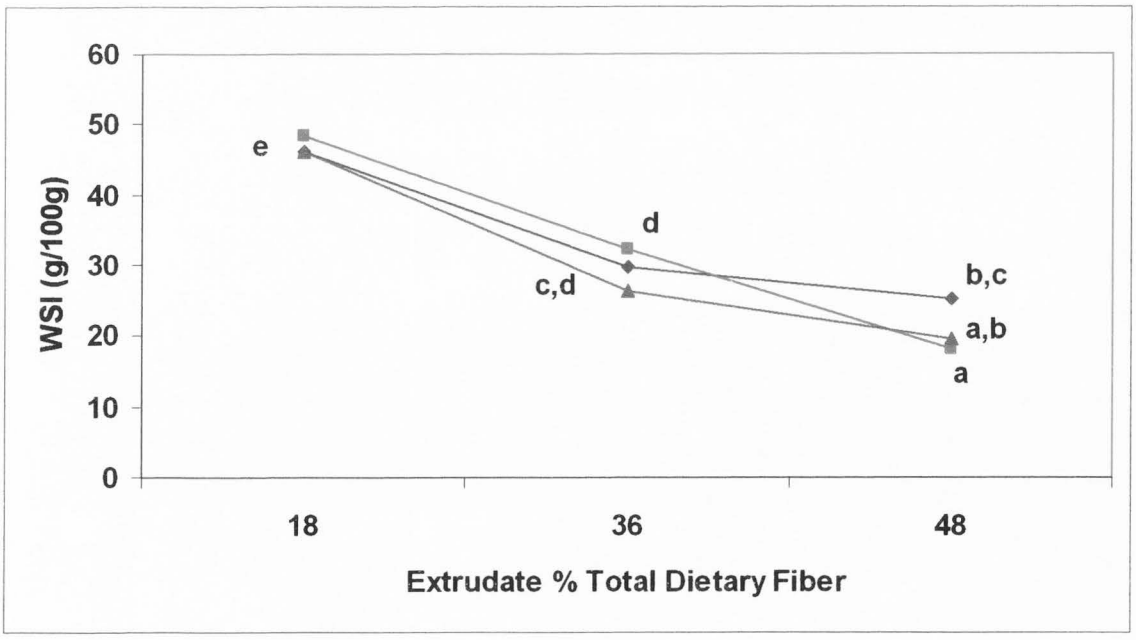


Fig. 7. WSI of extrudates (♦, Powdered Cellulose; ■, Wheat; ▲, Oat). Control (0% TDF), not shown, has a mean of 55.64 and letter sharing of 'f'. Points are means of all three extrusion blocks. Means sharing letter are not different at $p > 0.05$.

The total percentage of protein in extrudates resolublized after extrusion (total soluble protein) was influenced by the level of fiber ($p = 0.0278$) and the type of fiber used ($p = 0.0278$). Total soluble protein (Fig. 8) generally increased as the fiber level increased. However, powdered cellulose at the 48% TDF was higher in total soluble protein from the control and all levels of oat fiber. Generally, extrudates had >45% of the protein resolubilized after extrusion. This is indicative of the protein's involvement in some form of covalent bonding or cross-linking with other protein molecules, or with starch and/or fiber components. It was expected that 100% of the protein from the extrudates would be resolubilized after extrusion. As mentioned in the methods for chemical tests, the protein of ground extrudate samples was solubilized by the addition of SDS, thereby, denaturing the proteins. Any proteins involved with disulfide bonds were cleaved by the addition of BME and thus were able to be denatured and resolubilized after extrusion.

Water soluble protein ($p < 0.0001$, $p = 0.004$, $p < 0.0001$) and water soluble carbohydrate ($p = 0.0004$, $p < 0.0001$, $p < 0.0001$) were strongly influenced by fiber level, fiber type and fiber level/fiber type interaction, respectively. The percentage of protein soluble in water after extrusion (water soluble protein) was generally not significantly different between fiber types at any fiber level (Fig. 9). Water soluble protein for the control and oat at 48% TDF were significantly higher than all other fiber levels and fiber types.

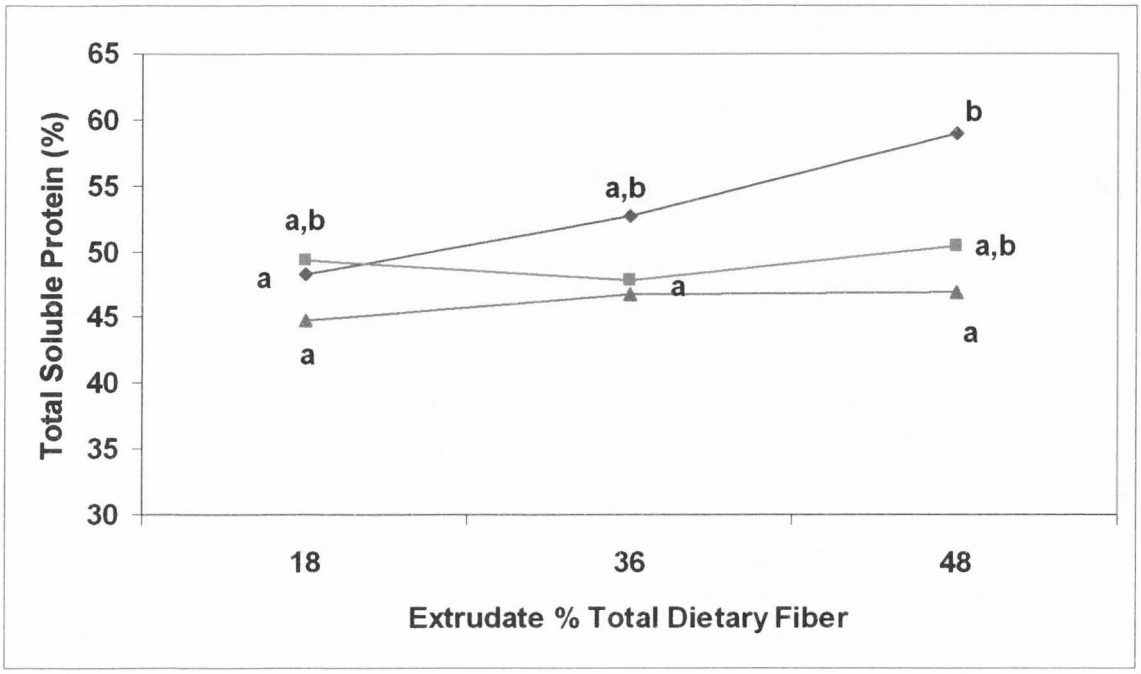


Fig. 8. Total soluble protein of extrudates (♦, Powdered Cellulose; ■, Wheat; ▲, Oat). Control (0% TDF), not shown, has a mean of 47.16 and letter sharing of 'a'. Points are means of all three extrusion blocks. Means sharing letter are not different at $p > 0.05$.

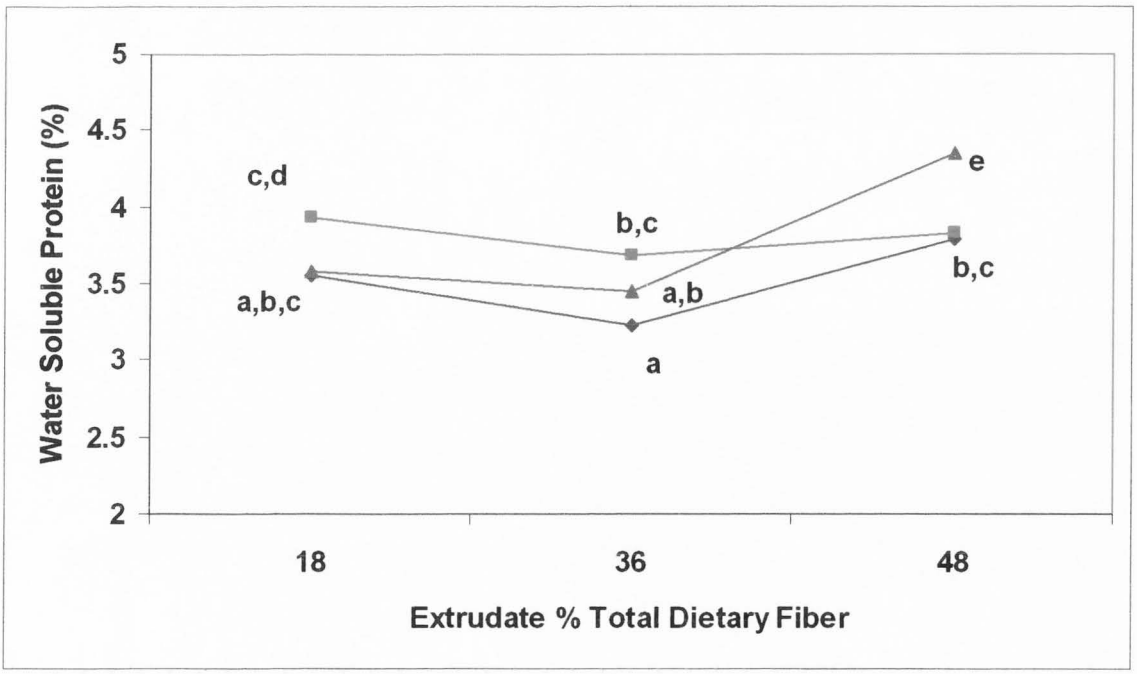


Fig. 9. Water soluble protein of extrudates (♦, Powdered Cellulose; ■, Wheat; ▲, Oat). Control (0% TDF), not shown, has a mean of 4.25 and letter sharing of 'e'. Points are means of all three extrusion blocks. Means sharing letter are not different at $p > 0.05$.

Different trends were observed for water soluble carbohydrate after extrusion (Fig. 10). The control was only significantly different the powdered cellulose at 48% TDF and the oat fiber at 18% TDF. No trend was observed for powdered cellulose and wheat fiber with an increase in fiber. Powdered cellulose was significantly higher than the wheat fiber at every fiber level. Oat fiber had a significant decrease in water soluble carbohydrate at the 36% TDF level.

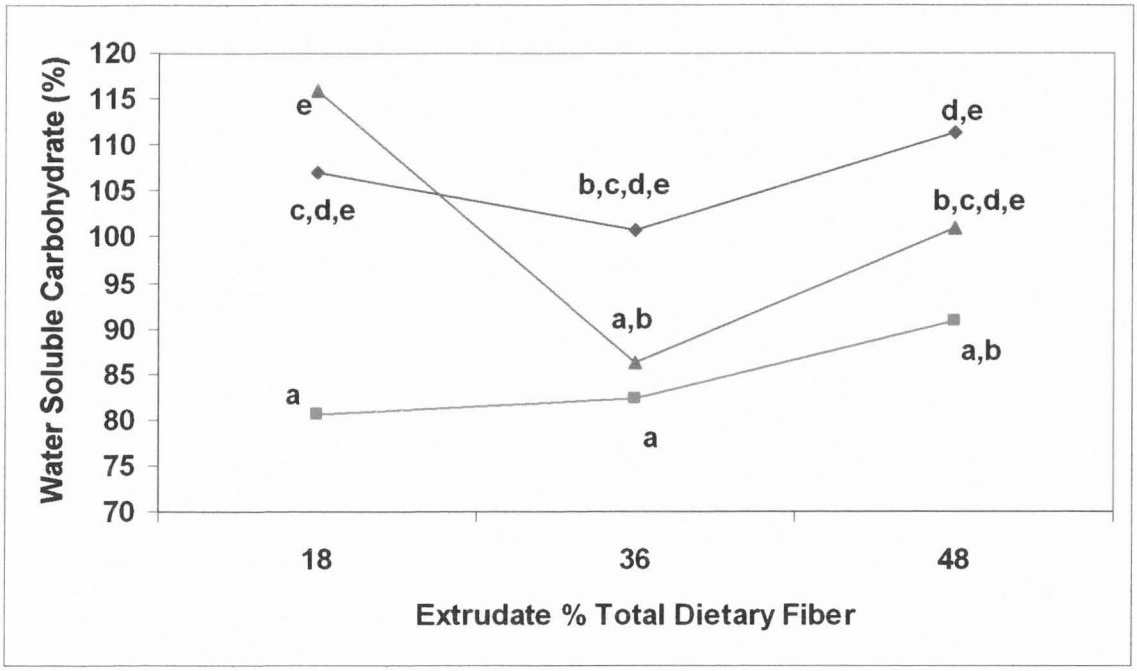


Fig. 10. Water soluble carbohydrate of extrudates (♦, Powdered Cellulose; ■, Wheat; ▲, Oat). Control (0% TDF), not shown, has a mean of 98.02 and letter sharing of 'a,b,c,d'. Points are means of all three extrusion blocks. Means sharing letter are not different at $p > 0.05$.

Water soluble carbohydrate was affected by both fiber content and fiber type. Hemicellulose, cellulose, and lignin have increased solubility through hydrolysis, dextrinization and or thermal degradation into low molecular weight fragments during extrusion (Fornal and others 1987; Huber 1991; Lue and others 1991; Camire and Flint 1991; Lukesova and others 1996; Gualberto and others 1997). The open structure and

low stability of the glucosidic bonds between pentose and hexose sugar units allow for easy hydrolysis of hemicellulose. Thus, soluble carbohydrate will be shifted upward about 4-5% (Huber 1991). This will account for the water soluble carbohydrate values above 100% for powdered cellulose and oat fiber. It is difficult to interpret the changes in water soluble carbohydrate because the fractions of dietary fiber (i.e. cellulose, hemicellulose, lignin) that comprise the fiber types are not known. The processing conditions of the fibers can affect functional properties of the fibers such as solubility. Wheat fiber had less water soluble carbohydrate than the control and the other fiber types but followed the same trend as the other fiber types between 36 and 47% TDF. The interactions of protein, starch and fiber, regardless of the fiber type or fiber level, are ambiguous and further analysis is needed. The fragmentation of fiber will affect analysis of WSI and WAI values. As stated before, the increase in WAI and decrease in WSI may reflect more of the nature of the fiber in the extrudates than the starch.

**Correlations Among Physical and Chemical Parameters**

There were limited correlations among chemical parameters (Table 7). Moisture content was negatively correlated with WSI. Water soluble protein and WAI were both positively correlated with WSI. WAI was also positively correlated with water soluble protein. These correlations may all be due to the presence of fiber in the extrudate.

Moisture content and WSI (Table 8) were strongly correlated with all four physical parameters (expansion ratio, air cell size, density, and breaking force). WAI was positively correlated with expansion ratio and air cell size. In general, WAI and WSI decreased, as the amount of fiber increased and starch decreased in extrudates. Thus,

more moisture was retained in the extrudate by the fiber preventing flash evaporation at the die causing extrudates to have smaller air cells, with less expansion and an increase of extrudate density and breaking force (Figs. 1-7, Appendix C Figs. C1 and C2). This is consistent with findings of Camire and King (1991).

Table 7. Correlations among chemical parameters. Bold text indicates significant ($p < 0.05$) coefficients

| | Moisture content | WAI[a] | WSI[b] | Water soluble carbohydrate | Total soluble protein | Water soluble protein |
|---|---|---|---|---|---|---|
| Moisture content | 1.00 | | | | | |
| WAI[a] | -0.03 | 1.00 | | | | |
| WSI[b] | **-0.80** | **0.31** | 1.00 | | | |
| Water soluble carbohydrate | -0.05 | 0.12 | 0.12 | 1.00 | | |
| Total soluble protein | 0.14 | -0.03 | -0.13 | 0.12 | 1.00 | |
| Water soluble protein | -0.04 | **0.46** | **0.30** | -0.02 | -0.07 | 1.00 |

a. Water absorption index
b. Water solubility index

Water soluble protein had low correlation with water soluble carbohydrate (Table 7) and was positively correlated with expansion ratio and air cell size (Table 8). There was very little water soluble protein at all fiber levels as well as for the control. Total soluble protein generally increased as fiber increased. Total soluble protein was not correlated with any chemical parameter (Table 7).

Since expansion ratio had low correlation with total and water soluble protein (Table 8), it was concluded that increased fiber was responsible for decreased expansion ratio rather than possible covalent interactions of starch and protein (Matthey and Hanna

1997; Taylor and others 2006). In contrast, water soluble carbohydrate was negatively correlated with expansion ratio and air cell size (Table 8). Water soluble carbohydrate analysis showed the control to have on average 98% solubility. Therefore, there were virtually no protein-starch covalent interactions in the control. The protein may have been involved in other covalent protein-protein interactions. Other possible reactions to decrease protein solubility may be Maillard or isopeptide reactions (Li and Lee 1998; Onwulata and others 1998; Taylor and others 2006).

Table 8. Correlations among physical and chemical parameters. Bold text indicates significant ($p < 0.05$) coefficients

| | Expansion ratio | Air cell size | Density | Breaking force |
|---|---|---|---|---|
| Moisture content | **-0.72** | **-0.54** | **0.90** | **0.84** |
| WAI[a] | **0.46** | **0.58** | -0.04 | 0.03 |
| WSI[b] | **0.92** | **0.71** | **-0.89** | **-0.82** |
| Water soluble carbohydrate | 0.05 | 0.00 | -0.04 | -0.05 |
| Total soluble protein | **-0.15** | 0.11 | **0.14** | 0.18 |
| Water soluble protein | **0.36** | **0.39** | -0.01 | 0.05 |

a. Water absorption index
b. Water solubility index

Total soluble protein was positively correlated with density and negatively correlated with expansion ratio (Table 8). It appears that correlations are partly due to fiber type. Powdered cellulose had the lowest density and breaking force at every fiber level with the highest total soluble protein and water soluble carbohydrate (Figs. 3, 4, 8, 10). Water soluble protein was the lowest for powdered cellulose (Fig. 9). The opposite was seen for the other two fibers in all cases. The differences total soluble protein, water

soluble protein, water soluble carbohydrate, density, and expansion ratio among fiber types are due to the compositional differences among fiber samples. Further analysis of the fiber components is needed to better understand the effects on extrudate characteristics.

**Extrusion Parameters**

Extrusion pressure was influenced by the level of fiber ($p<0.0001$) and by the type of fiber ($p = 0.0109$) (for detailed statistics on extrusion parameters see Appendix F Tables F1-F15). Pressure for all fiber types decreased at the 48% TDF (Fig. 11). At 36 and 48% TDF, there was no significant difference between fiber types.

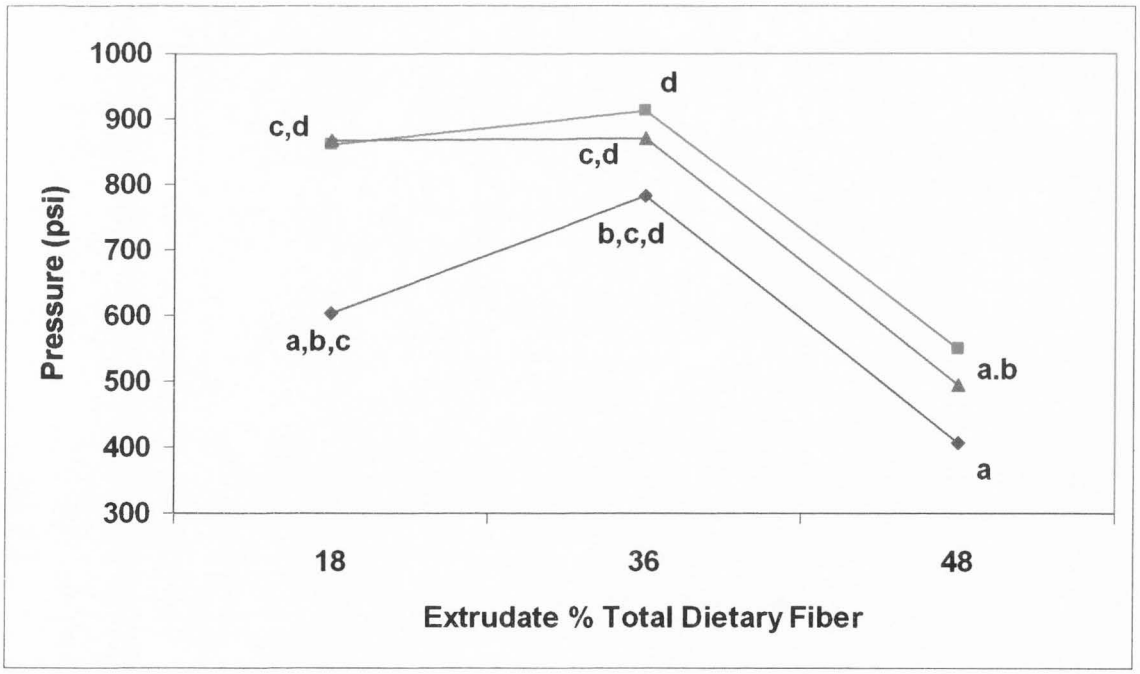


Fig. 11. Pressure during extrusion. (♦, Powdered Cellulose; ■, Wheat; ▲, Oat). Control (0% TDF), not shown, has a mean of 970 and letter sharing of 'd '. Points are means of triplicate extrusion runs. Means sharing letter are not different at $p > 0.05$.

Motor torque was greatly influence by the level of fiber ($p < 0.0001$) and by the interaction between the fiber level and fiber type ($p = 0.0408$). Unlike pressure, there was a statistically significant decrease of motor torque with an increase of fiber replacement at all levels (Fig. 12). Like pressure, there was no difference between fiber types at the 36 and 48% TDF levels. Powdered cellulose at the 18% TDF level was significantly different than the other fiber types and the control. A decrease in motor torque shows that less force is applied to the mix in the extruder.

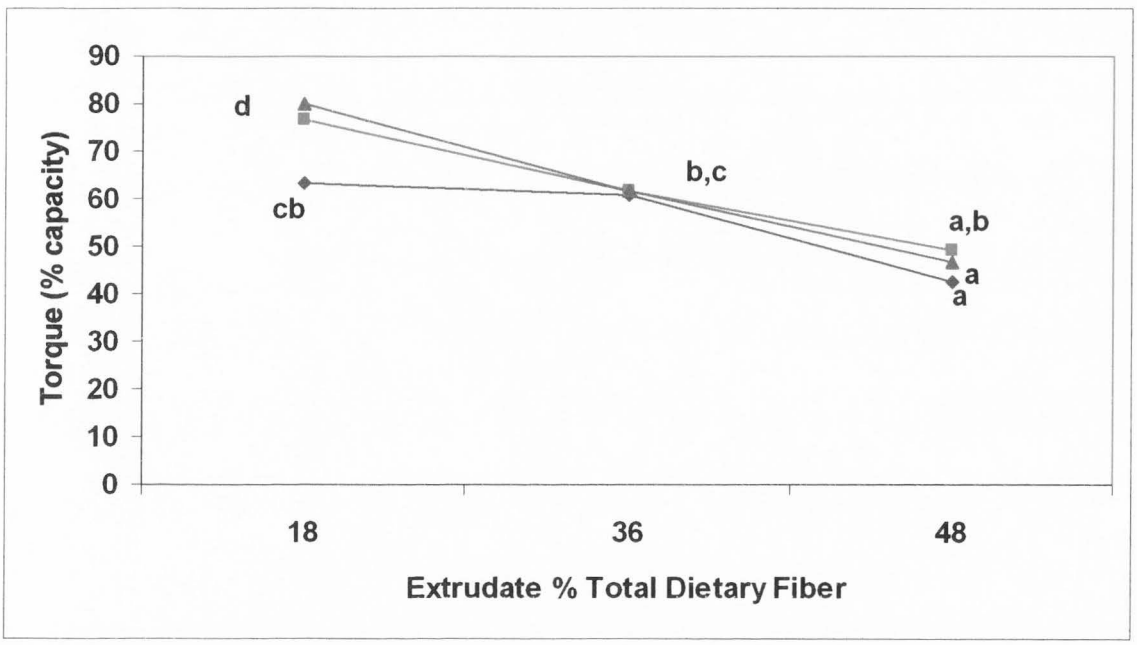


Fig. 12. Motor torque during extrusion. (♦, Powdered Cellulose; ■, Wheat; ▲, Oat). Control (0% TDF), not shown, has a mean of 86.67 and letter sharing of 'd '. Points are means of triplicate extrusion runs. Means sharing letter are not different at $p > 0.05$.

The temperature of the mixture (TOM) in the barrel of the extruder was significantly influenced only by the level of fiber addition ($p < 0.0001$). Die TOM was influenced by level of fiber, fiber type, and fiber type/ fiber level interactions ($p < 0.0001$, $p = 0.0146$, $p = 0.0397$, respectively). Die temperature was influenced by level of fiber,

fiber type, and fiber type/ fiber level interactions ($p < 0.0001$, $p < 0.0001$, $p < 0.0001$, respectively). The level of fiber significantly influenced barrel temp ($p < 0.0001$).

For all extrudates, TOM inside the barrel and die significantly decreased at the 48% TDF level (Figs. 13 and 14). There was no trend observed between fiber types. There was no difference for wheat fiber at all fiber levels for die TOM. Due to equipment malfunction, die TOM was not recorded for any extrusion runs of powdered cellulose extruded at 36% fiber level.

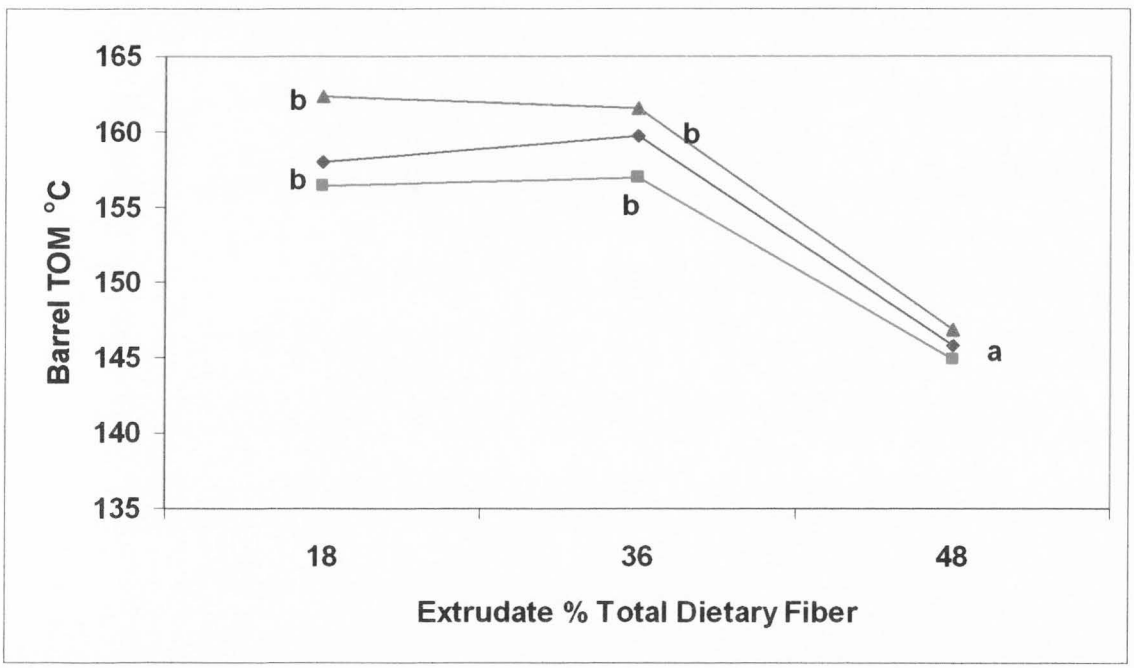


Fig. 13. TOM inside end of barrel during extrusion. (♦, Powdered Cellulose; ■, Wheat; ▲, Oat). Control (0% TDF), not shown, has a mean of 159.33 and letter sharing of 'b '. Points are means of triplicate extrusion runs. Means sharing letter are not different at $p > 0.05$.

With die temperature, there was no difference between fiber types at the 48% TDF level (Fig. 15). All fiber types had a decrease in die temperature at 48% TDF. Powdered cellulose and oat fiber had no difference between the 18 and 36% TDF levels

but both were statistically different from the 48% TDF level of fiber replacement. Powdered cellulose at the 18 and 36% TDF levels was statistically different from the oat and wheat fibers. Barrel temperature exhibited a similar trend (Fig. 16). There were no differences between fiber types at any fiber level. The highest level of TDF (48%) showed a statistically significant difference between the other replacement levels.

Residence time (the amount of time the mix was inside the extruder), significantly increased at the 48% TDF level (Fig.17). The level of fiber addition ($p < 0.0001$) greatly influenced residence time. This is a result of decreased feed rate and screw speed with an increase in fiber to optimize extrusion. There was no difference between fiber types.

Product flow rate (Fig. 18) was only influenced by the level of fiber incorporation ($p < 0.0001$). Fiber type did not affect product flow rate. Generally, product flow rate decreased with an increase in fiber level of the extrudate.

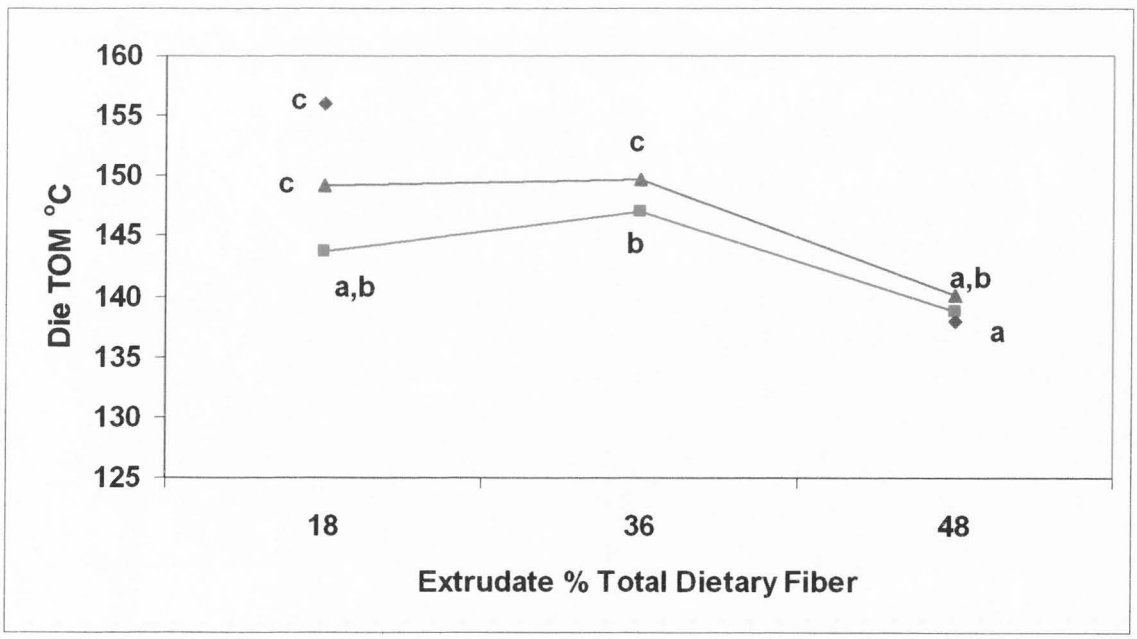


Fig. 14. TOM inside die during extrusion. (♦, Powdered Cellulose; ■, Wheat; ▲, Oat). Control (0% TDF), not shown, has a mean of 147.60and letter sharing of 'b '. Points are means of triplicate extrusion runs. Means sharing letter are not different at $p > 0.05$.

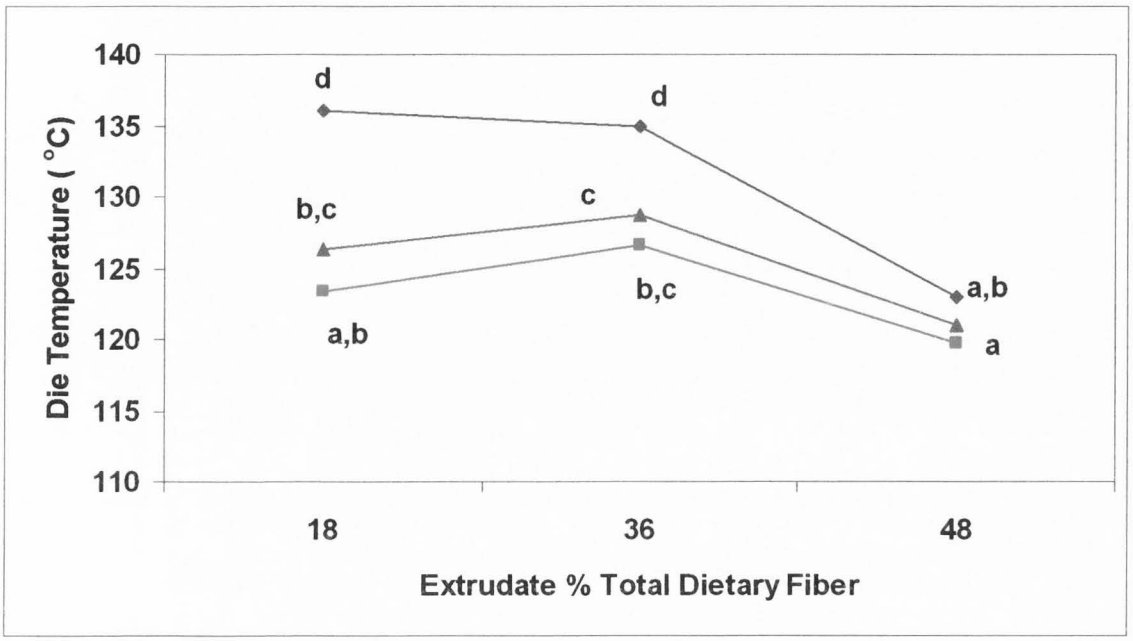


Fig. 15. Observed die temperature during extrusion. (♦, Powdered Cellulose; ■, Wheat; ▲, Oat). Control (0% TDF), not shown, has a mean of 129.33 and letter sharing of 'c '. Points are means of triplicate extrusion runs. Means sharing letter are not different at $p > 0.05$.

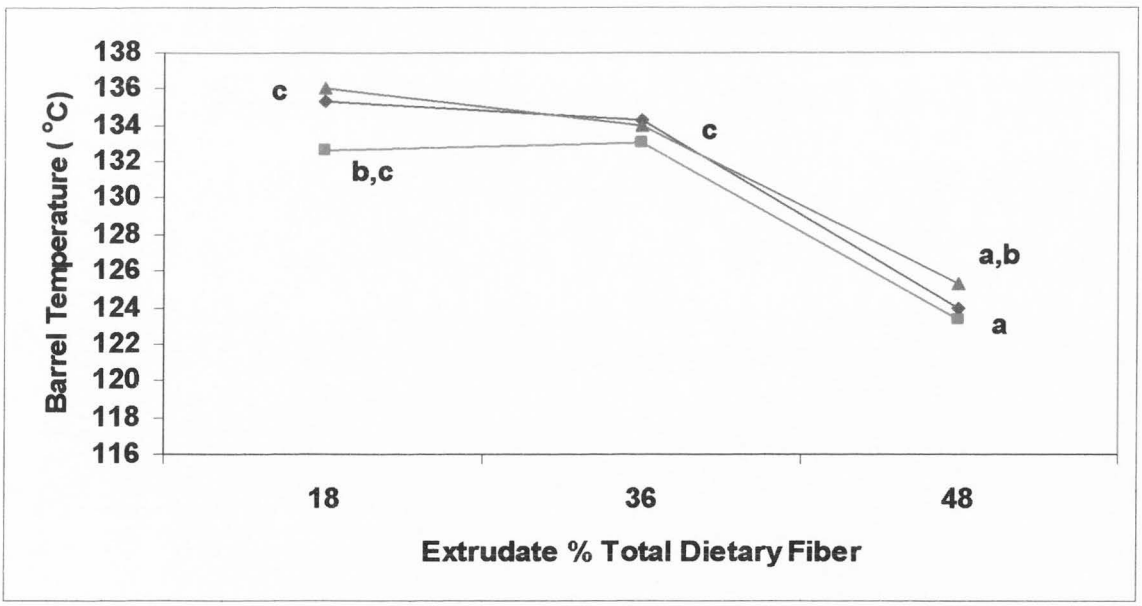


Fig. 16. Observed barrel temperature during extrusion. (♦, Powdered Cellulose; ■, Wheat; ▲, Oat). Control (0% TDF), not shown, has a mean of 135.67 and letter sharing of 'c '. Points are means of triplicate extrusion runs. Means sharing letter are not different at $p > 0.05$.

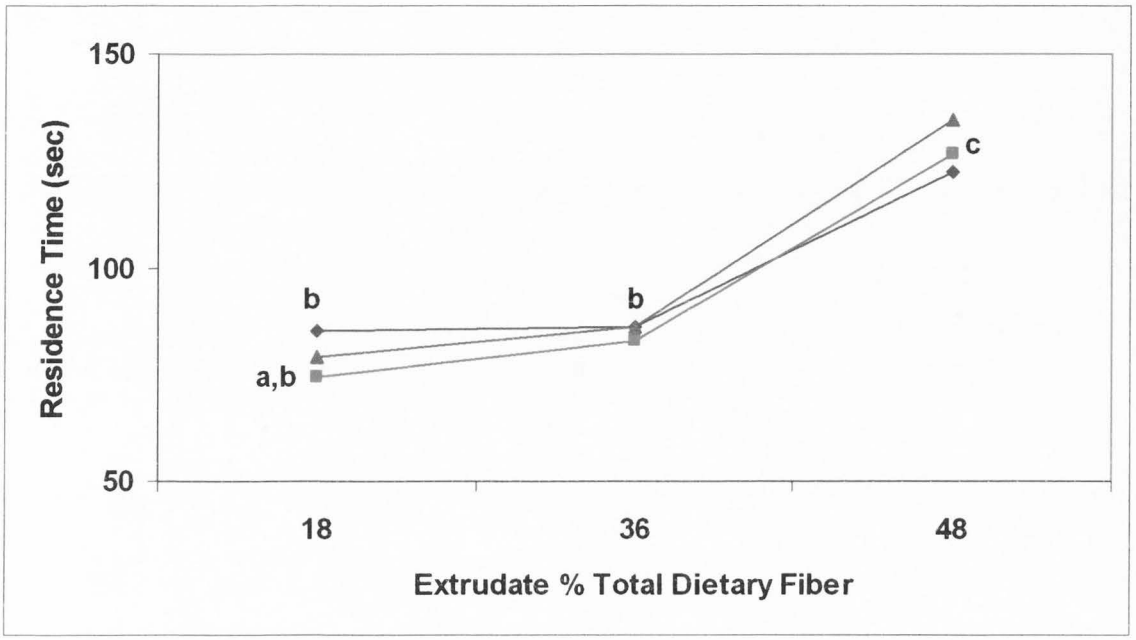


Fig. 17. Residence time during extrusion. (♦, Powdered Cellulose; ■, Wheat; ▲, Oat). Control (0% TDF), not shown, has a mean of 66.67 and letter sharing of 'a '. Points are means of triplicate extrusion runs. Means sharing letter are not different at $p > 0.05$.

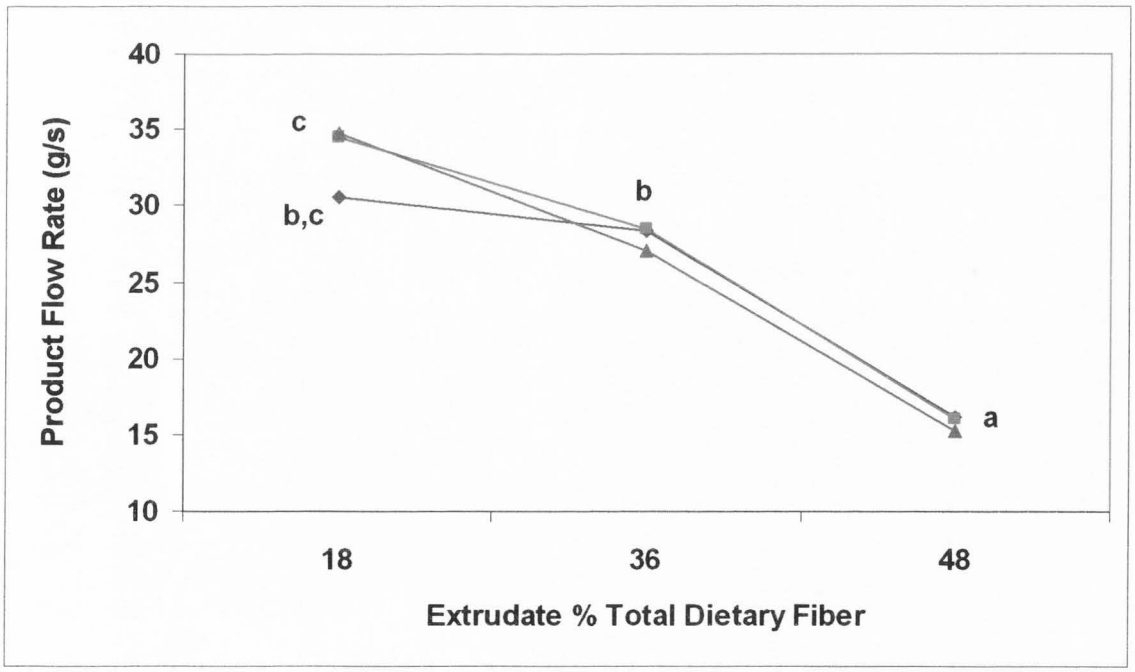


Fig. 18. Product flow rate during extrusion. (♦, Powdered Cellulose; ■, Wheat; ▲, Oat). Control (0% TDF), not shown, has a mean of 42.45 and letter sharing of 'e '. Points are means of triplicate extrusion runs. Means sharing letter are not different at $p > 0.05$.

**Correlations Among Physical, Chemical, and Extrusion Parameters**

All extrusion parameters were significantly correlated with one another, except for observed die temperature (Table 9) and generally, only the physical parameters were correlated with extrusion parameters (Table 10). As noted earlier, a decrease in expansion ratio was seen with an increase in fiber. This may also be attributed to pressure. Chinnaswamy and Hanna (1987) found the best expansion of starch extrudates occurred at 7 MPa or 1000 PSI. Even though these findings were for starch extrudates, there is probably an optimal extrusion pressure for maximum expansion in extrudates containing fiber. If the optimal pressure for fiber extrudates could be maintain during extrusion, maximal expansion could be achieved. Pressure was difficult to increase with the 48% TDF level because screw speed and dry feed rate had to be reduced to keep motor torque down in order to facilitate extrusion of such a high fiber formula. All extrusion parameters except residence time decreased at the 48% TDF level. This is consistent, since residence time was negatively correlated with all extrusion parameters.

The decrease in all temperature readings appears to also cause negative effects on extrudate characteristics. Heat generated from the extruder into the mixture can melt the proteins and gelatinize starch. Heat is necessary to cause vaporization of moisture at the die as the extrudate exits. A decrease in temperature can lead to a low viscosity of the extruder melt. This is detrimental to extrudate expansion, since the cellular matrix within the extrudate is unable to withstand the high vapor pressure upon exiting the extruder die and will collapse (Moraru and Kokini 2003). Alternatively, high temperatures can weaken the cellular matrix through either excessive softening and potential structural degradation of the starch melt (Moraru and Kokini 2003). Thus, a decrease in

temperature or an increase in temperature above an optimal temperature can reduce extrudate expansion (Moraru and Kokini 2003).

As screw speed and product flow rates changed for the various fiber levels, all dependent extrusion parameters were affected (Table 5). Even though independent extrusion parameters of dry feed rate, screw speed and temperature were optimized, it may be possible to improve on extrudate characteristics with increased fiber. Further manipulation of extrusion parameters may allow for desirable extrudate characteristics such as improved expansion ratio and decreased breaking strength even at high levels of fiber.

Table 9. Correlations among extrusion parameters. Bold text indicates significant ($p < 0.05$) coefficients

| | Pressure | Torque | Res. Time | Product Flow Rate | Die TOM | Barrel TOM | Die Temp | Barrel Temp |
|---|---|---|---|---|---|---|---|---|
| Pressure | 1.00 | | | | | | | |
| Torque | **0.81** | 1.00 | | | | | | |
| Residence Time | **-0.82** | **-0.88** | 1.00 | | | | | |
| Screw Speed | **0.61** | **0.59** | **-0.83** | | | | | |
| Dry Feed Rate | **0.64** | **0.66** | **-0.88** | | | | | |
| Product Flow Rate | **0.80** | **0.95** | **-0.94** | 1.00 | | | | |
| Die TOM | **0.53** | **0.55** | **-0.70** | **0.63** | 1.00 | | | |
| Barrel TOM | **0.77** | **0.69** | **-0.83** | **0.74** | **0.77** | 1.00 | | |
| Die Temp | 0.32 | **0.37** | **-0.60** | **0.51** | **0.88** | **0.70** | 1.00 | |
| Barrel Temp | **0.72** | **0.74** | **-0.85** | **0.80** | **0.81** | **0.95** | **0.71** | 1.00 |

Table 10. Correlations among extrudate physical, chemical, and extrusion parameters. Bold text indicates significant ($p < 0.05$) coefficients

| | Pressure | Torque | Res. time | Product flow | Die TOM | Barrel TOM | Die Temp | Barrel Temp |
|---|---|---|---|---|---|---|---|---|
| Moisture content | **-0.81** | **-0.88** | **0.96** | **-0.92** | **-0.74** | **-0.85** | **-0.63** | **-0.87** |
| WSI | **0.61** | **0.88** | **-0.83** | **0.91** | **0.49** | **0.55** | **0.37** | **0.65** |
| Expansion ratio | **0.61** | **0.90** | **-0.76** | **0.92** | **0.43** | **0.52** | **0.36** | **0.62** |
| Air cell size | **0.50** | **0.72** | **-0.61** | **0.77** | **0.40** | **0.37** | 0.28 | **0.48** |
| Density | **-0.68** | **-0.88** | **0.91** | **-0.93** | **-0.68** | **-0.78** | **-0.64** | **-0.84** |
| Breaking force | **-0.63** | **-0.77** | **0.87** | **-0.84** | **-0.69** | **-0.77** | **-0.65** | **-0.84** |
| Water soluble carbohydrate | 0.03 | 0.22 | -0.15 | 0.19 | 0.12 | 0.28 | 0.26 | **0.35** |
| Total soluble protein | 0.04 | -0.15 | -0.05 | -0.01 | -0.17 | 0.15 | 0.24 | 0.10 |
| Water soluble protein | 0.12 | 0.21 | 0.05 | 0.13 | -0.06 | -0.14 | -0.28 | -0.10 |
| WAI | 0.17 | 0.28 | -0.09 | 0.26 | .0.06 | -0.16 | -0.15 | -0.08 |

Liquid feed levels were kept the same throughout all extrusion runs. Manipulating liquid feed during extrusion will change extrudate characteristics. Increased liquid feed may allow for a higher dry feed rate, decreased residence time, faster screw speed, which could increase temperature and exiting pressure. Increased liquid feed may increase the amount of moisture available for starch gelatinization. This may also lead to improved extrudate characteristics such as expansion. However, the consumer acceptability of the extrudates will determine what is acceptable for extrudate characteristics both physically and chemically.

Interestingly, moisture content, WSI, and all physical parameters were correlated with all extrusion parameters. Moisture content, density, and breaking force were all highly positively correlated with residence time and negatively correlated with all other

extrusion parameters. The opposite held true for WSI and expansion ratio. Again, reducing residence time can help improved extrudate expansion since moisture content, breaking strength and density could be reduced, thereby improving expansion ratio and air cell size. Air cell size was generally positively correlated with all extrusion parameters. The exception was dry feed, die temperature and residence time. There was no correlation of air cell size with the dry feed rate or die temperature. The correlation with residence time was negative. No correlations among extrusion parameters were seen with WAI or total soluble protein.

**Conclusions**

Statistical differences were found between extrudates with the amount and type of fiber used. There was not always a linear association with the amount of fiber added and extrudate characteristics. Generally, the greatest differences with physical and chemical parameters were found with the extrudates with the highest fiber (48% TDF). There were differences between fiber types. Dependent extrusion parameters for extrudates with 18 and 36% TDF were generally comparable to the control (0% TDF). Chemical and physical characteristics were comparable between the control and extrudates with 18% TDF. Powdered cellulose was different from the wheat and oat fibers for most physical parameters. The fiber composition in powdered cellulose may account for differences among fiber types. The manufacturing and processing of each fiber type before extrusion may affect the performance of the fibers during extrusion. Finding a fiber with decreased water absorption ability could produce extrudates with decreased moisture and improved expansion.

The greatest factor affecting all parameters was the amount of fiber added to the extrudates. It is possible that the effects of fiber such as decreased air cell size, expansion ratio and increased density and breaking strength is due to the absence of starch and limited gelatinization and not solely the presence of fiber. Further manipulation in all extrusion parameters could change both physical and chemical effects on extrudates. Sensory evaluation testing is needed to determine acceptance or rejection of extrudates. In conclusion, the addition of dietary fiber > 30% in extruded products with limited starch is feasible, based on results of this study.

# SUMMARY AND FUTURE RESEARCH

In this study, dietary fiber was incorporated into an extruded snack product consisting of WPC80, normal cornstarch, and pregelatinized waxy cornstarch. Twelve different fiber types were extruded. From these twelve fiber samples, three dietary fiber types were selected for further research (powdered cellulose, wheat fiber and oat fiber). Selection was based on ease of extrusion, visible expansion, % TDF in the sample and sample availability. A 10 pound dry mix was made for each extrusion run consisting of WPC80, cornstarch and pregelatinized waxy cornstarch. Fiber replaced the normal cornstarch at levels of 30, 60, and 80% yielding extrudates with 16, 38, and 48% TDF. Each combination of fiber type and fiber level was extruded in triplicate. A control of WPC80, normal cornstarch and pregelatinized waxy cornstarch (0% TDF) was also extruded in triplicate. All extrusion samples had a total 32% protein (from WPC 80), and 10% pregelatinized waxy cornstarch. Cornstarch decreased based on the amount of fiber added.

Extrudate characteristics were evaluated based on physical parameters (expansion ratio, air cell size, density, and breaking strength) and chemical parameters (moisture content, WAI, WSI, water soluble carbohydrate, total and water soluble protein). The level of fiber had a greater impact than the type of fiber added on extrudate characteristics. Generally, as the amount of fiber increased, moisture content increased leading to decreased expansion ratio, WSI, and air cell size and an increase in total soluble protein, density, WAI, and breaking strength. Dependent extrusion parameters were evaluated. Compared to 0% TDF control, dietary fiber addition resulted in

decreased pressure, torque, temperatures and increased residence time. The greatest statistical differences were seen at 48% TDF extrudates for all evaluated parameters. It is unclear whether the increased amount of fiber affected chemical and physical parameters more so than the decrease in starch.

Dietary fiber can be incorporated into an extruded snack product. Extrudates with 18% TDF were comparable to extrudates with 0% TDF (control). Extrudates with 48% were significantly different than the control (0% TDF). It is concluded that 48% fiber addition under the aforementioned extrusion conditions is too high for product requirements of low extrudate density and high expansion ratio. Extrudates containing TDF as high as 36% may be acceptable for some products, such as chips, crackers, and other snack foods. Sensory testing evaluation of the extrudates is needed to indicate acceptance or rejection of dietary fiber enriched extrudates. Dietary fiber incorporation was shown to have effects on extrudate characteristics. Effects of fiber may be overcome through changes in fiber types, extrusion parameters, and reformulation (increase starch). Final end use of extrudates will determine what extrudate characteristics are needed and, hence, application of dietary fiber in extruded snack foods.

Further research is needed to illuminate the effects of fiber addition on an extruded high-fiber, high-protein snack food. Better understanding of extrusion on dietary fiber will improve development of dietary fiber analytical methods and the use of fiber in extruded products. Dietary fiber can produce extrudates with different characteristics such as an expanded product (18% TDF) to a very dense extrudate with no expansion (48% TDF). This allows for application to/and development of a wide range of extruded products. Different fiber combinations and fiber types may help overcome

detrimental extrudate characteristics. The possibility exists to incorporate dietary fiber even at levels >30% into extruded products.

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# APPENDICES

# Appendix A

## Extrusion Parameters for Fiber Selection

Table A1. Extrusion parameters for fiber selection. Set extrusion parameters of dry feed rate and screw speed and observed extrusion parameters of barrel temperature and die temperature.

| | **Feed rate** | **Barrel temp °C** | | | | **Die Temp** | **Screw seed** |
|---|---|---|---|---|---|---|---|
| **Fiber source** | **rpm** | **1** | **2** | **3** | **4** | **°C** | **rpm** |
| Orange fiber OF400 | 500 | 46 | 88 | 116 | 137 | 141 | 190 |
| Apple fiber AF 401 | 500 | 60 | 90 | 115 | 136 | 115* | 190 |
| Oat fiber HF 600 | 500 | 45 | 91 | 116 | 116 | 114* | 200 |
| Oat fiber HF 401 | 400 | 48 | 89 | 116 | 135 | 140 | 190 |
| Wheat Fiber WF 600 | 450 | 48 | 90 | 116 | 134 | * | 160 |
| Powdered Cellulose L601 | 500 | 45 | 89 | 115 | 136 | 140 | 180 |
| Oatvantage Oat fiber | 400 | 43 | 87 | 117 | 139 | 145 | 200 |
| Maizewize 60 | 400 | 42 | 88 | 115 | 132 | 145 | 160 |
| Maizewize 80 | 450 | 40 | 87 | 116 | 139 | 112* | 160 |
| Fibersol-2 | ** | | | | | | |
| Litesse | 400 | 45 | 76 | 113 | 136 | 113* | 190 |
| Oat Fiber X | ** | | | | | | |

*Either no readings were obtained or incorrect readings were obtained due to equipment malfunction.

**Extrusion run was not successful (i.e. product surging, seizing of extruded or inability to reach set extrusion parameters) and data could not be obtained.

# Appendix B

## Fiber Selection Extrudate Images

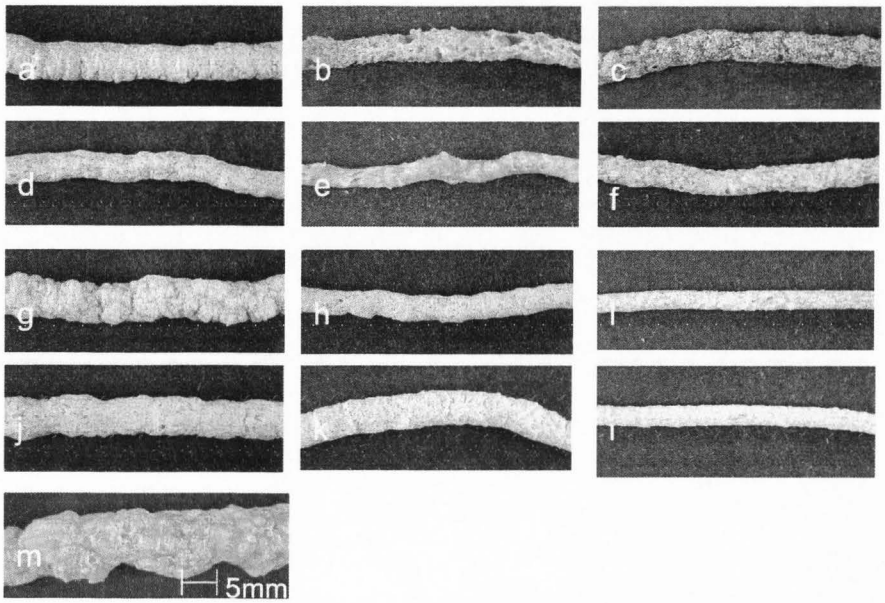


Figure B1. Fiber selection extrudate images. a. Vitacel Oat fiber HF600; b. Litesse; c. Vitacel apple fiber AF401; d. Oatvantage oat fiber; e. Fibersol-2; f. Maizewize 80 corn fiber; g. Maizewise 60 corn fiber; h. Vitacel orange fiber OF401; i. Vitacel oat fiber OF401; j. Vitacel powdered cellulose FCC L601; k. Vitacel wheat fiber WF600; l. Oat fiber X; m. Control (no fiber).

# Appendix C

## Exterior and Cross-sectional Images of Extrudates

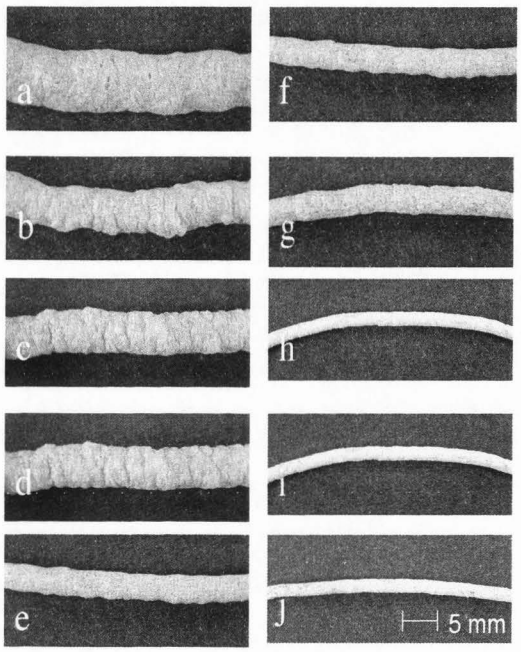


Figure C1. Exterior images of extrudates with 32% protein and varying levels of total dietary fiber (TDF). a, Control-32% WPC80 with no fiber; b, Powdered cellulose-18% TDF; c, Wheat fiber- 18% TDF; d, Oat fiber-18% TDF; e, Powdered cellulose-36% TDF; f, Wheat fiber- 36% TDF; g, Wheat fiber- 36% TDF; h, Powdered cellulose- 48% TDF; i, Wheat fiber-48% TDF; j, Oat fiber-48% TDF.

# Appendix C

## Exterior and Cross-sectional Images of Extrudates

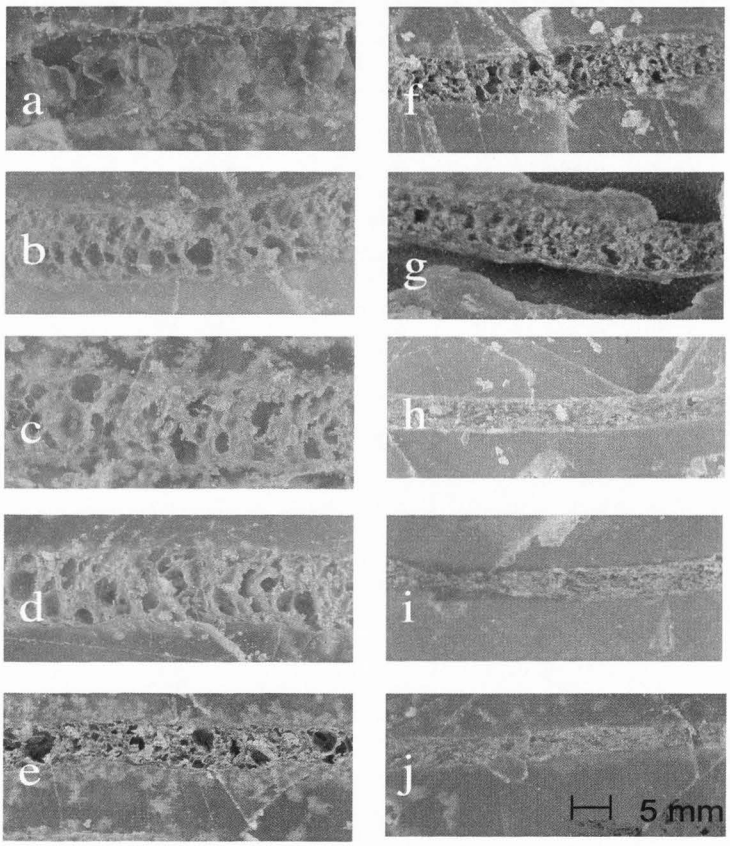


Figure C2. Air cell images of extrudates with 32% protein and varying levels of total dietary fiber (TDF). a, Control- 32% WPC80 with no fiber (0% TDF); b, Powdered cellulose-18% TDF; c, Wheat fiber- 18% TDF; d, Oat fiber- 18% TDF; e, Powdered cellulose- 36% TDF; f, Wheat fiber- 36% TDF; g, Wheat fiber- 36% TDF; h, Powdered Cellulose-48% TDF; i, Wheat fiber-48% TDF; j, Oat fiber-48% TDF.

# Appendix D

## ANOVA Tables, and Means for Physical Parameters

Table D1. ANOVA table for expansion ratio

| Source | DF | Type I SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Level | 3 | 8965.077029 | 2988.359010 | 4960.96 | <.0001 |
| Fiber | 2 | 2.691380 | 1.345690 | 2.23 | 0.1086 |
| Level*Fiber | 6 | 36.697431 | 6.116239 | 10.15 | <.0001 |

Table D2. Means for expansion ratio by fiber level/fiber type interaction. Means ± standard deviation. Means sharing letter are not different at $p > 0.05$

| Treatment | 0% Fiber | 18% Fiber | 36% Fiber | 48% Fiber |
|---|---|---|---|---|
| Control | 13.49 ± 1.40<br>e | | | |
| Powdered Cellulose | | 6.88 ± 0.54<br>d | 3.05 ± 0.29<br>c | 0.80 ± 0.05<br>a |
| Wheat Fiber | | 7.68 ± 0.58<br>d | 1.78 ± 0.13<br>b | 0.70 ± 0.04<br>a |
| Oat Fiber | | 7.31 ± 0.77<br>d | 1.89 ± 0.20<br>b | 0.70 ± 0.05<br>a |

Table D3. ANOVA table for air cell size ($cm^2$)

| Source | DF | Type I SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Level | 3 | 3.45223587 | 1.15074529 | 530.86 | <.0001 |
| Fiber | 2 | 0.00107537 | 0.00053768 | 0.25 | 0.7804 |
| Level*Fiber | 6 | 0.00362692 | 0.00060449 | 0.28 | 0.9468 |

Table D4. Means for air cell size ($cm^2$) by fiber level/fiber type interaction. Means ± standard deviation. Means sharing letter are not different at $p > 0.05$

| Treatment | 0% Fiber | 18% Fiber | 36% Fiber | 48% Fiber |
|---|---|---|---|---|
| Control | 0.2220 ± 0.0891<br>d | | | |
| Powdered Cellulose | | 0.0499 ± 0.0418<br>c | 0.0136 ± 0.0089<br>a,b | 0<br>a |
| Wheat Fiber | | 0.0342 ± 0.0115<br>a,b,c | 0.0143 ± 0.0040<br>a,b,c | 0<br>a |
| Oat Fiber | | 0.0389 ± 0.0149<br>b,c | 0.0114 ± 0.0019<br>a,b,c | 0<br>a |

Table D5. ANOVA table for breaking force (kPa)

| Source | DF | Type I SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Level | 3 | 124486267.3 | 41495422.4 | 1016.04 | <.0001 |
| Fiber | 2 | 5230204.2 | 2615102.1 | 64.03 | <.0001 |
| Level*Fiber | 6 | 5767492.2 | 961248.7 | 23.54 | <.0001 |

Table D6. Means for breaking force (kPa) by fiber level/fiber type interaction . Means ± standard deviation. Means sharing letter are not different at $p > 0.05$

| Treatment | 0% Fiber | 18% Fiber | 36% Fiber | 48% Fiber |
|---|---|---|---|---|
| Control | 16.68 ± 4.53<br>a | | | |
| Powdered Cellulose | | 71.57 ± 13.31<br>a | 366.50 ± 69.70<br>b | 1095.43 ± 429.39<br>e |
| Wheat Fiber | | 67.49 ± 16.15<br>a | 880.97±256.91<br>d | 1751.33 ± 322.47<br>f |
| Oat Fiber | | 73.50 ± 11.50<br>a | 611.65 ± 174.76<br>c | 1592.35 ± 315.73<br>f |

Table D7. ANOVA table for density ($g/cm^3$)

| Source | DF | Type I SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Level | 3 | 1.72518485 | 0.57506162 | 5834.79 | <.0001 |
| Fiber | 2 | 0.02516184 | 0.01258092 | 127.65 | <.0001 |
| Level*Fiber | 6 | 0.03111353 | 0.00518559 | 52.61 | <.0001 |

Table D8. Means for density ($g/cm^3$) by fiber level/fiber type interaction. Means ± standard deviation. Means sharing letter are not different at $p > 0.05$

| Treatment | 0% Fiber | 18% Fiber | 36% Fiber | 48% Fiber |
|---|---|---|---|---|
| Control | 0.0225 ±0.0029<br>a | | | |
| Powdered Cellulose | | 0.0291 ± 0.0028<br>a,b | 0.0693±0.0070<br>c | 0.1799 ± 0.0160<br>f |
| Wheat Fiber | | 0.0312 ± 0.0024<br>b | 0.1216±0.0086<br>e | 0.1979 ± 0.0160<br>g |
| Oat Fiber | | 0.0316 ± 0.0033<br>b | 0.1097±0.0598<br>d | 0.2072 ± 0.0186<br>h |

# Appendix E

## ANOVA Tables, and Means for Chemical Parameters

Table E1. ANOVA table for moisture content (%)

| Source | DF | Type I SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Level | 3 | 4566.600417 | 1522.200139 | 424.45 | <.0001 |
| Fiber | 2 | 3.153039 | 1.576519 | 0.44 | 0.6452 |
| Level*type | 6 | 58.478433 | 9.746406 | 2.72 | 0.0160 |

Table E2. Means for moisture content (%) by fiber level/fiber type interaction. Means ± standard deviation. Means sharing letter are not different at $p > 0.05$

| Treatment | 0% Fiber | 18% Fiber | 36% Fiber | 48% Fiber |
|---|---|---|---|---|
| Control | 9.73 ± 0.39<br>a | | | |
| Powdered Cellulose | | 13.03 ± 2.58<br>b,c,d | 13.95 ± 1.17<br>c,d | 24.08 ± 1.68<br>e |
| Wheat Fiber | | 11.73 ± 0.79<br>b,c | 14.60 ± 0.62<br>d | 23.60 ± 5.22<br>e |
| Oat Fiber | | 10.73 ± 0.95<br>a,b | 13.51 ± 0.80<br>c,d | 25.47 ± 1.37<br>e |

Table E3. ANOVA table for WAI

| Source | DF | Type I SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Level | 3 | 408455.5067 | 136151.8356 | 96.31 | <.0001 |
| Fiber | 2 | 17657.3067 | 8828.6533 | 6.25 | 0.0028 |
| Level*Fiber | 6 | 50792.2578 | 8465.3763 | 5.99 | <.0001 |

Table E4. Means for WAI (g/100g) by fiber level/fiber type interaction. Means ± standard deviation. Means sharing letter are not different at $p > 0.05$

| Treatment | 0% Fiber | 18% Fiber | 36% Fiber | 48% Fiber |
|---|---|---|---|---|
| Control | 707.33 ± 42.76<br>c | | | |
| Powdered Cellulose | | 575.87 ± 16.20<br>a,b | 527.56 ± 38.70<br>a | 578.58 ± 53.70<br>a,b |
| Wheat Fiber | | 525.33 ± 38.78<br>a | 576.93 ± 40.32<br>a,b | 652.80 ± 24.76<br>c |
| Oat Fiber | | 554.93 ± 28.17<br>a,b | 592.98 ± 20.66<br>b | 658.76 ± 43.25<br>c |

Table E5. ANOVA for WSI (g/100g)

| Source | DF | Type I SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Level | 3 | 20376.76769 | 6792.25590 | 457.90 | <.0001 |
| Fiber | 2 | 101.15352 | 50.57676 | 3.41 | 0.0371 |
| Level*Fiber | 6 | 354.97759 | 59.16293 | 3.99 | 0.0013 |

Table E6. Means for WSI (g/100g) by fiber level/fiber type interaction. Means ± standard deviation. Means sharing letter are not different at $p > 0.05$

| Treatment | 0% Fiber | 18% Fiber | 36% Fiber | 48% Fiber |
|---|---|---|---|---|
| Control | 55.64 ± 3.98<br>f | | | |
| Powdered Cellulose | | 46.09 ± 2.07<br>e | 29.64 ± 6.29<br>c,d | 25.33 ± 4.97<br>b,c |
| Wheat Fiber | | 48.31 ± 2.75<br>e | 32.14 ± 5.60<br>d | 18.0 ± 0.57<br>a |
| Oat Fiber | | 46.09 ± 3.85<br>e | 26.27 ± 2.01<br>c,d | 19.51 ± 1.97<br>a,b |

Table E7. ANOVA table for total soluble protein (%)

| Source | DF | Type I SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Level | 3 | 804.297072 | 268.0989024 | 3.10 | 0.0278 |
| Fiber | 2 | 1047.978859 | 523.989430 | 6.06 | 0.0028 |
| Level*Fiber | 6 | 890.451378 | 148.408563 | 1.72 | 0.1198 |

Table E8. Means for total soluble protein (%) by fiber level/fiber type interaction. Means ± standard deviation. Means sharing letter are not different at $p > 0.05$

| Treatment | 0% Fiber | 18% Fiber | 36% Fiber | 48% Fiber |
|---|---|---|---|---|
| Control | 47.16 ± 4.98<br>a | | | |
| Powdered Cellulose | | 48.31 ± 13.28<br>a | 52.62 ± 11.46<br>a,b | 58.85 ± 10.67<br>b |
| Wheat Fiber | | 49.33 ± 10.07<br>a,b | 47.75 ± 12.01<br>a | 50.35 ± 11.08<br>a,b |
| Oat Fiber | | 44.71 ± 7.61<br>a | 46.70 ± 7.66<br>a | 46.87 ± 7.54<br>a |

Table E9. ANOVA table for water soluble protein (%)

| Source | DF | Type I SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Level | 3 | 19.84514098 | 6.61504699 | 49.77 | <.0001 |
| Fiber | 2 | 2.16855024 | 1.08427512 | 8.16 | 0.0004 |
| Level*Fiber | 6 | 4.96743409 | 0.82790568 | 6.23 | <.0001 |

Table E10. Means for water soluble protein (%) by fiber level/fiber type interaction. Means ± standard deviation. Means sharing letter are not different at $p > 0.05$

| Treatment | 0% Fiber | 18% Fiber | 36% Fiber | 48% Fiber |
|---|---|---|---|---|
| Control | 4.25 ± 0.21<br>d,e | | | |
| Powdered Cellulose | | 3.55 ± 0.26<br>a,b,c | 3.22 ± 0.37<br>a | 3.79 ± 0.36<br>b,c |
| Wheat Fiber | | 3.93 ± 0.53<br>c,d | 3.68 ± 0.38<br>b,c | 3.83 ± 0.48<br>b,c |
| Oat Fiber | | 3.58 ± 0.52<br>a,b,c | 3.45 ± 0.24<br>a,b | 4.35 ± 0.37<br>e |

Table E11. ANOVA table for water soluble carbohydrate (%)

| Source | DF | Type I SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Level | 3 | 4732.394748 | 1577.464916 | 6.32 | 0.0004 |
| Fiber | 2 | 9992.194459 | 4996.097230 | 20.00 | <.0001 |
| Level*Fiber | 6 | 8728.795150 | 1454.799192 | 5.82 | <.0001 |

Table E12. Means for water soluble carbohydrate (%) by fiber level/fiber type interaction. Means ± standard deviation. Means sharing letter are not different at $p > 0.05$

| Treatment | 0% Fiber | 18% Fiber | 36% Fiber | 48% Fiber |
|---|---|---|---|---|
| Control | 98.02 ± 7.50<br>a,b,c,d | | | |
| Powdered Cellulose | | 107.01 ± 13.68<br>c,d,e | 100.68 ± 6.85<br>b,c,d,e | 111.27 ± 22.53<br>d,e |
| Wheat Fiber | | 80.68 ± 23.52<br>a | 82.34 ± 17.85<br>a | 90.81 ± 26.15<br>a,b,c |
| Oat Fiber | | 115.99 ± 13.93<br>e | 86.25 ± 17.16<br>a,b | 100.94 ± 8.66<br>b,c,d,e |

# Appendix F

## ANOVA Tables, and Means for Extrusion Parameters

Table F1. ANOVA table for pressure (psi)

| Source | DF | Type I SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Level | 3 | 1165808.333 | 388602.778 | 35.54 | <.0001 |
| Fiber | 2 | 120072.222 | 60036.111 | 5.49 | 0.0109 |
| Level*fiber | 6 | 72750.000 | 12125.000 | 1.11 | 0.3862 |

Table F2. Means for pressure (psi) by fiber level/fiber type interaction. Means ± standard deviation. Means sharing letter are not different at $p > 0.05$

| Treatment | 0% Fiber | 18% Fiber | 36% Fiber | 48% Fiber |
|---|---|---|---|---|
| Control | 970 ± 122.88<br>d | | | |
| Powdered Cellulose | | 603.33 ± 101.60<br>a,b,c | 783.33±30.55<br>b,c,d | 406.67 ± 11.55<br>a |
| Wheat Fiber | | 860.00 ± 50.00<br>c,d | 913.33 ± 55.08<br>d | 550.00 ± 168.23<br>a,b |
| Oat Fiber | | 866.67 ± 35.11<br>c,d | 870.00 ± 155.24<br>c,d | 493.33 ± 124.23<br>a,b |

Table F3. ANOVA table for motor torque (% capacity)

| Source | DF | Type I SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Level | 3 | 8004.972222 | 2668.324074 | 134.92 | <.0001 |
| Fiber | 2 | 220.666667 | 110.333333 | 5.58 | 0.0102 |
| Level*Fiber | 6 | 314.444444 | 52.407407 | 2.65 | 0.0408 |

Table F4. Means for motor torque (% capacity) by fiber level/fiber type interaction. Means ± standard deviation. Means sharing letter are not different at $p > 0.05$

| Treatment | 0% Fiber | 18% Fiber | 36% Fiber | 48% Fiber |
|---|---|---|---|---|
| Control | 86.67 ± 2.89<br>d | | | |
| Powdered Cellulose | | 63.33 ± 5.77<br>c | 61.00 ± 8.54<br>b,c | 42.67 ± 4.62<br>a |
| Wheat Fiber | | 76.67 ± 5.77<br>d | 61.67 ± 2.89<br>b,c | 49.33 ± 5.13<br>a,b |
| Oat Fiber | | 80.00 ± 0.00<br>d | 61.67 ± 2.89<br>b,c | 46.67 ± 2.89<br>a |

Table F5. ANOVA table for observed barrel temperature (°C)

| Source | DF | Type I SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Level | 3 | 757.6388889 | 252.5462963 | 39.02 | <.0001 |
| Fiber | 2 | 16.1666667 | 8.0833333 | 1.25 | 0.3048 |
| Level*Fiber | 6 | 11.6111111 | 1.9351852 | 0.30 | 0.9313 |

Table F6. ANOVA table for observed barrel TOM (°C)

| Source | DF | Type I SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Level | 3 | 1203.147500 | 401.049167 | 40.57 | <.0001 |
| Fiber | 2 | 58.748889 | 29.374444 | 2.97 | 0.0703 |
| Level*Fiber | 6 | 34.953333 | 5.825556 | 0.59 | 0.7356 |

Table F7. Means for observed barrel temperature (°C) and observed barrel TOM (°C) by level. Means ± standard deviation. Means sharing letter are not different at $p > 0.05$ within columns not between columns

| Level | Barrel Temperature °C | Barrel TOM °C |
|---|---|---|
| 0% Fiber | 135.67 ± 1.00 b | 159.33 ± 0.65 b |
| 18% Fiber | 134.67 ± 2.82 b | 158.93 ± 3.79 b |
| 36% Fiber | 133.78 ± 2.05 b | 159.40 ± 3.82 b |
| 48% Fiber | 124.22 ± 3.11 a | 145.88 ± 3.47 a |

Table F8. ANOVA table for observed die temperature (°C)

| Source | DF | Type I SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Level | 3 | 454.9722222 | 151.6574074 | 61.34 | <.0001 |
| Fiber | 2 | 239.0555556 | 119.5277778 | 48.35 | <.0001 |
| Level*Fiber | 6 | 154.2777778 | 25.7129630 | 10.40 | <.0001 |

Table F9. Means for observed die temperature (°C) by fiber level/fiber type interaction. Means ± standard deviation. Means sharing letter are not different at $p > 0.05$

| Treatment | 0% Fiber | 18% Fiber | 36% Fiber | 48% Fiber |
|---|---|---|---|---|
| Control | 129.33 ± 1.15 c | | | |
| Powdered Cellulose | | 136.00 ± 1.00 f | 135.00 ± 1.00 d | 123.00 ± 0.00 a,b |
| Wheat Fiber | | 123.33 ± 2.08 a,b | 126.67 ± 1.53 b,c | 119.67 ± 2.08 a |
| Oat Fiber | | 126.33 ± 3.06 b,c | 128.67 ± 1.53 c | 121.00 ± 1.00 a |

Table F10. ANOVA Table for observed die TOM (°C)

| Source | DF | Type I SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Level | 3 | 482.3274552 | 160.7758184 | 24.64 | <.0001 |
| Fiber | 2 | 41.8606454 | 20.9303227 | 3.21 | 0.0619 |
| Level*Fiber | 6 | 94.6015768 | 18.9203154 | 2.90 | 0.0397 |

Table F11. Means for observed die TOM (°C) by fiber level/fiber type interaction. Means ± standard deviation. Means sharing letter are not different at $p > 0.05$

| Treatment | 0% Fiber | 18% Fiber | 36% Fiber | 48% Fiber |
|---|---|---|---|---|
| Control | 147.60 ± 3.84<br>b | | | |
| Powdered Cellulose | | 156.10 ± 0.00<br>c | ---------- | 138.77 ± 0.49<br>a |
| Wheat Fiber | | 143.80 ± 2.79<br>a,b | 147.13 ± 1.04<br>b | 138.83 ± 2.60<br>a |
| Oat Fiber | | 149.27 ± 1.06<br>c | 149.67 ± 1.82<br>c | 140.13 ± 0.80<br>a,b |

Table F12. ANOVA table for residence time (seconds)

| Source | DF | Type I SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Level | 3 | 19006.33333 | 6335.44444 | 317.65 | <.0001 |
| Fiber | 2 | 98.00000 | 49.00000 | 2.46 | 0.1070 |
| Level*fiber | 6 | 342.00000 | 57.00000 | 2.86 | 0.0303 |

Table F13. Means for residence time (seconds) by fiber level/fiber type interaction. Means ± standard deviation. Means sharing letter are not different at $p > 0.05$

| Treatment | 0% Fiber | 18% Fiber | 36% Fiber | 48% Fiber |
|---|---|---|---|---|
| Control | 66.67 ± 2.08<br>a | | | |
| Powdered Cellulose | | 85.33 ± 4.16<br>b | 86.33 ± 2.52<br>b | 122.33 ± 11.15<br>c |
| Wheat Fiber | | 74.33 ± 1.52<br>a,b | 83.00 ± 4.36<br>b | 126.67 ± 5.77<br>c |
| Oat Fiber | | 79.00 ± 3.46<br>a,b | 86.33 ± 2.31<br>b | 134.67 ± 2.52<br>c |

Table F14. ANOVA table for product flow rate (g/s)

| Source | DF | Type I SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Level | 3 | 3345.788119 | 115.262706 | 595.42 | <.0001 |
| Fiber | 2 | 5.960089 | 2.980044 | 1.59 | 0.2245 |
| Level*fiber | 6 | 31.943356 | 5.323893 | 2.84 | 0.0310 |

Table F15. Means for product flow rate (g/s) by fiber level/fiber type interaction. Means ± standard deviation. Means sharing letter are not different at $p > 0.05$

| Treatment | 0% Fiber | 18%Fiber | 36%Fiber | 48%Fiber |
|---|---|---|---|---|
| Control | 42.45 ± 1.21 e | | | |
| Powdered Cellulose | | 30.63 ± 3.43 b,c | 28.28 ± 0.58 b | 16.15 ± 0.77 a |
| Wheat Fiber | | 34.53 ± 1.11 d | 28.52 ± 0.92 b | 15.98 ± 0.60 a |
| Oat Fiber | | 34.78 ± 1.01 c,d | 26.99 ± 1.19 b | 15.27 ± 0.74 a |