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Properties of feed ingredients and extrudated products

by

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ABSTRACT

Food is any substance consumed to provide nutritional support for the body. It is usually of plant or animal origin, and contains essential nutrients, such as fats, proteins, vitamins, or minerals. Animal-based food products play a significant role in the current U.S. diet. In 2003, the total meat consumption per capita was 90.5 kg/year. Since the U.S. has a high consumption of animal-based food products, the animal feed ingredients are fundamentally important. The ingredients can affect not only the quality of the animal-based food products, but also the potential human health.

The U.S. is the largest producer of animal feed in the world. Feed ingredients might include grains, milling byproducts, added vitamins, minerals, fats/oils, and other nutritional and energy sources. And kinds of feed ingredients are produced to use, like DDGS and soybean meal. Recently, some co-products of energy production, like DDGS are used as feed ingredient worldwide. This kind of co-product is nutrient rich and meets the requirement of animal feed nutrition. Since these feed ingredients are used worldwide, they must be transported a long distance to some domestic and international market. And sometimes they are stored for a long time before be used. So during transportation and storage, ingredients often became restricted. This is a major problem that can affect the quality of ingredients. These issue most likely results from many factors, including ingredients' moisture content, particle size, temperature and relative humidity of air or pressure.

A gluten-free diet excludes gluten protein. An increasing number of people are choosing gluten-free diets for either medical or personal reasons. The production of gluten-free snack foods has great potential. One method of processing that can be used to create gluten-free foods is extrusion. Extrusion is defined as a process where ingredients are pushed through a die of desirable shape. This process has been used in food, feed, and biomass. In food applications, extrusion processing has become an increasingly important manufacturing method.

The first part of this study was to investigate potential factors affecting flowability of feed ingredients, as well as examines the effect of three moisture content levels (10, 20 and 30% db) on the resulting physical and flow properties of feed ingredients. Certain amounts of water were added to adjust moisture content of ingredients and Carr indices were used to quantify the flowability of each ingredient. The results showed that moisture content had significant effects on physical and flow properties. According to Carr indices, flowability generally declined with increased moisture content. Using these, the best condition can be found for transportation and storage to maintain the good quality for ingredients when they are used.

The second part of this study was to test the extrudate properties for three gluten-free grains (millet, sorghum and teff) at two different moisture content levels (30%, 40% d.b.). Additionally, both raw grain and flours were tested prior to processing. Following extrusion, the bulk density, water activity, unit density, expansion ratio, and color were evaluated. It was found that initial grain condition (raw vs flour) and initial moisture content greatly impact extrudate physical properties. The most desirable moisture content and grain condition was 40% and flour.

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1. Introduction

Grains are seeds and fruits of cereal grasses. Today, grains are produced for three principal reasons: direct human consumption as daily food, animal feed and other uses including industrial consumption. Grains are important nutrient sources, such as dietary fiber, several B vitamins, and minerals, to maintain our bodies' health ("Nutrients and health benefits" 2015). There will be health benefits of eating grains, especially whole grains. People who have a healthy diet, which contains enough whole grains, can reduce the risk of heart disease, diabetes, and cancer. Also, grains are an important energy source, two kilograms of cooked whole grains provide about 1600 calories. Since people can not digest the raw grains, grains must be flaked, cracked, puffed, popped or ground before being consumed (Andrews 2009).

Maize, wheat, barley, sorghum and oats are the main grains used in animal feed and human food ("Basic foodstuffs" 2016). To produce feeds and foods, ingredients are selected carefully and blended. High nutritional feeds not only can maintain the health of the animals, but also can increase the quality of end products such as meat, milk, or eggs (Holden 2016). For last 5-10 years, there has been a large push to develop gluten-free products for both animal and human foods.

Industrial uses include malts for brewing, alcohol for fuels, starches, and sweeteners. Currently in the U.S., instead of being used as food or feed, one-quarter of all the grain crops, such as maize, ends up as biofuel (Vidal 2010). Co-products of biofuel (such as dried distiller's grains with soluble, corn gluten meal, corn oil, and brewer's grains) and traditional ingredients (such as corn, soybean meal, and urea) have become economically viable components (Mathews and McConnell 2009).

1.2. Literature Review

This chapter will discuss two major topics, including 1) flowability of feed ingredients, and 2) extrusion of gluten free grains.

1.2.1. Flowability of feed ingredients

Powder handling and processing now is a problem in industry because powder's properties are similar with both solids and liquids. When they are surrounded by air, the degree of aeration can affect the powder behavior. Many common manufacturing problems are related with powder flow, including non-uniformity in blending, inaccurate filling, obstructions, and stoppages. All these problems can cause rejected material, machine downtime, and defective end-products. Storage, handling, production, packing, distribution, and end use can all be negatively affected by common powder flow problems (Young 2007).

1.2.1.1. Types of feed ingredients

Soybean meal

Soybean meal is made by grinding the residual of soybeans (flakes) after removing most of the oil by the solvent extraction process. Soybean meal obtained by solvent extraction represents the "gold standard" for vegetable protein ingredients because it is widely available, actively traded, highly palatable, and rich in essential amino acids. The amino acids in soybean meal are highly digestible for swine and poultry. It complements other ingredients to create a balanced diet. Because it serves as an excellent source of rumen degradable protein, soybean meal allows microbes to produce maximum levels of high-quality microbial protein. A good source of amino acids, soybean meal, is also considered as a widely accepted alternative to fishmeal in aquaculture diets (Ingredients Catalog 2016).

High protein DDGS

DDGS, a co-product of the dry milling of corn, is considered as a medium-protein and high-energy ingredient. It contains a grain fraction and whole stillage by the yeast fermentation process from grain to ethanol. The numerous nutritional qualities of DDGS are valuable for a variety of animal species. For ruminants, this low-starch product offers a high level of protein, B vitamins, phosphorus, and highly digestible fiber. These unique characteristics also perform well in swine and poultry diets (Ingredients Catalog 2016).

Soy protein concentrate

Soy protein concentrate is a high-quality vegetable protein with low allergenicity characteristics. Soy protein concentrate is manufactured from soy flakes in which the soluble sugars and anti-nutritional factors are removed. Soy protein concentrate is used as a protein source for young ruminant, swine, poultry, and aquaculture diets. Since it has high protein content (65% crude protein) and an excellent amino acid profile, it can serve as an ideal replacement protein for fishmeal. Also, soy protein concentrate-based milk replacers, which are available in both powdered and granular forms, are an economical alternative as milk-based replacers (Ingredients Catalog 2016).

NF8

NF8 is known as a functional soy protein ingredient for young animal diets. This dried soybean meal fermentation product is produced by adding cultured Bacillus Subtilis and Pediococcus Pentosaceus and a unique micro-aerobic solid-state fermentation process. The product created by microbial fermentation of high protein soybean meal is low in anti-nutritional factors. Also, NF8 includes highly digestible vegetable protein. Anti-nutritional factors are removed during fermentation while the protein content is increased. To prevent damaging protein, the processing temperature is low ("NF8 Nutraferma" 2016).

Soy protein isolate

Similar with soy protein concentrate, soy protein isolate is also a high-quality vegetable protein with low allergenicity characteristics. It is manufactured using edible soy flakes through a series of unique processings, in which the anti-nutritional factors are reduced or eliminated. Soy protein isolate contains 90% crude protein which is well suited for young animal diets and milk replacers. Soy protein isolate is also considered as a great replacement for fishmeal in many diets because it has excellent water dispersion characteristics, a high protein content, and an excellent amino acid profile (Ingredients Catalog 2016).

Cottonseed meal

Cottonseed meal is a by-product of the cotton industry. It is produced by grinding the residual(flakes) after extracting most of the oil from cottonseed through the solvent extraction process. Since cottonseed meal contains many types of plant and animal proteins, it serves as an excellent protein source for beef and dairy diets. Cottonseed meal contains 40% bypass protein, making it valued in dairy lactation diets (Ingredients Catalog 2016). Also, cottonseed meal is used as a fertilizer. Since it is an organic fertilizer, cottonseed meal is safe to use in the home garden. The high organic matter content in cottonseed meal helps to improve soil texture and build humus; it is good for loosening tight, heavy soils. Since cottonseed meal can hold moisture and nutrients well, it promotes long lasting plant growth ("Cotton Seed Meal High-Quality Slow-Release Organic Fertilizer" 2016).

Pea bran

Pea bran, which is an insoluble fiber made from pea hulls, has an excellent water retention. The low-calorie content of pea bran will make it particularly suitable to use in many high-level nutritional applications ("Pea Bran" 2016). Pea bran , which is a fiber additive in pet foods, has a total dietary fiber content of around 83% and protein content around 7%. Even though it reduces blood sugar and provides roughage, pea fiber can still be a problem ingredient in dog food for some dogs. Pea fiber sometimes cannot be easily digested by dogs and peas can also affect the absorption of vitamins and minerals in the food (Rogers 2014).

Soy flour

Soy flour, derived from ground soybeans, is a great source of high-quality soy protein, dietary fiber and important bio-active components, such as isoflavones. Important bio-active components found naturally in soybeans can maintain healthy bones, and prevent prostate, breast cancers, and colorectal cancer. The content and profile of bio-active components vary depending on soy protein content in the food and the method for processing soy protein. Also, soy flour provides the basis for some soymilks and textured vegetable protein. It can improve taste and texture of many foods and reduce the fat absorbed in fried foods. The taste of soy flour varies depending on how it is processed ("Soy Fact Sheets" 2016).

Pea protein

Pea protein is extracted commonly from the yellow garden pea, which contains fleshy greenish seeds. Consumption of peas in their natural state does not necessarily produce the same health benefits as the protein, because potentially bioactive compounds or proteins are present in an inactive state in natural pea produce. Such compounds are activated by the use of enzymatic digestion. One principal and desirable effect of pea protein hydrolysate are the presence of compounds that act as ACE inhibitors. Inhibition can improve the blood flow and lower the blood pressure ("Pea Protein" 2016).

Fish meal

Fish meal is a common nutrient-rich feed ingredient used primarily in diets for domestic animals, and sometimes it can be used as a high-quality organic fertilizer. Fish meal can be manufactured using almost any type of seafood, but is using wild-caught, small marine fish that contain a high percentage of bones and oil. Fish meal is not suitable for direct human consumption, because most of them are caught for the sole purpose of fishmeal and fish oil production. A small percentage of fishmeal is made from the by-catch of other fisheries, and by-products during processing of various seafood products, which can be used for direct human consumption (Miles and Chapman 2016)

Corn gluten meal

Corn gluten meal is a co-product of the wet milling of corn. Since it contains a high level of bypass protein (55%), corn gluten meal performs well in high-producing dairy cattle diets. Also, it is used as an excellent protein source for both swine and poultry because it provides high protein, energy, methionine, and cystine. Also, corn gluten meal is considered as a valuable ingredient in pigmented broiler and layer feeding programs due to the high level of xanthophylls. Containing a large amount of highly digestible amino acids and no anti-nutritional factors, corn gluten meal functions as a replacement for fishmeal in aquaculture diets (Ingredients catalog 2016).

1.2.1.2. Factors affecting flowability of feed ingredients

Flowability is the ability of powders to flow. The flowability characteristic of powder is affected by both the physical properties of the material and the specific processing conditions in the handling system ("Powder Flowability" 2016). The flowability of feed is most likely affected by ingredients' moisture content, particle size, and relative humidity of the air. Also, there are some minor factors influencing flowability, like temperature and pressure.

Moisture content

Moisture content is a key factor affecting powder flowability. The effect of moisture on the flowability depends on the amount of water and its distribution. Ganesan et al. (2008) studied the flow properties of DDGS and found that if moisture content increased, DDGS flowability decreased. The main property it affected was the angle of repose. Based on their study, with the increase of moisture content, angle of repose increased, which mean DDGS flowability decreased. The bulk density of material and compressibility are other flowability index properties, which are related with moisture content. Generally, bulk density decreases and the compressibility increases with an increase in moisture content (Moreira and Peleg 1981; Yan and Barbosa-Canovas 1997). Also, the material's moisture content influences physical properties. With the increase of a powder's moisture content, the adhesion (Craik and Miller 1958) and cohesion (Moreira and Peleg 1981) increase.

Particle size

The particle size of bulk solids is important for flowability and other physical properties. Increasing particle size will increase the flowability of a material (Fitzpatrick et al. 2004a, b). The increase in particle size causes an increase in the surface area per unit mass. Particle size is also important for compressibility of materials. If the particle size increases, the compressibility will increase (Yan and Barbosa-Canovas 1997).

Relative humidity

Relative humidity of the air around the storage place also affects materials' properties. It cannot influence properties directly. When bulk materials, which many of them are hygroscopic, are exposed to humid conditions, they will absorb water from around the environment. This leads to the increase of moisture content and bulk strength (Marinelli and Carson 1992). Since the moisture content increase, the angle of repose will increase. As mentioned above, flowability of materials reduces with an increase in the angle of repose.

There are many observations that higher humidities had significant effects on the flowability of granular powders (Craik and Miller 1958; Irani et al. 1959; Peleg and Mannheim, 1973; Fitzpatrick et al. 2004b). To control the humidity, sulphuric acid, glycerol, or saturated salt solutions are often used (Rockland 1960). Saturated salt solutions are widely used, becaue the three phases, which are vapour, liquid and solid, are independent when changing the total moisture content. The salt solutions are suitable for a wide range of specific relative humidity conditions at different temperatures (Spencer 1926; Hodgman 1954).

1.2.1.3. Flowability-related properties

Angle of repose

The angle of repose is the angle between the horizontal and the slope of a heap of granular material dropped from some designated elevation. The angle of repose corresponds qualitatively to the flow properties of that material and is a direct indication of potential flowability (Carr 1965). A material with a lower angle of repose means the material is more flowable (Carr 1965). The angle of repose is considered a common method to measure flow properties (Craik and Miller 1958). Usually, with the increase of moisture content, angle of repose increases. Figure 1 shows the equipment to measure angle of repose.

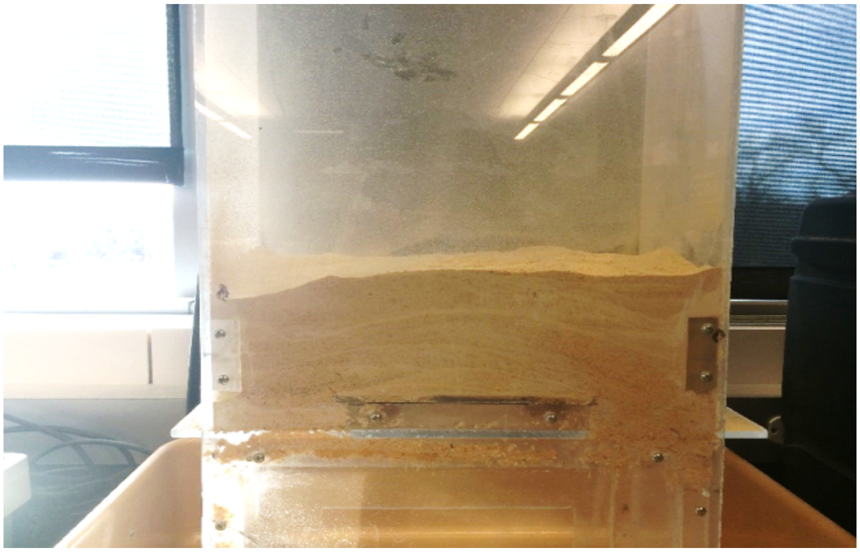

Figure 1. Angle of Repose Equipment

Bulk density

Bulk density is defined as the mass of particles that occupies a unit volume of a container. The bulk density of material is important for transportation and storage. There is two types of bulk density: aerated bulk density (ABD) and packed bulk density (PBD). ABD is determined by pouring a quantity of solid material into a known volume container. This represents a bulk solid that has not been compressed. PBD is the bulk density of the material after it has been compressed. This represents a material's actual bulk density in storage and transport. Particle size and moisture content are main factors affecting bulk density. The bulk density of material decreases with an increase in the particle size. Also, increasing the relative humidity will increase the moisture content of material. This leads to a decrease in bulk density (Yan and Barbosa-Canovas 1997). Figure 2 showed equipment to measure aerated bulk density and packed bulk density.

Figure 2. Equipment for bulk density measurement

Uniformity

The size and shape of the particles have a direct effect on a material's ability to flow. The coefficient of uniformity is the ratio between the screen size that will pass 60% of the material and the screen size that will pass only 10% of the material. The more uniform the mass of particles is in both shape and size, the more flowable it is likely to be. There is an index value for uniformity coefficient. The maximum index value is 100, which means the material flowability is very good. The smaller the uniformity value, the more homogeneous the particle sizes and shapes. A material that is more uniform will have a tendency to have better flowability than a material with a wide range of particle sizes.

Compressibility

Compressibility can be used to estimate the flowability of the material. After determining aerated and packed bulk densities, the compressibility of a material can be calculated by the equation:

$$100\,(P-A)\,/\,P = \%\ \text{Compressibility} \tag{1}$$

Where: P is packed bulk density (kg/cm^3); A is aerated bulk density (kg/cm^3).

This parameter provides an indication of particle size and the overall flowability of the material. The greater the compressibility of a material, the less flowable it is (Carr, 1965). Bulk solids with a compressibility number less than approximately 18 percent are considered free flowing.

Hausner ratio (HR)

The Hausner ratio indicates the cohesiveness of a powder. It is calculated by:

$$P\,/\,A = HR \tag{2}$$

Where: P is packed bulk density (kg/cm^3); A is aerated bulk density (kg/cm^3).

A Hausner ratio larger than 1.25 indicates that the powder will not flow easily while a value lower than 1.25 indicates a more free-flowing powder ().

1.2.1.4. Physical properties

Thermal properties

Thermal properties are the characteristics of a material that determine how it reacts when it is subjected to excessive heat or heat fluctuations over time. It includes thermal conductivity, volumetric specific heat, and thermal diffusivity. They are measured using a thermal meter.

Water activity

Water activity is the partial vapor pressure of water in a substance divided by the standard state partial vapor pressure of water. Water activity is a measure of the energy status of the water in a system. Usually, increasing the moisture content will lead the water activity to increase. The number of the water activity index varies from 0 to 1. They are measured using a water activity measurement meter.

Color

The color is very important when dealing with feed ingredients. L * is lightness level; a* is the green - red level and b* is the blue - yellow level in the color solid. Color changes can give information about the extent of browning reactions such as caramelization, maillard reaction, the degree of cooking and pigment degradation (Ilo and Berghofer, 1999). The color values are measured using a Minolta Chroma meter.

1.2.1.5. Conclusion

The flowability of feed ingredients is a major problem facing during the transportation and handling. Based on the literature review, there are many factors influencing the flowability of feed ingredients. Among all these factors, moisture content, which is choosen to be tesded, is the most effeced one. Also, the types of feed ingredients have a large variation. Even though DDGS and soybean meal are the most popular types, the other types are still being used in the industry. But there is few information about the other types of feed ingradients, thus, the test for the flowability was conducted using 11 types of feed ingredients as mentioned above.

1.2.2. Extrusion of gluten-free grains

Whole grains contain a wide range of nutrients that benefit human health. Currently, the main problem is whether the processing of whole grains affects their nutrients content. Although grain processing is considered to have a negative effect on nutritional value. Many factors support the processing of grains can enhance grain digesbility. First, the harvested whole grains generally cannot be consumed directly by humans, and require some processing before consumption. While removing the bran and the germ, the nutrient content of grain reduces, but milling of grains concentrates desirable grain components and removes poorly digesable compounds and contaminants. Cooking of grains generally increases digestibility of nutrients. For both human and animal models, processed grains often contain more nutrition value than unprocessed grains; it maybe because processing grains enhance nutrient bioavailability grains. Also, processing of grains provides shelf-stable products that are convenient and good tasting for consumers (Slavin, Jacobs and Marquart 2000).

1.2.2.1. Methods used to process grains

The methods to processe grains vary based on the specific grain and geographic area. The following techniques are widly used in industry.

Grinding

Grinding is typically performed using a hammermill. Screen size, hammermill size, power and speed, type of grain and moisture content of grain are factors influencing the partical size fineness of the end product. Variations in the quality of the final product may cause the differences in animal performance (Blezinger 2016).

Dry Rolling

For the dry rolling process, grain is passed through rollers which are usually grooved on the surface. The particle size of the final product is influenced by roller weight, the size of grooves, pressure, and spacing, the moisture content of the grain and rate of grain flow (Blezinger 2016).

Steam Rolling

Grain is exposed to steam for one to eight minutes before the kernel softens. Steam rolling produces a more intact, crimped-appearing product than dry rolling. The moisture content of the grain is increased since grain is exposed to steam. The value of crimping is not about feed efficiency over grinding or rolling; it has been grossly overemphasized. Particle size and physical form of crimped grain may improve palatability and animal acceptance in some instances (Blezinger 2016).

Pelleting

Before processing through a pellet mill, grain is usually grounded or rolled. The mechanization of feed handling is the primary advantage of this method. Even though animal feed efficiency is improved by using this method, there is still little, or no economic advantage exists. Benefits of pelleting seldom, if ever, can be expected to cover the cost of pelleting in complete rations (Blezinger 2016).

Steam Flaking

Grain is processed through steam under atmospheric conditions for usually 15 to 30 minutes, before rolling. To produce a very thin, flat flake; large, heavy roller mills are set at near zero tolerance. The produced flake usually weighs from 10 to 13 kg per bushel and contains 16 to 20 percent moisture. The flaking process causes gelatinization of the starch granules; this makes them more digestible. Steaming time, grain moisture, temperature, processing rate, type of grain, and roller size and tolerance are factors that influence the degree of flaking and level of gelatinization (Blezinger 2016).

Pressure Flaking

The grain goes through to steam under pressure for a short period. For example, $3.45*10^5$ pascal of grain go through the steam for one to two minutes. The continuous flow cooker is operated to inject and eject grain. Steam is injected into the cooker at the desired pressure until the grain in the chamber reaches a temperature about 150° C. When the grain is expelled from the cooker, it is cooled to below 200° F and 20 percent moisture before flaking. Flakes produced from this method may be less brittle and less subject to fragmenting during the mixing and feeding operation than those from steam flaking (Blezinger 2016).

Reconstituting

Dry grain is reconstituted to about 25 to 30 percent moisture by adding moisture and then stored whole in oxygen-limited conditions for 10 to 20 days before feeding. Grain should be stored whole and then rolled or ground before feeding to obtain the desired improvement in feed utilization (Blezinger 2016).

Chemical Preservation

Acids, which are usually propionic or a combination of propionic and acetic, are added to moist, early-harvested grain to preserve the whole kernel wet grain in conventional facilities, such as wooden bins or trench silos. With the high moisture content of grains, more acid is required for satisfactory preservation. Thus, the expense of preservation increases with the increase in moisture content of the grain. This method is used in conjunction with high-moisture-harvesting programs (Blezinger 2016).

Popping

The air-dried grain, which has a moisture content of 10 to 14 percent, is popped by heating it with high-temperature air at 370-430 °C for 15 to 30 seconds. The popping method cannot be used for all grains, but the final product has a very low moisture content of about 3 percent. Popping causes disruption of the starch granules by using natural moisture in the kernel to steam, gelatinize and expand the starch granules (Blezinger 2016).

Exploding

Raw grains are transfered into high tensile strength steel "bottles" which contain approximately 90 kg of grain each; and the steam is injected into the bottles to increase the pressure reaches $1.72*10^6$ pascal. After about 20 seconds, a valve opens to let the expanded grain with the hulls revemed out. Under the high pressure, moisture is forced into the kernels, which swell to several times their original size after releasing into the air. The product is served as breakfast cereals (Blezinger 2016).

Extrusion

Today, a variety of products such as pasta, snacks, cereals, and pet food are made using screw extrusion processes. This processing has been used in the production of food, drug carriers, and biomass. In food applications, extrusion processing has become in increasingly important manufacturing method. This is smiliar to a pellet mill where the feed is introduced into a chamber and then under pressure, it is pushed out of holes or dies to create a product. In extrusion, the product pushed through the die contains more moisture, and it may have a very high level of fat as well. Extruded products can be dried and then crumbled so that they can be handled and stored much like an ordinary grain. The heat in this process can do two things. One it destroys the anti-growth factors in legumes as previously discussion. Secondly, it also can be used to protect some of the protein in products, like soybeans, from breakdown in the rumen. Thus, creating a by-pass or extra protein that can be digested by the animal lower in the digestive tract ("Grain Processing" 2016).

For food processing, there are two major types of extruders, single screw extruder and twin-screw extruder. This study focused on the single screw extruder. The single screw extruder works by having one screw operate with a cylinder to combine the materials and push them through the die to form the shape of the final product. During this process, ingredients experience heating, mixing, and shearing. There are many advantages of extrusion processing over other conventional cooking processing methods. Firstly, extrusion processing has a lower cost than other processing methods. Also, the same extruder can be used to make different types of products.

1.2.2.2. Gluten-free grains

Gluten is a mixture of two proteins, gliadin and glutenin. It is found in wheat, rye, and barley. In the United States, about 3 million people have celiac disease, where the body's natural defense system reacts to gluten by attacking the lining of the small intestine. And without this lining, the body cannot absorb nutrients. Since this can result in serious health problems, gluten-free grain is considered in the diet ("'Gluten-Free' Now Means What It Says" 2014). The most popular glute-free grains are corn and rice, but millet, sorghum, and teff are also gluten-free grains.

Millet

Millet is widely grown around the world as a cereal crop for both human food and fodder. It is an important crops in the semi-arid tropics of Asia and Africa, especially in India, China, and Niger. Also, these countries are the top three in millet producing countries in the world ("Millet" 2010). This grain has relative high fiber and protein contents ("Millet, Raw Nutrition Facts & Calories" 2016).

Sorghum

Sorghum, which now is an important crop worldwide, is native to Africa, and used for food and fodder, the production of alcoholic beverages, and biofuels. The major sorghum producing countries are the United States, Nigeria, India and Mexico ("Sorghum Maps/Stats"

2016). Sorghum has high protein and fiber contents, so it is a suitable grain for extrusion ("Sorghum Nutrition Facts & Calories" 2016).

Teff

Teff is an annual cereal grain native to the African country of Ethiopia. It can be cultivated in a wide range of conditions, from marginal soils to drought conditions (("What Is Teff Grain" 2016)). With a relatively short growing season, teff produces a crop that provides grain for human food consumption and fodder for cattle. In the United States, teff largely remains an experimental crop, with a limited number of acres grown for this grain. This whole grain is high in protein, carbohydrate, and fiber ("Teff, Nutrition Facts & Calories" 2016).

1.2.2.3. Conclusion

Gluten-free grains, which have health benefits, are popular in the current human diet. Based on the literature review, millet, sorghum, and teff, which are not conmmon in the human diets, are gluten-free grains. To process these grains, extrusion is considered as an easy and convient method. Since there is few information about the extrusion of these three grain, the experiments were conducted to test the properties of these extrudates.

1.3. Thesis organisition

This thesis will mainly focus on two topics. The first one is the factors influencing flowability of feed ingredients. The second one is the properties of extrauded products.

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CHAPTER 2

RESEARCH OBJECTIVES AND HYPOTHESES

2.1. Research Objectives

The main objectives of this study were:

1. To investigate potential factors affecting flowability of feed ingredients, as well as examines the effect of three moisture content levels (10, 20 and 30% d.b.) on the resulting physical and flow properties of feeding ingredients.
2. To test the extrudate properties for three gluten-free grains (millet, sorghum, and teff) at two different moisture content levels (30%, 40% d.b.). Additionally, both raw grain and flours were tested before processing.

2.2. Hypotheses

2.2.1. Study 1

H_{01}: Increasing moisture content will not change the flowability of each ingredient.

H_{A1}: Increasing moisture content will change the flowability of each ingredient.

H_{02}: Increasing moisture content will not change the physical properties of each ingredient.

H_{A2}: Increasing moisture content will change the physical properties of each ingredient.

2.2.2. Study 2

H_{01}: Increasing moisture content will not change the properties of each extrudate.

H_{A1}: Increasing moisture content will change the properties of each extrudate.

H_{02}: Changing the particle size at the same moisture content level will not change the properties of each extrudate.

H_{A2}: Changing the particle size at the same moisture content level will change the properties of each extrudate.

CHAPTER 3

FACTORS INFLUENCING FEED INGREDIENT FLOWABILITY

3.1. Introduction

Animal-based food products have a significant role in the recent U.S. diet. In 2003, the total meat consumption per capita was 90.5 kg/year (USDA 2005). Since the U.S. has a high consumption of animal-based food products, the animal feed ingredients are fundamentally important. The ingredients can affect not only the quality of the animal-based food products but also the potential human health. The U.S. is the largest producer of animal feed in the world (Gill 2004). Feed ingredients might include grains, milling byproducts, added vitamins, minerals, fats/oils, and other nutritional and energy sources. The most used feed ingredients produced for feeding are distiller's dried grains with solubles (DDGS) and soybean meal. Recently, some co-products of ethonal production, like DDGS are used as feed ingredients worldwide. This kind of co-product is nutrient rich and meets the requirement of animal feed nutrition. Since these feed ingredients are used worldwide, they must be transported long distances to domestic and international markets, which often leads to a long storage period before being used. During transportation and storage, ingredients often became restricted. This is a major problem that can affect the quality of ingredients. These issues most likely result from many factors, including ingredients' moisture content, particle size, temperature and relative humidity of air or pressure.

The objectives of this study were to investigate potential factors affecting flowability of feed ingredients, as well as examines the effect of three moisture content levels (10, 20 and 30% db) on the resulting physical and flow properties of feed ingredients. Certain amounts of water were added to adjust the moisture content of ingredients, and Carr indices were used to quantify the flowability of each ingredient.

3.2. Materials and Methods

The experimental design was based on dependent variables of different kinds of grains and moisture content. DDGS, soybean meal, soy protein concentrate, NF8, soy protein isolate, cotton seed meal, pea bran, soy flour, pea protein, corn gluten meal and fish meal were tested. Moisture content for each ingredient was determined using a laboratory oven at 135^{o}C for four hours. The ingredients were mixed with appropriate quantities of water in a lab-scale mixer and stored overnight at refrigerated conditions to achieve 10% moisture content, 20% moisture content, and 30% moisture content (d.b.).

3.2.1. Physical properties

3.2.1.1. Thermal properties

Thermal conductivity, volumetric specific heat， and thermal diffusivity were measured by using a thermal meter (KD2 Pro Thermal Properties Analyzer, Decagon Devices, Pullman, WA, USA).Three measurements were made for each experimental run,

3.2.1.2. Water activity

Water activity was measured by using a water activity meter (Series 3 TE, AquaLab, Pullman, WA, USA). Three measurements were made for each experimental run.

3.2.1.3. Color

A chroma meter (CR-400 Chroma meter, Konica Minolta, Ramsey, NJ, USA) was used to determine the parameters of color measurement. L* value represented brightness/darkness of the ingredients, a* value quantified redness/greenness, and b* value denoted yellowness/blueness. The color measurement can be used for customer preference and quality controlling. Three measurements were made for each experimental run.

3.2.2. Flowability-related properties

3.2.2.1. Angle of repose

The angle of repose was determined by the dimensions of the powder pile. The equipment was made by lab. The powder is passed through a funnel which is lifted to allow the material to form a powder heap. Three measurements were made for each experimental run.

3.2.2.2. Bulk density

Aerated bulk density was determined by allowing an excess of powder to flow into a specific volume cylindrical cup (Matric Cup, Seedburo, Chicago, IL, USA) until it overflows. Carefully, scraped excess powder from the top of the cup by smoothly moving the edge of the blade of a spatula perpendicular to and in contact with the top surface of the cup, taking care to keep the spatula perpendicular to prevent packing or removal of powder from the cup. Any material from the side of the cup was removed, and the mass of the powder was determined. The ratio of the mass of the sample to the bulk volume was calculated.

Packed bulk density had the similar procedure as aerated bulk density. But before scraped the excess powder, the cup was hit on the table for 20 times to compress the powder.

For aerated bulk density, a 0.5 L container was used to measure. For packed bulk density, a 1 L container was used. Three measurements were made for each experimental run.

3.2.2.3. Uniformity

The coefficient of uniformity is a ratio between the screen size that will pass 60% of the sample and the screen size that will pass only 10% of the sample.

3.2.2.4. Compressibility

Compressibility was calculated using formula (1).

3.2.2.5. Hausner ratio

HR was calculated using formula (2).

3.2.3. Statistical analysis

The collected data were analyzed with two-way analysis of variance by using JMP software, with a type I error rate (α) of 0.05, to determine the main and interaction effects, and least significant differences between treatment combinations.

3.3. Results

Table 1. shows moisture content and water activity values for the feed ingredients as they were received.

Table 1. Original moisture content and water activity for feed ingredients; table shows mean values with standard deviations in parentheses.

	Moisture content (%)	Water activity
soybean meal	10.70	0.5
	(0.01)	(0.01)
high protein DDGS	6.40	0.43
	(0.01)	(0.01)
soy protein concentrate	8.70	0.3
	(0.01)	(0.01)
NF8	6.50	0.27
	(0.01)	(0.01)
soy protein isolate	6.30	0.24
	(0.01)	(0.02)
cotton seed meal	10.70	0.54
	(0.01)	(0.01)
pea bran	8.90	0.31
	(0.01)	(0.01)
soy flour	8.90	0.28
	(0.01)	(0.04)
pea protein	8.90	0.33
	(0.01)	(0.02)
fish meal	6.90	0.4
	(0.01)	(0.01)
corn gluten meal	7.80	0.33
	(0.01)	(0.03)

3.3.1. Soybean meal

For the original sample, Table 1 shows the moisture content is 10.7%, and water activity is 0.57. Since the original moisture content is greater than 10%, only 20% and 30% moisture content level were measured.

3.3.1.1. Physical properties analysis

For the thermal properties, thermal conductivity, volumetric specific heat, and thermal diffusivity were measured. Based on Table 2, changing moisture content from 20% to 30% had a significant effect on all the thermal properties. But increasing moisture content from 10.7% to

20% only significantly effect volumetric specific heat, and thermal diffusivity. With the moisture content from the original increased to 30%, thermal conductivity increased from 0.14 to 0.76. Volumetric specific heat ranged from 1.41 to 1.54 and thermal diffusivity varied from 0.01 to 0.17.

Usually, the color of samples changed when the sample increased the moisture content. From the chromameter results, it was observed that there was significant difference between moisture content levels for soybean meal. Table 2 shows that the brightness (L*) of soybean meal decreased from 76.23 to 56.44, the redness (a*) value decreased from 6.67 to -1.24 and the blue-yellow (b*) value decreased from 33.20 to 6.19, with the moisture content levels increased from original to 30%.

3.3.1.2. Flow properties analysis

For the angle of repose, Table 2 shows that when the sample increased moisture, AoR values did not have a significant difference. The mean value of AoR ranged from 36.83 to 45.1. ABD and PBD had a significant difference; they decreased from 646.22 to 544.47 and 690.56 to 596.23 with the moisture content increased to 30%. Compressibility, which is calculated using ABD and PBD, was significantly affected by moisture content, it decreased with the increase of moisture content. The mean values of compressibility varied from 6.42% to 8.68%. For the mass flow rate, Table 2 shows that it decreased from 281.84 to 215.2 with the increase of moisture content to 30%. Based on Table 2, uniformity of soybean meal was not affected by moisture content level. There was not a significant effect on the HR value when increasing moisture content level to 30%. The HR value ranged from 1.07 to 1.10.

Table 2. Flowability and physical properties for soybean meal at different moisture content level

	Thermal properties			Color		
Moisture Content (%)	Thermal Conductivity (W/(m*K))	Volumetric Specific Heat (MJ/(m^3*K))	Thermal Diffusivity (mm^2/s)	L*	a*	b*
10.7	0.14 a (0.01)	1.42 a (0.01)	0.09 a (0.01)	76.23 a (2.06)	6.67 a (0.77)	33.2 a (1.55)
10	-	-	-	-	-	-
20	0.14 a (0.01)	1.41 b (0.01)	0.01 b (0.01)	67.92 a (6.46)	-1.62 b (0.33)	6.95 b (1.79)
30	0.76 b (0.01)	1.54 c (0.01)	0.17 c (0.01)	56.44 b (2.71)	-1.24 c (0.15)	6.19 b (0.62)

Moisture Content (%)	AoR (^{o})	ABD (g/L)	PBD (g/L)	Uniformity	Compressibility	HR	Mass flow (g/s)
10.7	38.03 a (5.06)	646.22 a (4.11)	690.56 a (8.82)	2 a (0.01)	6.42 a (0.01)	1.07 a (0.02)	281.84 a (25.05)
10	-	-	-	-	-	-	-
20	36.83 a (2.41)	572.87 b (7.89)	618.7 b (4.25)	2.07 a (0.01)	7.41 b (0.01)	1.08 a (0.01)	248.08 ab (16.28)
30	45.1 a (3.87)	544.47 c (5.56)	596.23 c (6.65)	2.15 a (0.01)	8.68 c (0.01)	1.10 a (0.01)	215.2 b (10.25)

[a] Means with different letters in a column were significantly different ($P < 0.05$); values in parantheses are standard deviation

3.3.2. High protein DDGS

For the original sample, Table 1 shows the moisture content is 6.4%, and water activity is 0.43. Since the original moisture content is lower than 10%, the 10%, 20% and 30% moisture content level were measured.

3.3.2.1. Physical properties analysis

For the thermal properties, based on Table 3, with the moisture content increased from original to 30%, thermal conductivity had a significant difference, the values of thermal conductivity increased from 0.12 to 0.16. Volumetric specific heat had a significant difference between 6.4%, 10%, and 20% moisture content levels and did not have a significant difference between 20% and 30% moisture content levels; the values increased from 1.07 to 1.44. And thermal diffusivity did not have a significant change with the increase of moisture content level. The values varied from 0.07 to 0.11.

From the chromameter results, it was observed that the difference between treatments for high protein DDGS did exist, for the original sample and 10% moisture content, the change was significant only on a* and b*. Between 10% and 20% moisture content, the change was significant for L*, a*, and b*. And for 20% and 30% moisture content, the change was not significant only on b*. Table 3 shows that when the moisture content varied from the original to 30%, the brightness (L*) of high protein DDGS varied from 72.57 to 63.5, the redness (a*) value decreased from 9.67 to -3.09 and the blue-yellow (b*) value ranged from 42.73 to 16.05.

3.3.2.1. Flow properties analysis

For the angle of repose, Table 3 shows that when the moisture content increased from original to 30%, AoR values did not have a significant difference. The mean value of AoR ranged from 44.3 to 50.43. ABD did not have a significant change only between 6.4% and 10% moisture content. The mean values decreased from 576.09 to 457.93. And PBD decreased from 620.65 to 504.93 with the moisture content increased to 30%. The PBD value had a significant difference between 10%, 20%, and 30% moisture content. Compressibility for high protein DDGS was significantly increased for moisture content between 10%, 20%, and 30. The mean values of compressibility varied from 7.18% to 9.31%. For the mass flow rate, Table 3 shows that it was significantly affected by moisture content, it decreased from 105.6 to 62.7 with the increase of moisture content to 30%. Based on Table 3, uniformity of soybean meal has no significant difference between moisture content level. The uniformity ranged from 2 to 2.08.

There was only a significant effect on the HR value between 20% and 30% moisture content level. The HR value ranged from 1.08 to 1.20.

Table 3. Physical and flowability properties for high protein DDGS at different moisture content level

	Thermal properties			Color		
Moisture Content (%)	Thermal Conductivity (W/(m*K))	Volumetric Specific Heat (MJ/(m^3*K))	Thermal Diffusivity (mm^2/s)	L*	a*	b*
6.4	0.12 a (0.01)	1.07 a (0.06)	0.11 a (0.01)	71.82 a (3.34)	9.67 a (0.68)	42.73 a (2.53)
10	0.13 ab (0.01)	0.12 b (0.01)	0.10 a (0.01)	72.57 a (1.10)	7.58 b (0.11)	35.53 b (0.91)
20	0.13 b (0.01)	1.32 c (0.01)	0.07 a (0.05)	63.50 b (4.65)	-2.65 c (0.37)	16.05 c (1.05)
30	0.16 c (0.01)	1.44 c (0.01)	0.11 a (0.001)	69.38 a (1.42)	-3.09 a (0.57)	18.06 c (2.19)

Moisture Content (%)	AoR (^{o})	ABD (g/L)	PBD (g/L)	Uniformity	Compressibility	HR	Mass flow (g/s)
6.4	44.70 a (4.68)	576.09 a (2.85)	620.65 a (5.02)	2.00 a (0.04)	7.18 a (0.01)	1.08 a (0.01)	105.6 a (10.38)
10	44.30 a (2.71)	564.54 a (0.88)	610.21 a (8.12)	2.03 a (0.01)	7.48 a (0.01)	1.08 a (0.02)	97.19 ab (10.63)
20	46.00 a (2.79)	487.33 b (5.15)	535.70 b (4.35)	2.02 a (0.03)	9.02 b (0.02)	1.10 a (0.02)	84.85 b (0.02)
30	50.43 a (3.07)	457.93 c (7.92)	504.93 c (6.26)	2.08 a (0.06)	9.31 b (0.02)	1.20 b (0.03)	62.70 c (0.03)

[a] Means with different letters in a column were significantly different ($P < 0.05$); values in parantheses are standard deviation

3.3.3. Soy protein concentrate

For the original sample, Table 1 shows the moisture content is 8.7%, and water activity is 0.3. Since the original moisture content is lower than 10%, the 10%, 20% and 30% moisture content level were measured.

3.3.3.1. Physical properties analysis

For the thermal properties, based on Table 4, with the moisture content increased from original to 30%, thermal conductivity and thermal diffusivity had a significant difference.

Thermal conductivity increased from 0.11 to 0.16, and thermal diffusivity increased from 0.11 to 0.12. Volumetric specific heat also had significant difference between different moisture content levels except 20% and 30%; the value increased from 0.99 to 1.34

From the chromameter results, it was observed that the difference between original sample and 10% moisture content was significant only on b*. And for 20% and 30% moisture content, the change also was significant only on a*. The change between 10% and 20% moisture content was significant on all parameters. Table 4 shows that when the moisture content varied from original to 30%, the brightness (L*) of high protein DDGS varied from 97.92 to 78.51, the redness (a*) value ranged from 1.38 to 2.22 and the blue-yellow (b*) value decreased from 12.59 to -23.16.

3.3.3.2. Flow properties analysis

For the angle of repose, Table 4 shows that when moisture content increased from original to 30%, AoR values did not have a significant difference. The mean value of AoR ranged from 51.87 to 54.13. ABD and PBD had a significant change when the moisture content increased. The mean values of ABD decreased from 496.47 to 402.73. PBD decreased from 549.96 to 470.67 with the moisture content increased to 30%. Compressibility for soy protein concentrate was significantly affected by moisture content. The mean values of compressibility increased from 9.73% to 14.43%. For the mass flow rate, Table 4 shows that there was no significant difference only between 8.7% and 10% moisture content level. The mass flow rate decreased from 101.67 to 53.78 with the increase of moisture content to 30%. Based on Table 4, uniformity of soybean meal was not significantly affected by moisture content level. The uniformity ranged from1.41 to 1.61. There was only a significant effect on the HR value between 20% and 30% moisture content level. The HR value ranged from 1.11 to 1.17.

Table 4. Physical and flowability properties for soy protein concentrate at different moisture content level

	Thermal properties			Color		
Moisture Content (%)	Thermal Conductivity (W/(m*K))	Volumetric Specific Heat (MJ/(m^3*K))	Thermal Diffusivity (mm^2/s)	L*	a*	b*
8.7	0.11 a (0.01)	0.99 a (0.07)	0.11 a (0.01)	97.92 a (1.36)	1.38 a (0.21)	12.59 a (0.68)
10	0.13 b (0.01)	1.15 b (0.01)	0.11 ab (0.01)	95.63 a (1.17)	1.66 a (0.42)	9.39 b (0.23)
20	0.15 c (0.01)	1.3 c (0.03)	0.12 b (0.01)	78.51 b (2.65)	2.22 b (0.05)	-24.13 c (0.64)
30	0.16 d (0.01)	1.34 c (0.01)	0.12 c (0.01)	81.12 b (2.66)	1.69 a (0.016)	-23.16 c (1.06)

Moisture Content (%)	AoR (°)	ABD (g/L)	PBD (g/L)	Uniformity	Compressibility	HR	Mass flow (g/s)
8.7	51.87 a (6.40)	496.47 a (11.21)	549.96 a (9.44)	1.41 a (0.01)	9.73 a (0.03)	1.11 a (0.03)	101.67 a (13.11)
10	53.33 a (1.72)	462.90 b (5.20)	517.31 b (11.18)	1.53 a (0.03)	10.32 b (0.012)	1.12 a (0.01)	102.66 a (11.55)
20	53.13 a (4.68)	437.57 c (9.15)	499.00 c (11.56)	1.61 a (0.02)	12.31 c (0.01)	1.14 a (0.01)	76.78 b (7.04)
30	54.12 a (2.91)	402.73 d (6.37)	470.67 d (6.37)	1.54 a (0.01)	14.43 d (0.01)	1.17 b (0.01)	53.78 c (9.68)

[a] Means with different letters in a column were significantly different (P < 0.05); values in parantheses are standard deviation

3.3.4. NF8

For the original sample, Table 1 shows the moisture content is 6.5%, and water activity is 0.27. Since the original moisture content is lower than 10%, the 10%, 20% and 30% moisture content level were measured.

3.3.4.1. Physical properties analysis

For the thermal properties, based on Table 5, the moisture content of NF8 had a significant effect on all the thermal properties. With the moisture content increased from original to 30%, thermal conductivity increased from 0.13 to 0.17. Volumetric specific heat increased from 1.25 to 1.7, and thermal diffusivity did not have a significant change. The values increased from 0.11 to 0.15.

From the chromameter results, it was observed that the moisture content of NF8 had a significant effect on L* and b*. There was only a significant difference between 10% and 20% moisture content level on a*. Table 5 shows that when the moisture content increased from the original to 30%, the brightness (L*) of high protein DDGS decreased from 73.67 to 44.81, the redness (a*) value decreased from 8.79 to 2.64 and the blue-yellow (b*) value decreased from 25.65 to 3.6.

3.3.4.2. Flow properties analysis

For the angle of repose, Table 2 shows that when the moisture content increased from original to 30%, AoR values did not have a significant difference. The mean value of AoR ranged from 39.57 to 58.57. ABD and PBD had a significant change when the moisture content increased. The mean values of ABD decreased from 7578.82 to 542.73. And PBD decreased from 843.29 to 584.1 with the moisture content increased to 30%. Compressibility for NF8 was significantly affected by moisture content. The mean values of compressibility varied from 5.13% to 7.08%. For the mass flow rate, Table 5 shows that it was significantly affected by moisture content when was increased from 10% to 30%. The mean value of mass flow rate decreased from 607.31 to 501.13 with the increase of moisture content to 30%. Based on Table 5, uniformity of soybean meal was not significantly affected by moisture content level. The uniformity ranged from 4.00 to 4.15. There was not a significant effect on the HR value for the moisture content level only between 6.5% and 10%. The HR value ranged from 1.05 to 1.08.

Table 5. Physical and flowability properties for NF8 at different moisture content level

	Thermal properties			Color		
Moisture Content (%)	Thermal Conductivity (W/(m*K))	Volumetric Specific Heat (MJ/(m^3*K))	Thermal Diffusivity (mm^2/s)	L*	a*	b*
6.5	0.13 a (0.01)	1.25 a (0.02)	0.11 a (0.01)	73.67 a (2.51)	8.79 a (0.28)	25.65 a (1.58)
10	0.14 b (0.01)	1.35 b (0.05)	0.11 b (0.01)	65.44 b (1.89)	8.53 a (0.98)	21.8 b (0.49)
20	0.17 c (0.01)	1.50 c (0.01)	0.12 b (0.01)	55.06 c (3.70)	3.11 b (0.18)	6.93 c (0.42)
30	0.25 d (0.01)	1.70 d (0.01)	0.15 c (0.01)	44.81 d (0.32)	2.64 b (0.14)	3.60 d (0.44)

Moisture Content (%)	AoR (°)	ABD (g/L)	PBD (g/L)	Uniformity	Compressibility	HR	Mass flow (g/s)
6.5	39.57 a (2.75)	778.82 a (8.25)	843.29 a (7.29)	4.00 a (0.02)	6.46 a (0.01)	1.06 a (0.03)	607.31 a (26.61)
10	44.6 bc (2.54)	728.06 b (5.01)	782.92 b (14.42)	4.15 a (0.03)	7.01 b (0.01)	1.07 a (0.03)	602.60 a (19.55)
20	44.00 b (2.61)	578.80 c (7.82)	610.10 c (4.11)	4.05 a (0.03)	5.13 c (0.01)	1.05 b (0.01)	543.98 b (21.04)
30	48.57 c (1.16)	542.73 d (6.96)	584.10 d (5.55)	4.08 a (0.03)	7.08 d (0.01)	1.08 c (0.01)	501.13 c (11.46)

[a] Means with different letters in a column were significantly different ($P < 0.05$); values in parantheses are standard deviation

3.3.5. Soy protein isolate

For the original sample, Table 1 shows the moisture content is 6.3%, and water activity is 0.24. Since the original moisture content is lower than 10%, the 10%, 20% and 30% moisture content level were measured.

3.3.5.1. Physical properties analysis

For the thermal properties, based on Table 6, moisture content had a significant effect on all the thermal properties except volumetric specific heat between 6.3% and 10% moisture content level. With the moisture content increased from original to 30%, thermal conductivity increased from 0.09 to 0.22. Volumetric specific heat increased from 0.78 to 1.4, and thermal diffusivity did not have a significant change. The values varied from 0.12 to 0.18.

From the chromameter results, it was observed that the significant difference between treatments for soy protein isolate was only existed on blue-yellow (b*) value, but for the 20% and 30% moisture content, the change was not significant. Table 6 shows that when the moisture content varied from the original to 30%, the brightness (L*) of high protein DDGS varied from 90.14 to 94.98, the redness (a*) value ranged from 1.16 to 1.72 and the blue-yellow (b*) value decreased from 18.01 to -21.95.

3.3.5.2. Flow properties analysis

For the angle of repose, Table 6 shows that when the moisture content increased from original to 30%, AoR values did not have significant change. The mean value of AoR ranged from 53.5 to 54.9. ABD did not have a significant change when increased the moisture content from 6.3% to 10%. The mean values varied from 285.97 to 329.51. But PBD was significantly affected by moisture content, PBD decreased from 449.66 to 397.53 with the moisture content increased to 30%. Compressibility for soy protein isolate was significantly affected by moisture content only between 10% and 20%. The mean values of compressibility varied from 25.12% to 28.03%. For the mass flow rate, there were significant changes from 10% to 30% moisture content. Table 6 shows that it decreased from 149.9 to 98.37 with the increase of moisture content to 30%. Based on Table 6, uniformity and HR of soy pritein isolate was not significantly affected by moisture content level. The uniformity ranged from 2.01 to 2.14. The HR value ranged from 1.34 to 1.39.

Table 6. Physical and flowability properties for soy protein isolate at different moisture content level

	Thermal properties			Color		
Moisture Content (%)	Thermal Conductivity (W/(m*K))	Volumetric Specific Heat (MJ/(m^3*K))	Thermal Diffusivity (mm^2/s)	L*	a*	b*
6.3	0.09 a (0.01)	0.78 a (0.03)	0.12 a (0.01)	92.93 a (1.35)	1.72 a (0.06)	18.10 a (0.45)
10	0.11 b (0.01)	0.85 a (0.04)	0.14 b (0.01)	94.98 a (3.12)	1.95 a (0.51)	14.94 b (0.76)
20	0.17 c (0.01)	0.96 b (0.06)	0.18 c (0.02)	91.82 a (4.95)	1.16 a (0.08)	-21.79 c (0.63)
30	0.22 d (0.01)	1.40 c (0.01)	0.16 b (0.01)	90.14 a (5.36)	1.37 a (0.52)	-21.95 c (1.36)

Moisture Content (%)	AoR (°)	ABD (g/L)	PBD (g/L)	Uniformity	Compressibility	HR	Mass flow (g/s)
6.3	53.83 a (2.70)	329.51 a (13.74)	449.66 a (7.06)	2.01 a (0.02)	26.68 a (0.05)	1.37 a (0.08)	149.9 a (19.85)
10	53.5 a (2.01)	321.77 a (6.73)	424.69 b (12.32)	2.06 a (0.01)	24.21 b (0.02)	1.32 a (0.03)	134.76 a (17.89)
20	53.83 a (2.96)	327.53 a (14.01)	384.53 c (11.21)	2.14 a (0.01)	14.84c (0.01)	1.17 b (0.01)	125.56 ab (13.62)
30	54.90 a (2.31)	295.97 b (4.36)	347.33 d (8.44)	2.09 a (0.03)	14.78 c (0.01)	1.17 b (0.02)	98.37 b (10.72)

[a] Means with different letters in a column were significantly different ($P < 0.05$); values in parantheses are standard deviation

3.3.6. Cotton seed meal

For the original sample, Table 1 shows the moisture content is 10.7%, and water activity is 0.54. Since the original moisture content is greater than 10%, only 20% and 30% moisture content level were measured.

3.3.6.1. Physical properties analysis

For the thermal properties, based on Table 7, moisture content had a significant effect on the thermal conductivity and thermal diffusivity when increased from 10.7% to 20%. And moisture content had a significant effect on volumetric specific heat when increased from 20% to 30%.With the moisture content increased from original to 30%, thermal conductivity increased from 0.12 to 0.16. Volumetric specific heat increased from 1.25 to 1.41, and thermal diffusivity increased from 0.1 to 0.12.

From the chromameter results, it was observed that the moisture content was significantly affected all the color parameters. Table 7 shows that when the moisture content varied from the original to 30%, the brightness (L*) of high protein DDGS decreased from 42.12 to 30.69, the redness (a*) value ranged from 3.99 to 8.46 and the blue-yellow (b*) value decreased from 18.41 to 2.41.

3.3.6.2. Flow properties analysis

For the angle of repose, Table 7 shows that when the moisture content increased from original to 30%, AoR values did not have a significant change. The mean value of AoR ranged from 44.87 to 46.8. ABD and PBD had a significant change when increased the moisture content. The mean values decreased from 596.84 to 510.8. And PBD decreased from 682.25 to 597.23 with the moisture content increased to 30%. Compressibility for cotton seed meal was significantly affected by the moisture content. The mean values of compressibility increased from 12.52% to 14.47%. For the mass flow rate, Table 7 shows that it decreased from 639.57 to 545.72 with the increase of moisture content to 30%. It was significantly affected by 10.7% and 20% moisture content level. Based on Table 7, uniformity of cottonseed meal was not significantly affected by moisture content level. The uniformity ranged from 4.00 to 4.11. There was not a significant effect on the HR value btween moisture content levels. The HR value ranged from 1.14 to 1.17.

Table 7. Physical and flowability properties for cotton seed meal at different moisture content level

	Thermal properties			Color		
Moisture Content (%)	Thermal Conductivity (W/(m*K))	Volumetric Specific Heat (MJ/(m^3*K))	Thermal Diffusivity (mm^2/s)	L*	a*	b*
10.7	0.12 a (0.01)	1.25 a (0.03)	0.10 a (0.01)	42.12 a (0.43)	8.46 a (0.29)	18.41 a (0.35)
10	-	-	-	-	-	-
20	0.15 b (0.01)	1.29 a (0.04)	0.11 b (0.01)	39.38 b (2.04)	3.99 b (0.16)	3.27 b (0.48)
30	0.16 b (0.01)	1.41 b (0.01)	0.12 b (0.01)	30.69 c (1.03)	4.39 c (0.11)	2.41 c (0.27)

Moisture Content (%)	AoR (^{o})	ABD (g/L)	PBD (g/L)	Uniformity	Compressibility	HR	Mass flow (g/s)
10.7	46.80 a (1.55)	596.84 a (6.70)	682.25 a (6.87)	4.00 a (0.03)	12.52 a (0.02)	1.14 a (0.02)	639.57 a (52.52)
10	-	-	-	-	-	-	-
20	44.87 a (2.16)	558.50 b (10.25)	643.13 b (8.21)	4.06 a (0.01)	13.16 b (0.01)	1.15 a (0.02)	564.33 b (21.73)
30	45.63 a (2.95)	510.80 c (7.50)	597.23 c (7.02)	4.11 a (0.04)	14.47 c (0.01)	1.17 a (0.01)	545.72 b (12.06)

[a] Means with different letters in a column were significantly different ($P < 0.05$); values in parantheses are standard deviation

3.3.7. Pea bran

For the original sample, Table 1 shows the moisture content is 8.9%, and water activity is 0.31. Since the original moisture content is lower than 10%, the 10%, 20% and 30% moisture content level were measured.

3.3.7.1. Physical properties analysis

For the thermal properties, based on Table 8, moisture content had a significant effect on the thermal conductivity and volumetric specific heat. And thermal diffusivity had a significant change from 8.9% to 20% moisture content level. With the moisture content increased from original to 30%, thermal conductivity increased from 0.12 to 0.15. Volumetric specific heat ranged from 0.95 to 1.13 and thermal diffusivity varied from 0.11 to 0.15.

From the chromameter results, it was observed that the difference between moisture content levels for L* was significant. The difference of a* from 10% to 30% moisture content was significant. And the difference of b* from 8,9% to 20% moisture content was significant. Table 8 shows that when the moisture content varied from the original to 30%, the brightness (L*) of high protein DDGS varied from 59.61 to 81.06, the redness (a*) value ranged from -3.15 to 1.97 and the blue-yellow (b*) value decreased from 21.89 to -7.49.

3.3.7.2. Flow properties analysis

For the angle of repose, Table 8 shows that when moisture content increased from original to 30%, AoR values did not have a significant change. The mean value of AoR increased from 40.4 to 46.87. ABD had a significant change when increased the moisture content. The mean values decreased from 686.03 to 627.27. And PBD only significantly changed between 20% and 30% moisture content level. It decreased from 691.75 to 640.67 with the moisture content increased to 30%. Compressibility for pea bran was not significantly affected by moisture content. The mean values of compressibility varied from 0.82% to 2.09%. For the mass flow rate, Table 8 shows that only changing moisture content from 10% to 20% had a significant difference. It decreased from 121.93 to 85.3 with the increase of moisture content to 30%. Based on Table 8, uniformity of soybean meal was not significantly affected by moisture content level. The uniformity ranged from 2.65 to 2.98. There was not a significant effect on the HR value for the different moisture content level. The HR value ranged from 1.01 to 1.02.

Table 8. Physical and flowability properties for pea bran at different moisture content level

	Thermal properties			Color		
Moisture Content (%)	Thermal Conductivity (W/(m*K))	Volumetric Specific Heat (MJ/(m^3*K))	Thermal Diffusivity (mm^2/s)	L*	a*	b*
8.9	0.12 a (0.01)	1.13 a (0.02)	0.11 a (0.01)	77.81 a (1.18)	1.93 a (0.03)	21.89 a (0.64)
10	0.13 b (0.01)	1.09 b (0.01)	0.11 b (0.01)	74.00 b (2.07)	1.97 a (0.44)	18.14 b (0.66)
20	0.14 c (0.01)	0.95 c (0.01)	0.15 c (0.01)	81.06 c (1.54)	-3.15 b (0.03)	-6.83 c (0.65)
30	0.15 d (0.01)	1.06 d (0.01)	0.15 c (0.01)	59.61 d (1.54)	-1.05 c (0.11)	-7.49 c (0.62)

Moisture Content (%)	AoR (°)	ABD (g/L)	PBD (g/L)	Uniformity	Compressibility	HR	Mass flow (g/s)
8.9	40.40 a (1.90)	686.03 a (12.08)	691.75 a (16.58)	2.83 a (0.01)	0.82 a (0.01)	1.01 a (0.01)	121.93 a (9.68)
10	44.50 a (2.20)	660.71 b (5.26)	673.51 a (9.43)	2.74 a (0.04)	1.89 a (0.01)	1.02 a (0.01)	123.46 a (7.91)
20	45.70 a (3.64)	660.42 b (17.24)	668.53 a (15.46)	2.65 a (0.01)	1.22 a (0.01)	1.01 a (0.01)	97.25 b (9.87)
30	46.87 a (2.60)	627.27 c (11.08)	640.67 b (7.07)	2.98 a (0.05)	2.09 a (0.01)	1.02 a (0.01)	85.30 b (9.74)

[a] Means with different letters in a column were significantly different ($P < 0.05$); values in parantheses are standard deviation

3.3.8. Soy flour

For the original sample, Table 1 shows the moisture content is 5.8%, and water activity is 0.28. Since the original moisture content is lower than 10%, 10%, the 20% and 30% moisture content level were measured. But when increased the moisture content to 20%, soy flour became semi-solid. Only original and 10% moisture content was measured.

3.3.8.1. Physical properties analysis

For the thermal properties, based on Table 9, moisture content had an effect on the thermal properties except volumetric specific heat. With the moisture content increased from the original to 10%, thermal conductivity increased from 0.11 to 0.12. Volumetric specific heat increased from 1.02 to 1.05, and thermal diffusivity increased from 0.11 to 0.12.

Table 9 shows that when the moisture content varied from original to 10%, all the color parameters had a significant change. The brightness (L*) of soy flour decreased from 92.92 to 75.32, the redness (a*) value decreased from -0.95 to -3.67 and the blue-yellow (b*) value decreased from 24.26 to 18.49.

3.3.8.2. Flow properties analysis

For the angle of repose, Table 9 shows that when the moisture content increased from the original to 10%, AoR values did not have a significant change. It increased from 54 to 56.6. ABD also did not have a significant difference between 5.8% and 10% moisture content level, but PBD had a significant difference. ABD decreased from 390.66 to 377.42. And PBD decreased from 535.26 to 496.03 with the moisture content increased to 10%. Compressibility and mass flow did not have a significant change when increasing moisture content from 5.8% to 10%. Compressibility for soy flour decreased from 26.97% to 23.9%. For the mass flow rate, Table 9 shows that it decreased from 98.48 to 85.35 with the increase of moisture content to 10%. Based on Table 9, uniformity of soybean meal was not significantly affected by moisture content level. The uniformity ranged from 2.84 to 2.96. There was not a significant effect on the HR value for the different moisture content level. The HR value ranged from 1.31 to 1.37

Table 9. Physical and flowability properties for soy flour at different moisture content level

	Thermal properties			Color		
Moisture Content (%)	Thermal Conductivity (W/(m*K))	Volumetric Specific Heat (MJ/(m^3*K))	Thermal Diffusivity (mm^2/s)	L*	a*	b*
5.8	0.11 a (0.01)	1.02 a (0.04)	0.11 a (0.01)	92.92 a (0.16)	-0.95 a (0.04)	24.26 a (0.25)
10	0.12 b (0.01)	1.05 a (0.01)	0.12 b (0.01)	75.32 b (1.71)	-3.67 b (0.83)	18.49 b (0.12)
20	-	-	-	-	-	-
30	-	-	-	-	-	-

Moisture Content (%)	AoR (^{o})	ABD (g/L)	PBD (g/L)	Uniformity	Compressibility	HR	Mass flow (g/s)
5.8	54.00 a (2.35)	390.66 a (6.67)	535.26 a (12.93)	2.84 a (0.01)	26.97 a (0.03)	1.37 a (0.06)	98.48 a (20.77)
10	56.60 a (3.54)	377.42 a (7.40)	496.03 b (6.46)	2.96 a (0.01)	23.90 a (0.02)	1.31 a (0.04)	85.35 a (9.36)
20	-	-	-	-	-	-	-
30	-	-	-	-	-	-	-

[a] Means with different letters in a column were significantly different ($P < 0.05$); values in parantheses are standard deviation

3.3.9. Pea protein

For the original sample, Table 1 shows the moisture content is 8.9%, and water activity is 0.33. Since the original moisture content is lower than 10%, 10%, the 20% and 30% moisture content level were measured. But when increased the moisture content to 30%, soy flour became semi-solid. Only original, 10% and 20% moisture content was measured.

3.3.9.1. Physical properties analysis

For the thermal properties, based on Table 10, moisture content had a significant effect on volumetric specific heat. For thermal conductivity and thermal diffusivity, there was a significant difference between 10% and 20% moisture content level. With the moisture content increased from original to 20%, thermal conductivity ranged from 0.10 to 0.16. Volumetric specific heat increased from 0.85 to 1.21, and thermal diffusivity increased from 0.12 to 0.13.

Table 10. shows that when the moisture content varied from original to 20%, the brightness (L*) of pea protein did not have a significant change, it decreased from 94.43 to 88.98. The redness (a*) value only had a significant difference between 10% and 20%. The a* value decreased from 1.63 to -3.6 and the blue-yellow (b*) value decreased from 24.44 to -3.6. There was a significant difference between all different moisture content levels.

3.3.9.2. Flow properties analysis

For the angle of repose, Table 10 shows that when the moisture content increased from original to 20%, AoR values was not significantly affected. ABD had significant change between moisture content levels, and PBD was significantly affected by moisture content. ABD decreased from 391.08 to 365.47, and PBD decreased from 452.43 to 415.93 with the moisture content increased to 20%. Compressibility did not have a significant difference between moisture content levels. Compressibility for pea protein varied from 12.13% to 13.86%. For the mass flow rate, there was only a significant difference between 10% and 20% moisture content level. Table 10 shows that it decreased from 133.25 to 98.10 with the increase of moisture content to 20%. Based on Table 10, uniformity and HR of pea protein was not significantly affected by moisture content level. The uniformity ranged from 2.00 to 2.09. The HR value ranged from 1.14 to 1.16.

Table 10. Physical and flowability properties for pea protein at different moisture content level

	Thermal properties			Color		
Moisture Content (%)	Thermal Conductivity (W/(m*K))	Volumetric Specific Heat (MJ/(m^3*K))	Thermal Diffusivity (mm^2/s)	L*	a*	b*
8.9	0.11 a (0.01)	0.85 a (0.05)	0.12 a (0.01)	94.35 a (0.96)	1.63 a (0.16)	24.44 a (1.10)
10	0.10 a (0.01)	0.92 b (0.01)	0.12 a (0.01)	93.56 a (2.10)	1.37 a (0.29)	21.13 b (0.57)
20	0.16 b (0.01)	1.21 c (0.01)	0.13 b (0.01)	88.98 a (5.12)	-3.60 b (0.43)	-7.57 c (1.53)
30	-	-	-	-	-	-

Moisture Content (%)	AoR (°)	ABD (g/L)	PBD (g/L)	Uniformity	Compressibility	HR	Mass flow (g/s)
8.9	49.97 a (1.33)	391.08 a (4.44)	452.43 a (6.27)	2.00 a (0.01)	13.55 a (0.02)	1.16 a (0.02)	133.25 a (23.94)
10	50.43 a (2.90)	372.98 b (4.54)	432.97 b (4.68)	2.04 a (0.02)	13.86 a (0.02)	1.16 a (0.02)	143.96 a (14.99)
20	55.17 a (2.39)	365.47 c (7.97)	415.93 c (8.09)	2.09 a (0.01)	12.13 a (0.01)	1.14 a (0.01)	98.10 b (10.83)
30	-	-	-	-	-	-	-

[a] Means with different letters in a column were significantly different ($P < 0.05$); values in parantheses are standard deviation

3.3.10. Fish meal

For the original sample, Table 1 shows the moisture content is 6.9%, and water activity is 0.40. Since the original moisture content is lower than 10%, the 10%, 20% and 30% moisture content level were measured.

3.3.10.1. Physical properties analysis

For the thermal properties, based on Table 11, moisture content had a significant effect on volumetric specific heat. Increasing moisture content from 6.9% to 10% moisture content was not significantly change the thermal conductivity and thermal diffusivity. With the moisture content increased from original to 30%, thermal conductivity increased from 0.11 to 0.35. Volumetric specific heat increased from 1.10 to 2.19, and thermal diffusivity increased from 0.10 to 0.15.

From the chromameter results, it was observed that the difference of all color parameter between moisture content for the fish meal was significant. But for L* and a*, when increasing moisture content from 20% to 30%, the change was not significant. Table 11 shows that when the moisture content varied from original to 30%, the brightness (L*) of fish meal decreased from 46.88 to 32.06, the redness (a*) value decreased from 6.54 to 0.87 and the blue-yellow (b*) value decreased from 22.81 to 1.54.

3.3.10.2. Flow properties analysis

For the angle of repose, Table 11 shows that when the moisture content increased from original to 30%, AoR values did not have a significant change. The mean value of AoR increased from 53.33 to 59.33. When increased the moisture content, the mean values of ABD and PBD had a significant difference. ABD decreased from 556.43 to 486.43, and PBD decreased from 639.01 to 577.17. Compressibility for the fish meal was not significantly affected by moisture content. The mean values of compressibility varied from 12.92% to 15.72%. For the mass flow rate, the change was significant except increasing moisture content from 6.9% to 10%. Table 11 shows that it decreased from 276.02 to 188.98 with the increase of moisture content to 30%. Based on Table 11, uniformity of soybean meal was not significantly affected by moisture content level. The uniformity ranged from 1.99 to 2.14. There was not a significant effect on the HR value for the different moisture content level. The HR value ranged from 1.15 to 1.19.

Table 11. Physical and flowability properties for fish meal at different moisture content level

	Thermal properties			Color		
Moisture Content (%)	Thermal Conductivity (W/(m*K))	Volumetric Specific Heat (MJ/(m^3*K))	Thermal Diffusivity (mm^2/s)	L*	a*	b*
6.9	0.11 a (0.01)	1.10 a (0.03)	0.10 a (0.01)	46.88 a (0.17)	6.54 a (0.07)	22.81 a (0.15)
10	0.12 a (0.01)	1.23 b (0.02)	0.10 a (0.01)	43.12 b (2.19)	4.56 b (0.42)	17.36 b (0.33)
20	0.30 b (0.01)	1.65 c (0.02)	0.12 b (0.01)	32.78 c (1.92)	0.91 c (0.12)	3.97 c (0.63)
30	0.35 c (0.01)	2.19 d (0.01)	0.15 c (0.01)	32.06 c (1.74)	0.87 c (0.17)	1.54 d (0.10)

Moisture Content (%)	AoR (^{o})	ABD (g/L)	PBD (g/L)	Uniformity	Compressibility	HR	Mass flow (g/s)
6.9	53.33 a (2.08)	556.43 a (9.67)	639.01 a (4.91)	1.99 a (0.01)	12.92 a (0.02)	1.15 a (0.03)	276.02 a (11.71)
10	55.23 a (3.29)	538.91 b (4.20)	624.21 b (7.79)	2.03a (0.01)	13.65 a (0.02)	1.16 a (0.03)	267.28 a (11.41)
20	56.60 a (2.27)	514.80 c (12.48)	596.37 c (7.00)	2.14 a (0.03)	13.68 a (0.02)	1.16 a (0.03)	214.33 b (10.99)
30	59.33 a (2.10)	486.43 d (7.72)	577.17 d (7.74)	2.07 a (0.01)	15.72 a (0.01)	1.19 a (0.01)	188.98 c (8.714)

[a] Means with different letters in a column were significantly different ($P < 0.05$); values in parantheses are standard deviation

3.3.11. Corn gluten meal

For the original sample, Table 1 shows the moisture content is 7.8%, and water activity is 0.33. Since the original moisture content is lower than 10%, the 10%, 20% and 30% moisture content level were measured.

3.3.11.1. Physical properties analysis

For the thermal properties, based on Table 12, moisture content had a significant effect on the volumetric specific heat (C) and thermal diffusivity (D). Thermal conductivity (K) and thermal resistivity (ρ) did not have a significant difference between 20% and 30% moisture content level. With the moisture content increased from original to 30%, thermal conductivity (K) increased from 0.11 to 0.16. Thermal resistivity (ρ) decreased from 911.83 to 634.23. Volumetric specific heat (C) ranged from 1.04 to 1.26, and thermal diffusivity (D) increased from 0.10 to 0.13.

From the chromameter results, it was observed that there was no significant difference between moisture content for L*. The a* was not significantly changed for the moisture content between 20% and 30%. And b* was not significantly changed between 7.8% and 10%. Table 12 shows that when the moisture content varied from original to 30%, the brightness (L*) of high protein DDGS decreased from 69.38 to 61.14, the redness (a*) value decreased from 7.36 to -8.14 and the blue-yellow (b*) value ranged from 37.58 to 54.9.

3.3.11.2. Flow properties analysis

For the angle of repose, Table 12 shows that when the moisture content increased from original to 30%, AoR values did not have a significant change. The mean value of AoR increased from 43.53 to 46.20. ABD had a significant difference between 7.8% and 10% and between 20% and 30% moisture content level. PBD had a significant difference from 10% to 30% moisture content levels. When increased the moisture content, the mean values of ABD decreased from 547.83 to 487.87. And PBD decreased from 561.15 to 504.97 with the moisture content increased to 30%. Compressibility for corn gluten meal was not significantly affected by moisture content. The mean values of compressibility varied from 1.18% to 3.39%. For the mass flow rate, there was a significant change from 10% to 30% moisture content levels. Table 12 shows that it decreased from 183.21 to 107.27 with the increase of moisture content to 30%. Based on Table 12, uniformity of soybean meal was not significantly affected by moisture content level. The uniformity ranged from 1.98 to 2.12. There was not a significant effect on the HR value for the different moisture content level. The HR value ranged from 1.01 to 1.04.

Table 12. Physical and flowability properties for corn gluten meal at different moisture content level

	Thermal properties			Color		
Moisture Content (%)	Thermal Conductivity (W/(m*K))	Volumetric Specific Heat (MJ/(m^3*K))	Thermal Diffusivity (mm^2/s)	L*	a*	b*
7.8	0.11 a (0.01)	1.04 a (0.02)	0.10 a (0.01)	69.38 a (0.29)	7.36 a (0.03)	54.90 a (0.30)
10	0.13 b (0.01)	1.14 b (0.02)	0.12 b (0.01)	65.49 a (2.47)	4.54 b (0.39)	51.76 a (0.35)
20	0.16 c (0.01)	1.26 c (0.02)	0.12 ab (0.01)	64.08 a (5.22)	-9.13 c (0.77)	37.58 b (3.37)
30	0.16 c (0.01)	1.23 d (0.01)	0.13 c (0.01)	61.14 a (3.34)	-8.14 c (0.70)	41.64 c (1.66)

Moisture Content (%)	AoR (^{o})	ABD (g/L)	PBD (g/L)	Uniformity	Compressibility	HR	Mass flow (g/s)
7.8	43.53 a (2.20)	547.83 a (0.01)	561.15 a (11.78)	1.98 a (0.01)	2.35 a (0.02)	1.02 a (0.02)	183.21 a (19.66)
10	44.70 a (3.20)	529.6 b (6.52)	535.94 a (5.80)	2.02 a (0.01)	1.18 a (0.01)	1.01 a (0.01)	165.26 a (9.51)
20	45.07 a (2.96)	517.63 b (9.89)	527.67 b (9.42)	2.07 a (0.01)	2.33 a (0.01)	1.02 a (0.01)	136.64 b (15.46)
30	46.20 a (2.19)	487.87 c (8.67)	504.97 c (8.97)	2.12 a (0.01)	3.36 a (0.01)	1.04 a (0.01)	107.27 c (6.51)

[a] Means with different letters in a column were significantly different ($P < 0.05$); values in parantheses are standard deviation

3.4. Discussion and Implications

3.4.1. Physical properties

3.4.1.1. Thermal properties

For all thermal properties, there was a significant difference between moisture content. In general, when increasing the moisture content, thermal conductivity, volumetric specifit heat, and thermal diffusiovity was increased. Thermal conductivity is the properties of material to conduct heat. It is observed that thermal conductivity increases with increase in moisture content because higher the moisture content greater the water particles and hence conduction heat transfer in the ingredients. Volumetric specifit heat is the ability of a given volume of a substance to store internal energy. Since water has a large heat capacity, when the water content was increased, the volumetric specifit heat was increased. Thermal diffusivity is the thermal conductivity divided by heat capacity at constant pressure. This value describes how quickly a material reacts to a change in temperature.

3.4.2. Flowability properties

According to Carr classifications, materials with an AoR less than 40° should flow easily, but those greater than 45° probably would not flow well (Carr, 1965). Materials with compressibility values less than 25% are considered as “good flowable materials,” but those greater than 25% are considered as “less flowable materials” (Carr 1965). The uniformity of all ingredients was less than 6.0, which falls in the flowability category of “very good.” A Hausner ratio of less than 1.25 indicates a powder that is free flowing, and greater than 1.25 indicates poor flow ability.

3.4.2.1. Soybean meal

As the results for the Carr tests indicate (Table 2), some difference between the moisture content levels were observed. The difference of AoR, HR, and unifromity for soybean meal was not significant when increasing the moisture content. The ABD, PDB, and mass flow were singnificantly decreased with the increase of moisture content. However, the compressibility was significantly higher when increasing the moisture content. Accroding to Carr classifications, all conpressibility value represented soybeam meal is free flowing. In totality, all of the Carr test results have shown that increasing the moisture content should decrease the flowability of soybean meal, but it was still a good flowable material.

To further explore the relationship between all 14 variables used in this study for soybean meal, correlation were determined. The strength of the linear relationship between two variables is quantified by the correlation coefficient (Table 13). From the table, moisture content had high correlations with thermal properties, color, and flow properties. The coorelation between moisture content and thermal conductivity is 0.88, which means there is a high positive linear relation between moisture content and thermal conductivity. The correlation coefficients between color and moisture content showed that moisture content had a strong negative linear effect on all color properties (with an r value of -0.92 between moisture content and L*, and an r value of -0.83 between moisture content and a*, and an r value of -0.86 between moisture content and b*). For the flow properties, the ABD, PBD, and mass flow values had a high negative relation to the moisture content (with an r value of -0.96 between moisture content and ABD, and an r value of -0.95 between moisture content and PBD, and an r value of -0.86 between moisture content and mass flow). Additionally, compressibility and HR values were highly related to the moisture cotent as well (with an r value of 0.82 between moisture content and compressibility, and an r value of 0.82 between moisture content and HR).

3.4.2.2. High protein DDGS

As the results for the Carr tests indicate (Table 3), some difference between the moisture content levels were observed. The difference of AoR and unifromity for high protein DDGS was not significant when increasing the moisture content. The ABD, PDB, and mass flow were singnificantly decreased with the increase of moisture content. However, the compressibility was significantly higher when increasing the moisture content. Accroding to Carr classifications, all conpressibility value represented soybeam meal is free flowing. In totality, all of the Carr test results have shown that increasing the moisture content should decrease the flowability of high protein DDGS, but it was still a good flowable material.

To further explore the relationship between all 14 variables used in this study for high protein DDGS, correlation were determined. The strength of the linear relationship between two variables is quantified by the correlation coefficient (Table 14). From the table, moisture content had high correlations with thermal properties, color, and flow properties. The coorelation between moisture content and thermal conductivity is 0.94, which means there is a high positive linear relation between moisture content and thermal conductivity. The correlation coefficients between color and moisture content showed that moisture content had a strong negative linear effect on the color properties (with an r value of -9.83 between moisture content and a*, and an r value of -0.89 between moisture content and b*). For the flow properties, the ABD, PBD, and mass flow values had a high negative relation to the moisture content (with an r value of -0.98 between moisture content and ABD, and an r value of -0.98 between moisture content and PBD, and an r value of -0.87 between moisture content and mass flow). Additionally, compressibility and HR values were related to the moisture cotent as well (with an r value of 0.59 between moisture content and compressibility, and an r value of 0.59 between moisture content and HR).

3.4.2.3. Soy protein concentrate

As the results for the Carr tests indicate (Table 4), some difference between the moisture content levels were observed. The difference of AoR and unifromity for soy protein concentrate was not significant when increasing the moisture content. The ABD, PDB, and mass flow were singnificantly decreased with the increase of moisture content. However, the compressibility was significantly higher when increasing the moisture content. Accroding to Carr classifications, all conpressibility value represented soy protein concentrate is free flowing. In totality, all of the

Carr test results have shown that increasing the moisture content should decrease the flowability of soy protein concentrate, but it was still a good flowable material.

To further explore the relationship between all 14 variables used in this study for soy protein concentrate, correlation were determined. The strength of the linear relationship between two variables is quantified by the correlation coefficient (Table 15). From the table, moisture content had high correlations with thermal properties, color, and flow properties. The coorelation between moisture content and thermal conductivity is 0.94, which means there is a high positive linear relation between moisture content and thermal conductivity. The correlation coefficients between color and moisture content showed that moisture content had a strong negative linear effect on the color properties (with an r value of -0.85 between moisture content and L*, and an r value of -0.90 between moisture content and b*). For the flow properties, the ABD, PBD, and mass flow values had a high negative relation to the moisture content (with an r value of -0.94 between moisture content and ABD, and an r value of -0.90 between moisture content and PBD, and an r value of -0.92 between moisture content and mass flow). Additionally, compressibility and HR values were highly related to the moisture cotent as well (with an r value of 0.80 between moisture content and compressibility, and an r value of 0.81 between moisture content and HR).

3.4.2.4. NF8

As the results for the Carr tests indicate (Table 3), some difference between the moisture content levels were observed. The difference of AoR, HR, and unifromity for soybean meal was not significant when increasing the moisture content. The ABD, PDB, and mass flow were singnificantly decreased with the increase of moisture content. However, the compressibility was significantly higher when increasing the moisture content. Accroding to Carr classifications, all conpressibility value represented soybeam meal is free flowing. In totality, all of the Carr test results have shown that increasing the moisture content should decrease the flowability of soybean meal, but it was still a good flowable material.

To further explore the relationship between all 14 variables used in this study for NF8, correlation were determined. The strength of the linear relationship between two variables is quantified by the correlation coefficient (Table 16). From the table, moisture content had high correlations with thermal properties, color, and flow properties. The coorelation between moisture content and thermal conductivity is 0.97, which means there is a high positive linear relation between moisture content and thermal conductivity. The correlation coefficients between color and moisture content showed that moisture content had a strong negative linear effect on all color properties (with an r value of -0.97 between moisture content and L*, and an r value of -0.93 between moisture content and a*, and an r value of -0.96 between moisture content and b*). For the flow properties, the ABD, PBD, and mass flow values had a high negative relation to the moisture content (with an r value of -0.96 between moisture content and ABD, and an r value of -0.95 between moisture content and PBD, and an r value of -0.93 between moisture content and mass flow).

3.4.2.5. Soy protein isolate

As the results for the Carr tests indicate (Table 6), some difference between the moisture content levels were observed. The difference of AoR, HR, and unifromity for soy protein ioslate was not significant when increasing the moisture content. The ABD, PDB, and mass flow were singnificantly decreased with the increase of moisture content. However, the compressibility was significantly higher only when increasing the moisture content from 10% to 20%. Accroding to Carr classifications, all conpressibility value represented soy protein isolate is considered as a less flowable ingredient. In totality, all of the Carr test results have shown that increasing the moisture content should decrease the flowability of soy protein isolate, and it was not a good flowable material.

To further explore the relationship between all 14 variables used in this study for soybean meal, correlation were determined. The strength of the linear relationship between two variables is quantified by the correlation coefficient (Table 17). From the table, moisture content had high correlations with thermal properties, color, and flow properties. The coorelation between moisture content and thermal conductivity is 0.99, which means there is a high positive linear relation between moisture content and thermal conductivity. The correlation coefficients between color and moisture content showed that moisture content had a strong negative linear effect on the color properties (with an r value of -0.51 between moisture content and a*, and an r value of -0.92 between moisture content and b*). For the flow properties, the ABD, PBD, and mass flow values had a high negative relation to the moisture content (with an r value of -0.69 between moisture content and ABD, and an r value of -0.97 between moisture content and PBD, and an r value of -0.80 between moisture content and mass flow). Additionally, compressibility and HR values were highly related to the moisture cotent as well (with an r value of 0.78 between moisture content and compressibility, and an r value of 0.86 between moisture content and HR).

3.4.2.6. Cottonseed meal

As the results for the Carr tests indicate (Table 7), some difference between the moisture content levels were observed. The difference of AoR, HR, and unifromity for cottemseed meal was not significant when increasing the moisture content. The ABD, PDB, and mass flow were singnificantly decreased with the increase of moisture content. However, the compressibility was significantly higher when increasing the moisture content. Accroding to Carr classifications, all conpressibility value represented cottonseed meal is free flowing. In totality, all of the Carr test results have shown that increasing the moisture content should decrease the flowability of cottenseed meal, but it was still a good flowable material.

To further explore the relationship between all 14 variables used in this study for soybean meal, correlation were determined. The strength of the linear relationship between two variables is quantified by the correlation coefficient (Table 18). From the table, moisture content had high correlations with thermal properties, color, and flow properties. The coorelation between moisture content and thermal conductivity is 0.92, which means there is a high positive linear relation between moisture content and thermal conductivity. The correlation coefficients between color and moisture content showed that moisture content had a strong negative linear effect on all color properties (with an r value of -0.94 between moisture content and L*, and an r value of -0.81 between moisture content and a*, and an r value of -0.88 between moisture content and b*). For the flow properties, the ABD, PBD, and mass flow values had a high negative relation to the moisture content (with an r value of -0.98 between moisture content and ABD, and an r value of -0.99 between moisture content and PBD, and an r value of -0.78 between moisture content and mass flow). Additionally, compressibility and HR values were related to the moisture cotent as well (with an r value of 0.60 between moisture content and compressibility, and an r value of 0.61 between moisture content and HR).

3.4.2.7. Pea bran

As the results for the Carr tests indicate (Table 8), some difference between the moisture content levels were observed. The difference of AoR, HR, compressibility and unifromity for bea bran was not significant when increasing the moisture content. The ABD, PDB, and mass flow were singnificantly decreased with the increase of moisture content. Accroding to Carr classifications, all conpressibility value represented bea bran is free flowing. In totality, all of the Carr test results have shown that increasing the moisture content had no effect on the flowability of pea bran, and it was considered as a good flowable material.

To further explore the relationship between all 14 variables used in this study for soybean meal, correlation were determined. The strength of the linear relationship between two variables is quantified by the correlation coefficient (Table 19). From the table, moisture content had high correlations with thermal properties, color, and flow properties. The coorelation between moisture content and thermal conductivity is 0.94, which means there is a high positive linear relation between moisture content and thermal conductivity. The correlation coefficients between color and moisture content showed that moisture content had a strong negative linear effect on all color properties (with an r value of -0.70 between moisture content and L*, and an r value of -0.71 between moisture content and a*, and an r value of -0.92 between moisture content and b*). For the flow properties, the ABD, PBD, and mass flow values had a high negative relation to the moisture content (with an r value of -0.81 between moisture content and ABD, and an r value of -0.81 between moisture content and PBD, and an r value of -0.89 between moisture content and mass flow).

3.4.2.8. Soy flour

As the results for the Carr tests indicate (Table 9), no difference between the moisture content levels were observed. Accroding to Carr classifications, conpressibility value represented soy flour is not flow well. In totality, all of the Carr test results have shown that increasing the moisture content did not affect the flowability of soy flour, and it was a less flowable material.

To further explore the relationship between all 14 variables used in this study for soybean meal, correlation were determined. The strength of the linear relationship between two variables is quantified by the correlation coefficient (Table 20). From the table, moisture content had high correlations with thermal properties, color, and flow properties. The coorelation between moisture content and thermal conductivity is 0.89, which means there is a high positive linear relation between moisture content and thermal conductivity. The correlation coefficients between color and moisture content showed that moisture content had a strong negative linear effect on all color properties (with an r value of -0.99 between moisture content and L*, and an r value of -0.94 between moisture content and a*, and an r value of -0.99 between moisture content and b*). For the flow properties, the ABD and PBD values had a high negative relation to the moisture content (with an r value of -0.76 between moisture content and ABD, and an r value of -0.92 between moisture content and PBD). Additionally, compressibility and HR values were related to the moisture cotent as well (with an r value of -0.59 between moisture content and compressibility, and an r value of -0.59 between moisture content and HR).

3.4.2.9. Pea protein

As the results for the Carr tests indicate (Table 10), some difference between the moisture content levels were observed. The difference of AoR, HR, compressibility, and unifromity for pea protein was not significant when increasing the moisture content. The ABD, PDB, and mass flow were singnificantly decreased with the increase of moisture content. Accroding to Carr classifications, all conpressibility value represented soybeam meal is free flowing. In totality, all of the Carr test results have shown that increasing the moisture content did not affect the flowability of pea protein, but it was a good flowable material.

To further explore the relationship between all 14 variables used in this study for soybean meal, correlation were determined. The strength of the linear relationship between two variables is quantified by the correlation coefficient (Table 21). From the table, moisture content had high correlations with thermal properties, color, and flow properties. The coorelation between moisture content and thermal conductivity is 0.98, which means there is a high positive linear relation between moisture content and thermal conductivity. The correlation coefficients between color and moisture content showed that moisture content had a strong negative linear effect on all color properties (with an r value of -0.67 between moisture content and L*, and an r value of -0.99 between moisture content and a*, and an r value of -0.99 between moisture content and b*). For the flow properties, the ABD, PBD, and mass flow values had a high negative relation to the moisture content (with an r value of -0.89 between moisture content and ABD, and an r value of -0.84 between moisture content and PBD, and an r value of -0.77 between moisture content and mass flow).

3.4.2.10. Fish meal

As the results for the Carr tests indicate (Table 11), no difference between the moisture content levels were observed. Accroding to Carr classifications, conpressibility value represented fish meal flows well. In totality, all of the Carr test results have shown that increasing the moisture content did not affect the flowability of fish meal, and it was a good flowable material.

To further explore the relationship between all 14 variables used in this study for soybean meal, correlation were determined. The strength of the linear relationship between two variables is quantified by the correlation coefficient (Table 22). From the table, moisture content had high correlations with thermal properties, color, and flow properties. The coorelation between moisture content and thermal conductivity is 0.98, which means there is a high positive linear relation between moisture content and thermal conductivity. The correlation coefficients between color and moisture content showed that moisture content had a strong negative linear effect on all color properties (with an r value of -0.91 between moisture content and L*, and an r value of -0.91 between moisture content and a*, and an r value of -0.95 between moisture content and b*). For the flow properties, the ABD, PBD, and mass flow values had a high negative relation to the moisture content (with an r value of -0.96 between moisture content and ABD, and an r value of -0.96 between moisture content and PBD, and an r value of -0.96 between moisture content and mass flow). Additionally, compressibility and HR values were related to the moisture cotent as well (with an r value of 0.59 between moisture content and compressibility, and an r value of 0.60 between moisture content and HR).

3.4.2.11. Corn gluten meal

As the results for the Carr tests indicate (Table 11), no difference between the moisture content levels were observed. Accroding to Carr classifications, conpressibility value represented corn gluten meal flows well. In totality, all of the Carr test results have shown that increasing the moisture content did not affect the flowability of corn gluten meal, and it was a good flowable material.

To further explore the relationship between all 14 variables used in this study for soybean meal, correlation were determined. The strength of the linear relationship between two variables is quantified by the correlation coefficient (Table 23). From the table, moisture content had high correlations with thermal properties, color, and flow properties. The coorelation between moisture content and thermal conductivity is 0.87, which means there is a high positive linear relation between moisture content and thermal conductivity. The correlation coefficients between color and moisture content showed that moisture content had a strong negative linear effect on all color properties (with an r value of -0.68 between moisture content and L*, and an r value of -0.89 between moisture content and a*, and an r value of -0.80 between moisture content and b*). For the flow properties, the ABD, PBD, and mass flow values had a high negative relation to the moisture content (with an r value of -0.93 between moisture content and ABD, and an r value of -0.87 between moisture content and PBD, and an r value of -0.92 between moisture content and mass flow). Additionally, compressibility and HR values were related to the moisture cotent as well (with an r value of 0.51 between moisture content and compressibility, and an r value of 0.51 between moisture content and HR).

3.5. Conclusions

Physical and flow properties of 11 feed ingredients under the different moisture content levels were determined. Differences were observed for physical and flow properties of all 11 feed ingredients. The most important finding was that moisture content significantly affected many properties of feed ingredients. For the physical properties, color values were influenced by the moisture content. And the thermal properties decreases with the increase of moisture content. For flowability properties, moisture content had a significant effect on ABD, PBD, and mass flow. Overall, feed ingredients flowability generally declined with an increase in moisture content.

3.6. Appendix

Table 13. Correlation coefficients of properties for soybean meal

	MC	*Thermal Conductivity*	*Volumetric Specific Heat*	*Thermal Diffusivity*	*L**	*a**	*b**	*AoR*	*ABD*	*PBD*	*Uniformity*	*Compressibility*	*HR*	*Mass flow*
MC	1.00													
Thermal Conductivity	0.88	1.00												
Volumetric Specific Heat	0.81	0.99	1.00											
Thermal Diffusivity	0.48	0.84	0.89	1.00										
L*	-0.92	-0.84	-0.77	-0.50	1.00									
a*	-0.83	-0.47	-0.36	0.09	0.71	1.00								
b*	-0.86	-0.52	-0.42	0.02	0.79	0.99	1.00							
AoR	0.60	0.74	0.75	0.67	-0.59	-0.21	-0.26	1.00						
ABD	-0.96	-0.71	-0.62	-0.22	0.88	0.94	0.96	-0.48	1.00					
PBD	-0.95	-0.68	-0.59	-0.18	0.86	0.95	0.97	-0.45	0.99	1.00				
Uniformity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00			
Compressibility	0.82	0.74	0.67	0.43	-0.77	-0.64	-0.69	0.53	-0.82	-0.75	0.00	1.00		
HR	0.82	0.75	0.67	0.44	-0.77	-0.64	-0.69	0.53	-0.82	-0.75	0.00	1.00	1.00	
Mass flow	-0.88	-0.76	-0.69	-0.39	0.79	0.70	0.75	-0.64	0.87	0.85	0.00	-0.81	-0.81	1.00

Table 14. Correlation coefficients of properties for high protein DDGS

	MC	*Thermal Conductivity*	*Volumetric Specific Heat*	*Thermal Diffusivity*	*L**	*a**	*b**	*AoR*	*ABD*	*PBD*	*Uniformity*	*Compressibility*	*HR*	*Mass flow*
MC	1.00													
Thermal Conductivity	0.94	1.00												
Volumetric Specific Heat	0.98	0.88	1.00											
Thermal Diffusivity	-0.05	0.13	-0.15	1.00										
L*	-0.41	-0.19	-0.53	0.76	1.00									
a*	-0.93	-0.80	-0.96	0.24	0.64	1.00								
b*	-0.89	-0.74	-0.93	0.34	0.71	0.99	1.00							
AoR	0.62	0.58	0.66	-0.12	-0.09	-0.50	-0.44	1.00						
ABD	-0.98	-0.90	-0.97	0.16	0.54	0.98	0.94	-0.56	1.00					
PBD	-0.98	-0.89	-0.98	0.12	0.52	0.97	0.93	-0.59	0.99	1.00				
Uniformity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00			
Compressibility	0.59	0.63	0.56	-0.34	-0.48	-0.62	-0.64	0.18	-0.67	-0.57	0.00	1.00		
HR	0.59	0.63	0.57	-0.34	-0.48	-0.62	-0.64	0.19	-0.67	-0.57	0.00	1.00	1.00	
Mass flow	-0.87	-0.84	-0.81	-0.12	0.29	0.79	0.77	-0.43	0.82	0.81	0.00	-0.58	-0.58	1.00

Table 15. Correlation coefficients of properties for soy protein concentrate

	MC	*Thermal Conductivity*	*Volumetric Specific Heat*	*Thermal Diffusivity*	*L**	*a**	*b**	*AoR*	*ABD*	*PBD*	*Uniformity*	*Compressibility*	*HR*	*Mass flow*
MC	1.00													
Thermal Conductivity	0.94	1.00												
Volumetric Specific Heat	0.87	0.97	1.00											
Thermal Diffusivity	0.91	0.83	0.73	1.00										
L*	-0.84	-0.89	-0.87	-0.77	1.00									
a*	0.35	0.52	0.55	0.43	-0.66	1.00								
b*	-0.90	-0.93	-0.91	-0.78	0.97	-0.63	1.00							
AoR	0.18	0.26	0.24	0.08	-0.11	0.05	-0.16	1.00						
ABD	-0.94	-0.97	-0.95	-0.86	0.82	-0.40	0.86	-0.27	1.00					
PBD	-0.90	-0.94	-0.90	-0.92	0.81	-0.51	0.83	-0.19	0.97	1.00				
Uniformity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00			
Compressibility	0.80	0.78	0.81	0.54	-0.64	0.05	-0.73	0.37	-0.83	-0.66	0.00	1.00		
HR	0.81	0.79	0.81	0.56	-0.65	0.05	-0.73	0.36	-0.84	-0.67	0.00	1.00	1.00	
Mass flow	-0.92	-0.84	-0.73	-0.83	0.77	-0.37	0.83	-0.24	0.79	0.75	0.00	-0.67	-0.69	1.00

Table 16. Correlation coefficients of properties for NF8

	MC	Thermal Conductivity	Volumetric Specific Heat	Thermal Diffusivity	L*	a*	b*	AoR	ABD	PBD	Uniformity	Compressibility	HR	Mass flow
MC	1.00													
Thermal Conductivity	0.97	1.00												
Volumetric Specific Heat	0.99	0.97	1.00											
Thermal Diffusivity	0.93	0.98	0.94	1.00										
L*	-0.97	-0.93	-0.98	-0.88	1.00									
a*	-0.93	-0.83	-0.89	-0.74	0.90	1.00								
b*	-0.96	-0.87	-0.94	-0.80	0.96	0.98	1.00							
AoR	0.75	0.75	0.82	0.76	-0.84	-0.58	-0.69	1.00						
ABD	-0.96	-0.87	-0.94	-0.80	0.96	0.98	1.00	-0.69	1.00					
PBD	-0.95	-0.85	-0.92	-0.77	0.95	0.97	0.99	-0.67	1.00	1.00				
Uniformity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00			
Compressibility	-0.23	-0.03	-0.16	0.04	0.23	0.39	0.36	0.01	0.36	0.44	0.00	1.00		
HR	-0.23	-0.04	-0.16	0.04	0.23	0.39	0.35	0.00	0.36	0.44	0.00	1.00	1.00	
Mass flow	-0.93	-0.90	-0.91	-0.82	0.93	0.89	0.92	-0.75	0.90	0.89	0.00	0.19	0.19	1.00

Table 17. Correlation coefficients of properties for soy protein isolate

	MC	Thermal Conductivity	Volumetric Specific Heat	Thermal Diffusivity	L*	a*	b*	AoR	ABD	PBD	Uniformity	Compressibility	HR	Mass flow
MC	1.00													
Thermal Conductivity	0.99	1.00												
Volumetric Specific Heat	0.94	0.92	1.00											
Thermal Diffusivity	0.67	0.71	0.42	1.00										
L*	-0.40	-0.34	-0.29	-0.34	1.00									
a*	-0.51	-0.49	-0.36	-0.58	0.38	1.00								
b*	-0.92	-0.93	-0.76	-0.83	0.36	0.65	1.00							
AoR	0.21	0.25	0.18	0.16	-0.11	-0.22	-0.17	1.00						
ABD	-0.69	-0.63	-0.83	-0.09	0.11	0.19	0.45	0.22	1.00					
PBD	-0.97	-0.96	-0.92	-0.69	0.32	0.49	0.91	-0.09	0.70	1.00				
Uniformity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00			
Compressibility	-0.78	-0.80	-0.63	-0.84	0.20	0.36	0.79	-0.09	0.43	0.82	0.00	1.00		
HR	-0.86	-0.88	-0.71	-0.84	0.36	0.53	0.91	-0.28	0.29	0.88	0.00	0.81	1.00	
Mass flow	-0.80	-0.79	-0.81	-0.39	0.15	0.10	0.68	0.17	0.76	0.80	0.00	0.66	0.57	1.00

Table 18. Correlation coefficients of properties for cottonseed meal

	MC	*Thermal Conductivity*	*Volumetric Specific Heat*	*Thermal Diffusivity*	*L**	*a**	*b**	*AoR*	*ABD*	*PBD*	*Uniformity*	*Compressibility*	*HR*	*Mass flow*
MC	1.00													
Thermal Conductivity	0.92	1.00												
Volumetric Specific Heat	0.91	0.88	1.00											
Thermal Diffusivity	0.85	0.87	0.71	1.00										
L*	-0.94	-0.86	-0.95	-0.72	1.00									
a*	-0.81	-0.87	-0.60	-0.95	0.62	1.00								
b*	-0.88	-0.91	-0.69	-0.96	0.71	0.99	1.00							
AoR	-0.23	-0.10	-0.11	-0.45	0.06	0.37	0.35	1.00						
ABD	-0.98	-0.89	-0.89	-0.77	0.92	0.77	0.84	0.21	1.00					
PBD	-0.98	-0.89	-0.87	-0.82	0.95	0.79	0.86	0.21	0.98	1.00				
Uniformity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00			
Compressibility	0.60	0.55	0.62	0.29	-0.49	-0.40	-0.45	-0.14	-0.70	-0.54	0.00	1.00		
HR	0.61	0.56	0.62	0.29	-0.50	-0.40	-0.46	-0.13	-0.71	-0.55	0.00	1.00	1.00	
Mass flow	-0.78	-0.75	-0.68	-0.72	0.61	0.77	0.81	0.48	0.80	0.73	0.00	-0.74	-0.74	1.00

Table 19. Correlation coefficients of properties for pea bran

	MC	*Thermal Conductivity*	*Volumetric Specific Heat*	*Thermal Diffusivity*	*L**	*a**	*b**	*AoR*	*ABD*	*PBD*	*Uniformity*	*Compressibility*	*HR*	*Mass flow*
MC	1.00													
Thermal Conductivity	0.94	1.00												
Volumetric Specific Heat	-0.50	-0.58	1.00											
Thermal Diffusivity	0.92	0.93	-0.78	1.00										
L*	-0.69	-0.60	-0.22	-0.37	1.00									
a*	-0.71	-0.74	0.93	-0.91	-0.01	1.00								
b*	-0.92	-0.92	0.80	-0.99	0.37	0.92	1.00							
AoR	0.61	0.66	-0.52	0.62	-0.38	-0.50	-0.62	1.00						
ABD	-0.81	-0.79	0.28	-0.68	0.76	0.42	0.69	-0.44	1.00					
PBD	-0.81	-0.82	0.30	-0.70	0.73	0.45	0.70	-0.46	0.98	1.00				
Uniformity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00			
Compressibility	0.35	0.24	-0.06	0.24	-0.44	-0.07	-0.25	0.12	-0.54	-0.35	0.00	1.00		
HR	0.35	0.24	-0.05	0.24	-0.44	-0.06	-0.25	0.12	-0.54	-0.35	0.00	1.00	1.00	
Mass flow	-0.89	-0.81	0.55	-0.86	0.49	0.74	0.87	-0.55	0.74	0.76	0.00	-0.26	-0.26	1.00

Table 20. Correlation coefficients of properties for soy flour

	MC	*Thermal Conductivity*	*Volumetric Specific Heat*	*Thermal Diffusivity*	*L**	*a**	*b**	*AoR*	*ABD*	*PBD*	*Uniformity*	*Compressibility*	*HR*	*Mass flow*
MC	1.00													
Thermal Conductivity	0.89	1.00												
Volumetric Specific Heat	0.59	0.76	1.00											
Thermal Diffusivity	0.91	0.85	0.53	1.00										
L*	-0.99	-0.86	-0.58	-0.87	1.00									
a*	-0.94	-0.91	-0.55	-0.98	0.90	1.00								
b*	-1.00	-0.88	-0.55	-0.91	0.99	0.94	1.00							
AoR	0.47	0.53	0.49	0.29	-0.48	-0.40	-0.48	1.00						
ABD	-0.76	-0.67	-0.10	-0.79	0.71	0.84	0.78	-0.44	1.00					
PBD	-0.92	-0.88	-0.80	-0.89	0.91	0.89	0.90	-0.35	0.51	1.00				
Uniformity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00			
Compressibility	-0.59	-0.59	-0.85	-0.53	0.61	0.49	0.54	-0.10	-0.05	0.83	0.00	1.00		
HR	-0.59	-0.60	-0.87	-0.53	0.61	0.49	0.55	-0.13	-0.04	0.84	0.00	1.00	1.00	
Mass flow	-0.45	-0.11	-0.19	-0.49	0.46	0.35	0.42	0.28	0.08	0.55	0.00	0.60	0.59	1.00

Table 21. Correlation coefficients of properties for pea protein

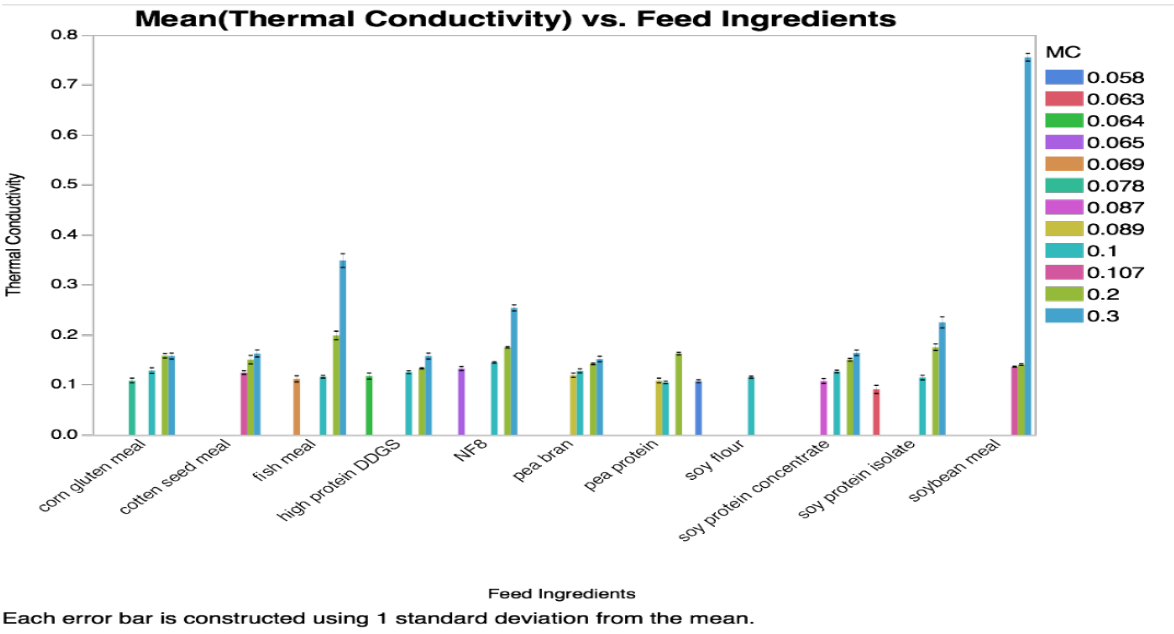
	MC	*Thermal Conductivity*	*Volumetric Specific Heat*	*Thermal Diffusivity*	*L**	*a**	*b**	*AoR*	*ABD*	*PBD*	*Uniformity*	*Compressibility*	*HR*	*Mass flow*
MC	1.00													
Thermal Conductivity	0.98	1.00												
Volumetric Specific Heat	0.99	0.95	1.00											
Thermal Diffusivity	0.90	0.95	0.86	1.00										
L*	-0.67	-0.70	-0.63	-0.75	1.00									
a*	-0.99	-0.98	-0.98	-0.91	0.63	1.00								
b*	-1.00	-0.98	-0.98	-0.91	0.68	0.99	1.00							
AoR	0.78	0.74	0.77	0.58	-0.44	-0.72	-0.79	1.00						
ABD	-0.89	-0.85	-0.87	-0.78	0.47	0.91	0.88	-0.54	1.00					
PBD	-0.84	-0.74	-0.85	-0.61	0.44	0.83	0.82	-0.66	0.90	1.00				
Uniformity	-0.50	-0.49	-0.49	-0.48	0.06	0.57	0.45	-0.08	0.65	0.60	1.00			
Compressibility	-0.19	-0.06	-0.24	0.12	0.08	0.13	0.17	-0.46	0.10	0.53	0.12	1.00		
HR	-0.20	-0.07	-0.25	0.11	0.09	0.14	0.18	-0.46	0.11	0.54	0.13	1.00	1.00	
Mass flow	-0.77	-0.75	-0.75	-0.65	0.56	0.75	0.75	-0.82	0.55	0.60	0.23	0.31	0.32	1.00

Table 22. Correlation coefficients of properties fish meal

	MC	*Thermal Conductivity*	*Volumetric Specific Heat*	*Thermal Diffusivity*	*L**	*a**	*b**	*AoR*	*ABD*	*PBD*	*Uniformity*	*Compressibility*	*HR*	*Mass flow*
MC	1.00													
Thermal Conductivity	0.98	1.00												
Volumetric Specific Heat	1.00	0.99	1.00											
Thermal Diffusivity	0.97	1.00	0.98	1.00										
L*	-0.91	-0.81	-0.89	-0.80	1.00									
a*	-0.91	-0.80	-0.88	-0.79	0.96	1.00								
b*	-0.95	-0.86	-0.93	-0.85	0.98	0.99	1.00							
AoR	0.72	0.68	0.71	0.65	-0.70	-0.62	-0.67	1.00						
ABD	-0.96	-0.92	-0.96	-0.90	0.87	0.89	0.92	-0.80	1.00					
PBD	-0.96	-0.91	-0.96	-0.91	0.93	0.93	0.95	-0.71	0.95	1.00				
Uniformity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00			
Compressibility	0.59	0.59	0.60	0.54	-0.43	-0.46	-0.49	0.69	-0.74	-0.48	0.00	1.00		
HR	0.59	0.60	0.60	0.55	-0.43	-0.46	-0.50	0.70	-0.74	-0.49	0.00	1.00	1.00	
Mass flow	-0.96	-0.92	-0.95	-0.91	0.90	0.93	0.95	-0.69	0.93	0.94	0.00	-0.56	-0.56	1.00

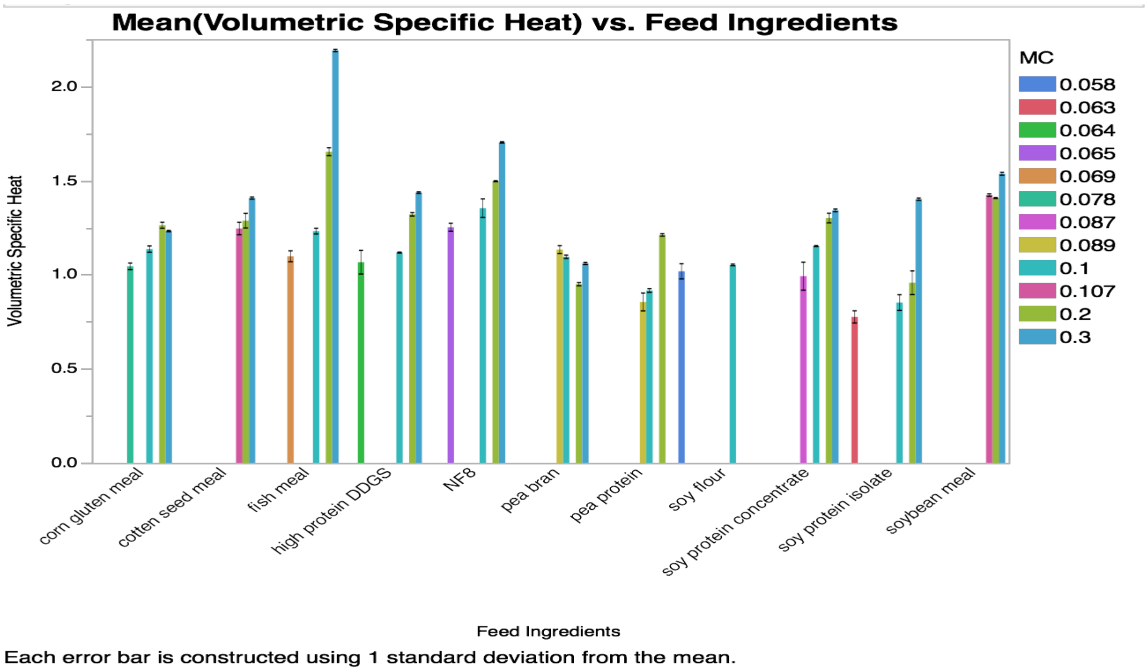
Table 23. Correlation coefficients of properties for corn gluten meal

	MC	*Thermal Conductivity*	*Volumetric Specific Heat*	*Thermal Diffusivity*	*L**	*a**	*b**	*AoR*	*ABD*	*PBD*	*Uniformity*	*Compressibility*	*HR*	*Mass flow*
MC	1.00													
Thermal Conductivity	0.87	1.00												
Volumetric Specific Heat	0.81	0.97	1.00											
Thermal Diffusivity	0.79	0.92	0.88	1.00										
L*	-0.68	-0.66	-0.68	-0.57	1.00									
a*	-0.89	-0.95	-0.95	-0.83	0.59	1.00								
b*	-0.80	-0.92	-0.96	-0.75	0.70	0.95	1.00							
AoR	0.37	0.41	0.31	0.63	-0.07	-0.35	-0.19	1.00						
ABD	-0.93	-0.83	-0.76	-0.88	0.56	0.81	0.66	-0.54	1.00					
PBD	-0.87	-0.85	-0.80	-0.92	0.57	0.79	0.67	-0.59	0.96	1.00				
Uniformity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00			
Compressibility	0.51	0.19	0.11	0.11	-0.12	-0.32	-0.18	-0.01	-0.44	-0.18	0.00	1.00		
HR	0.50	0.19	0.11	0.11	-0.12	-0.31	-0.17	-0.02	-0.43	-0.18	0.00	1.00	1.00	
Mass flow	-0.92	-0.81	-0.77	-0.76	0.60	0.85	0.75	-0.31	0.88	0.79	0.00	-0.59	-0.59	1.00



Each error bar is constructed using 1 standard deviation from the mean.

Figure 3. Bar chart for thermal conductivity



Each error bar is constructed using 1 standard deviation from the mean.

Figure 4. Bar chart for volumetric specific heat

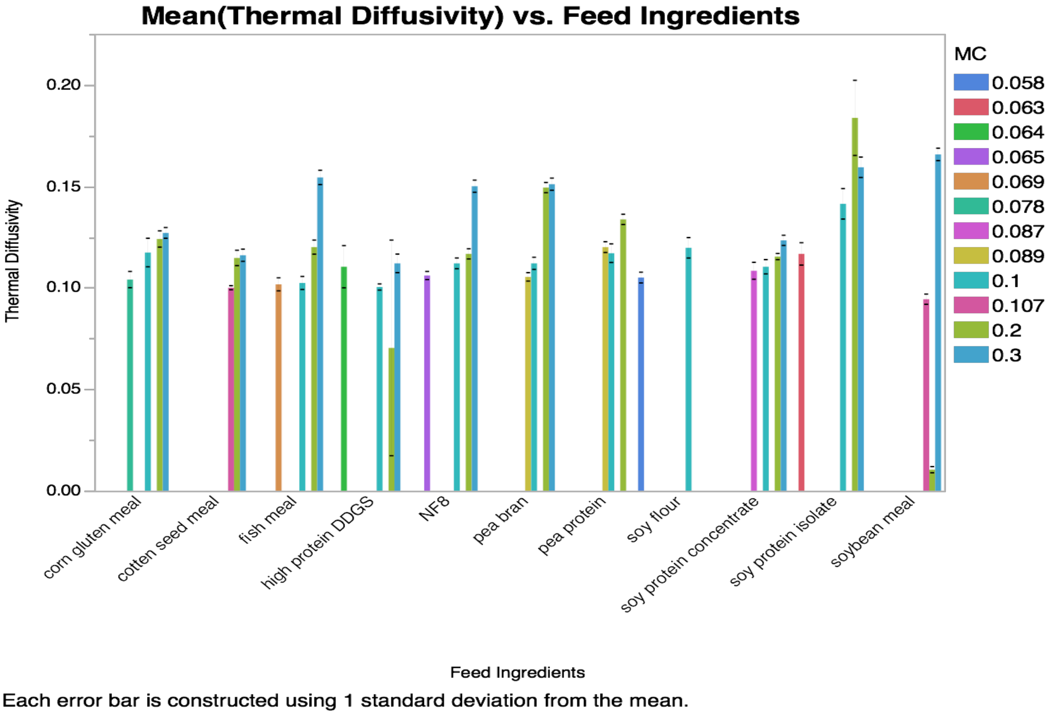


Figure 5. Bar chart for thermal diffusivity

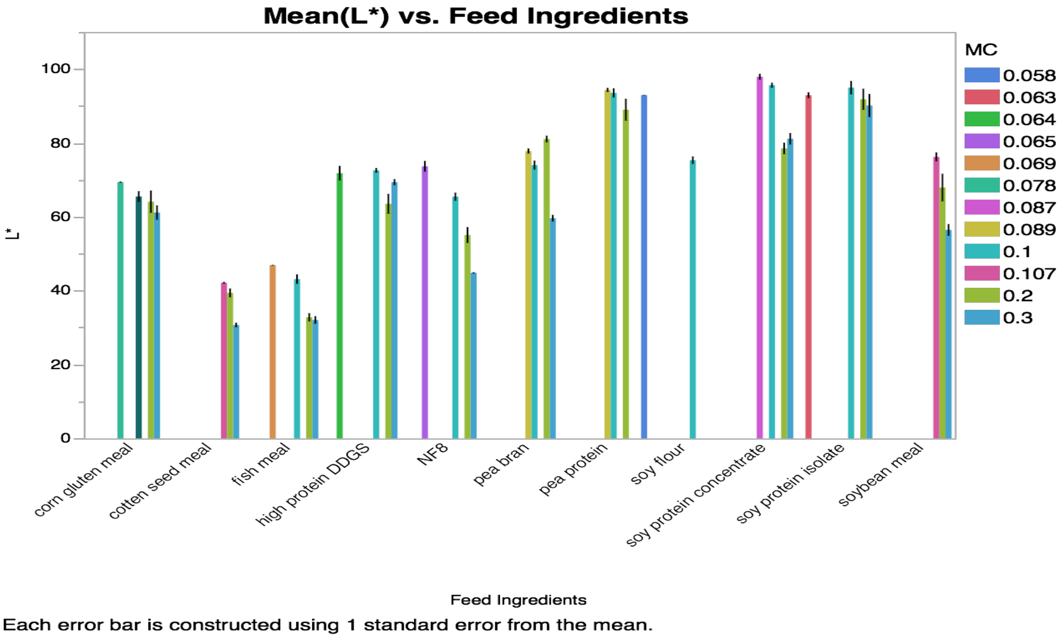


Figure 6. Bar chart for color L*

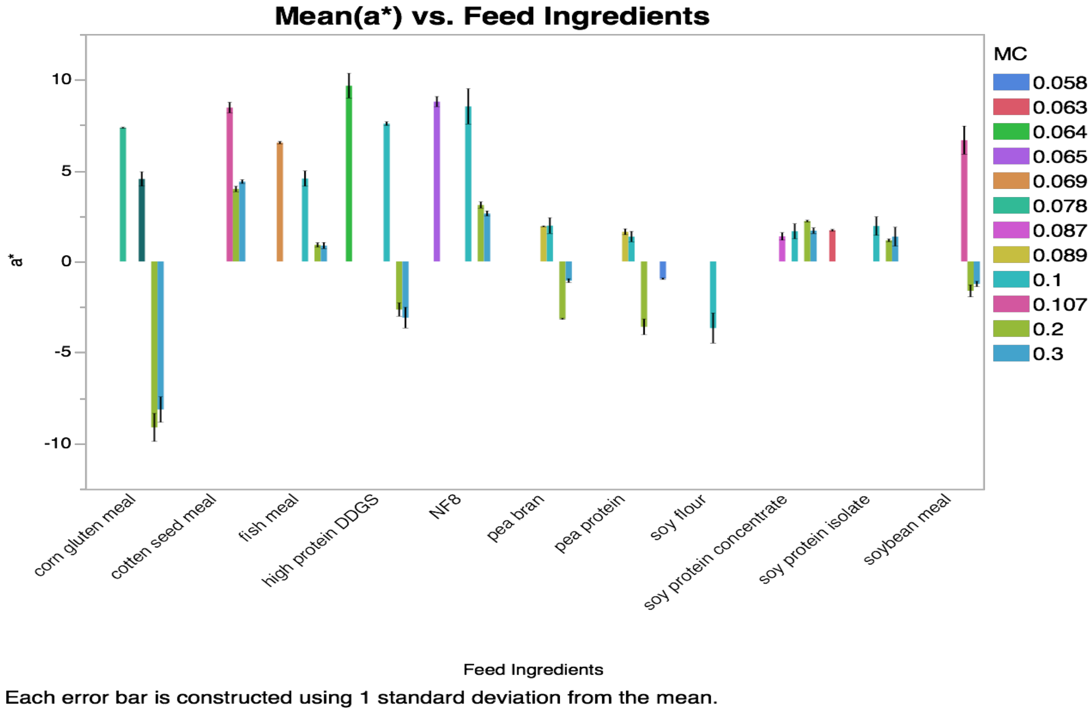


Figure 7. Bar chart for color a*

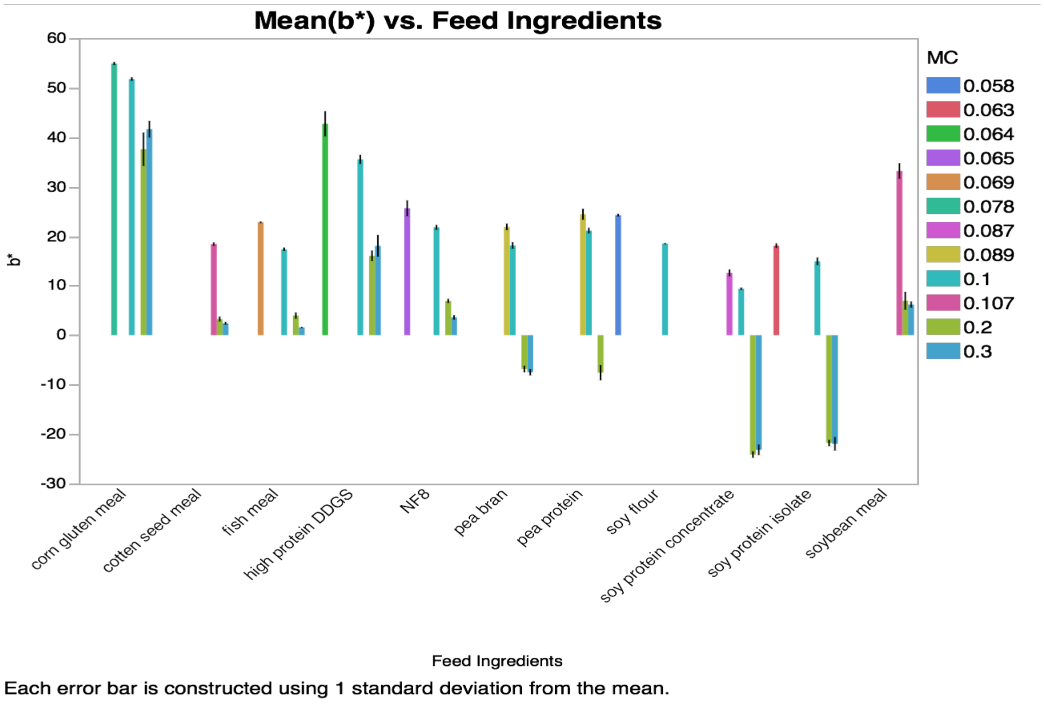


Figure 8. Bar chart for color b*

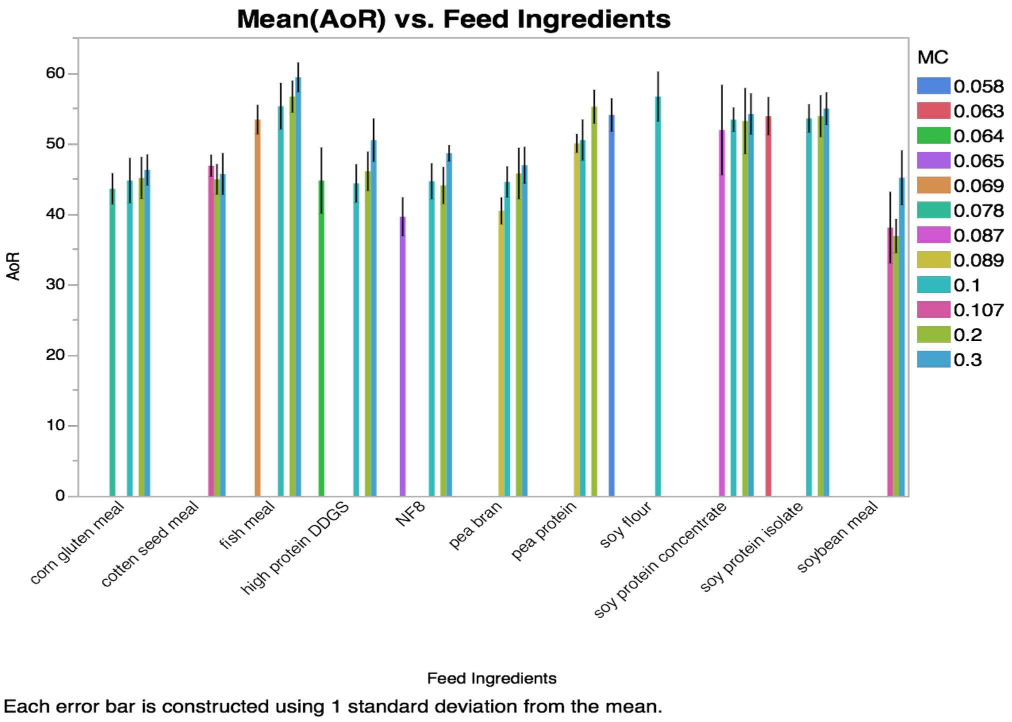


Figure 9. Bar chart for angle of repose

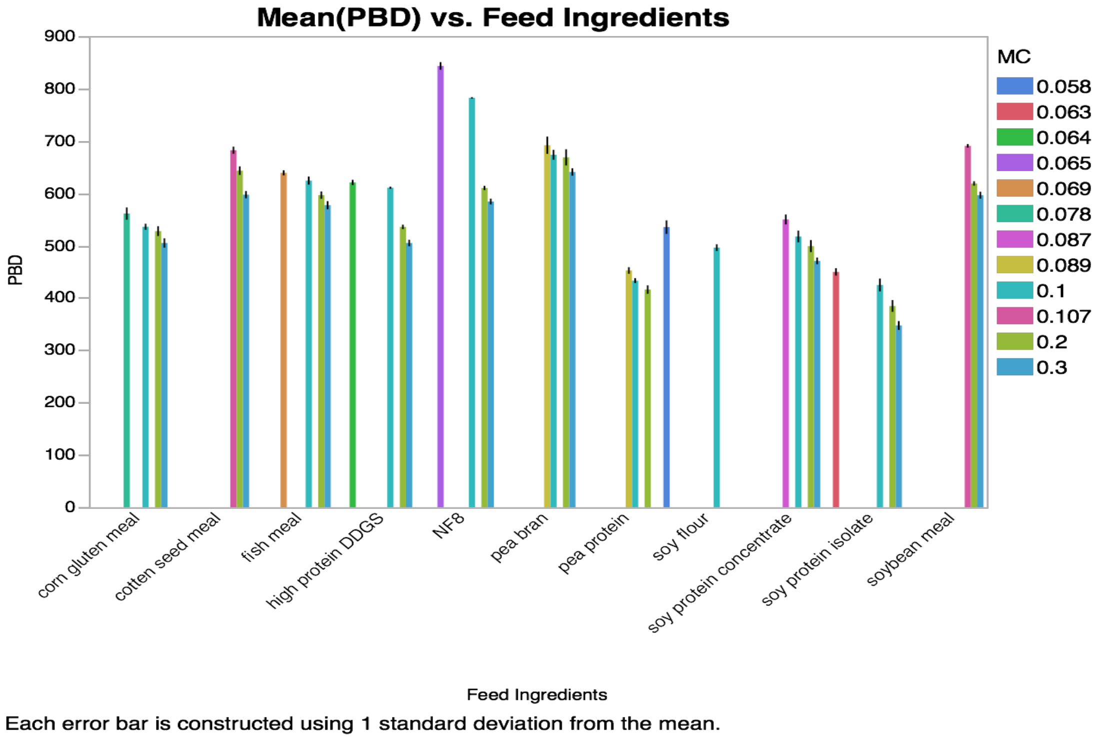
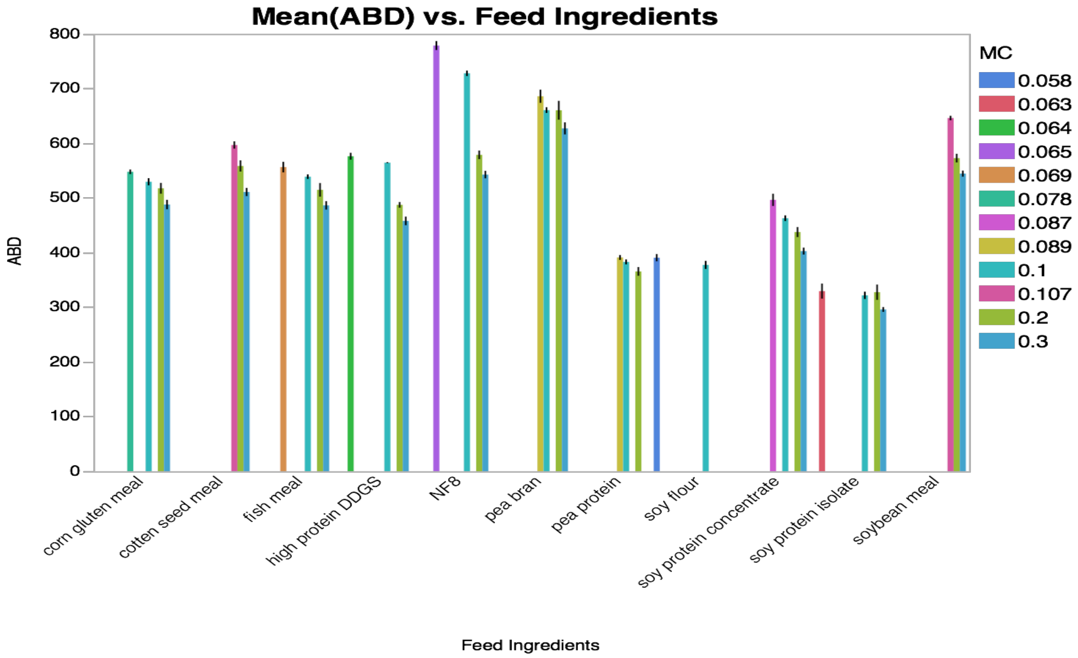
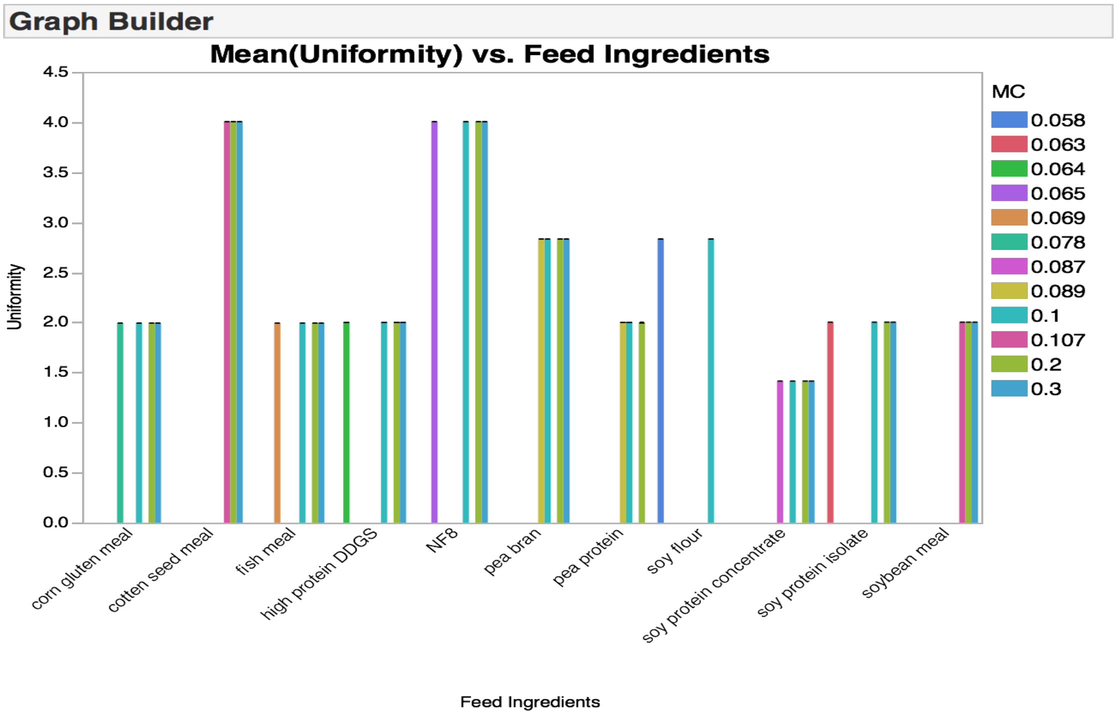


Figure 10. Bar chart for PBD



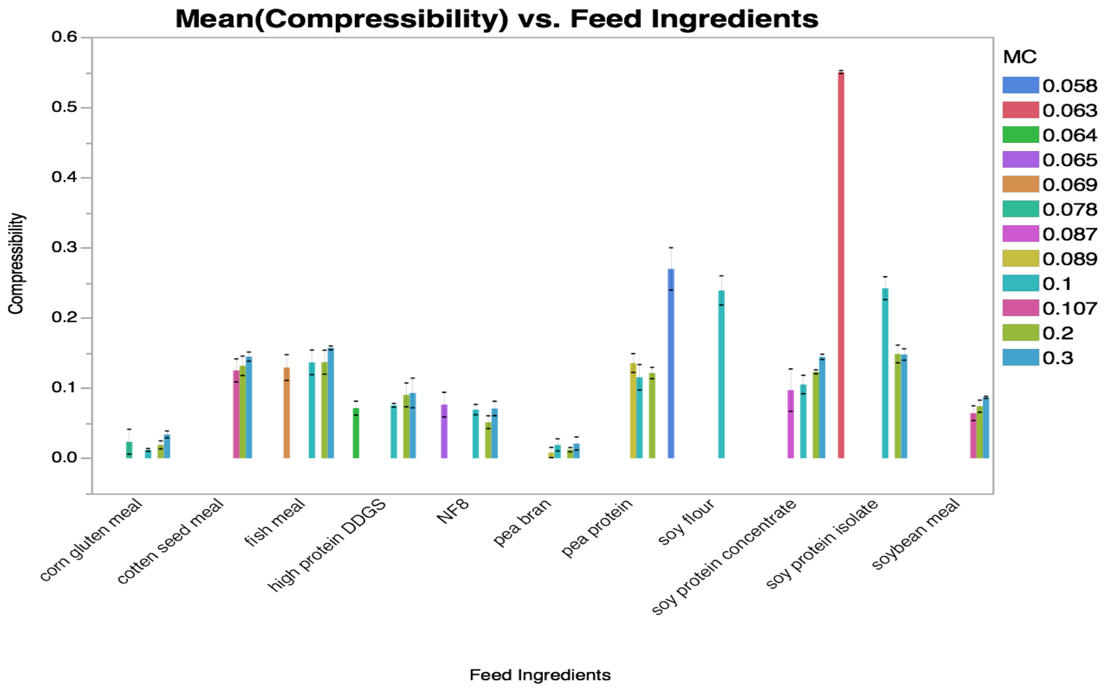
Each error bar is constructed using 1 standard deviation from the mean.

Figure 11. Bar chart for ABD



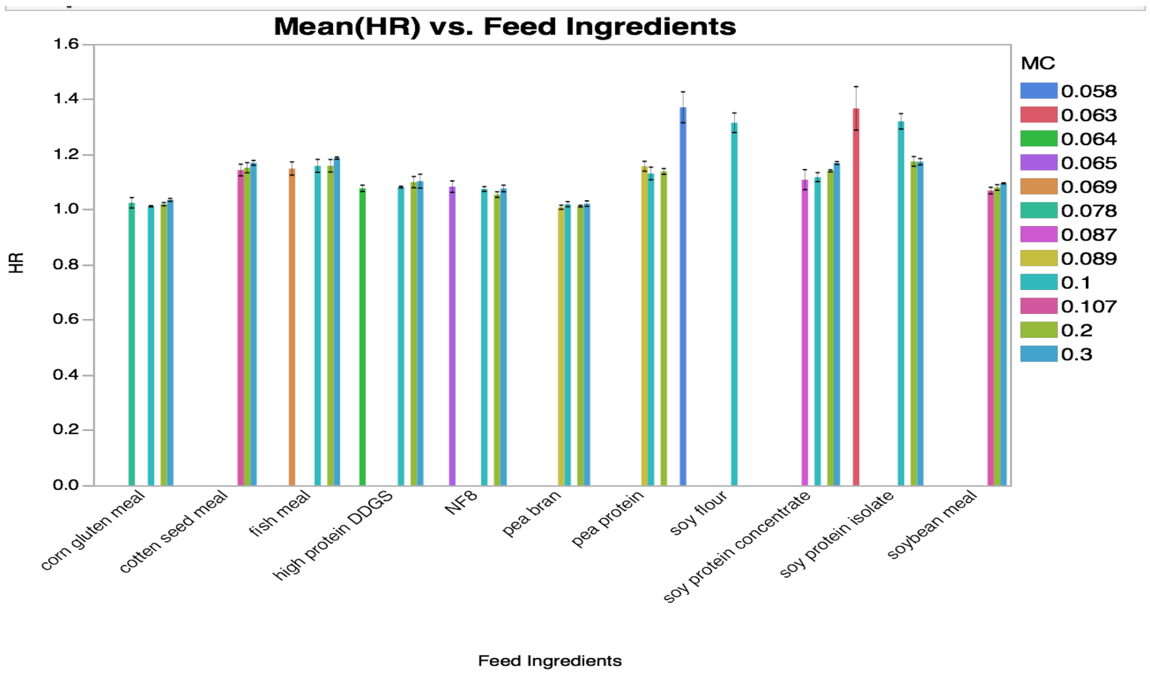
Each error bar is constructed using 1 standard deviation from the mean.

Figure 12. Bar chart for uniformity



Each error bar is constructed using 1 standard deviation from the mean.

Figure 13. Bar chart for compressibity



Each error bar is constructed using 1 standard deviation from the mean.

Figure 14. Bar chart for HR

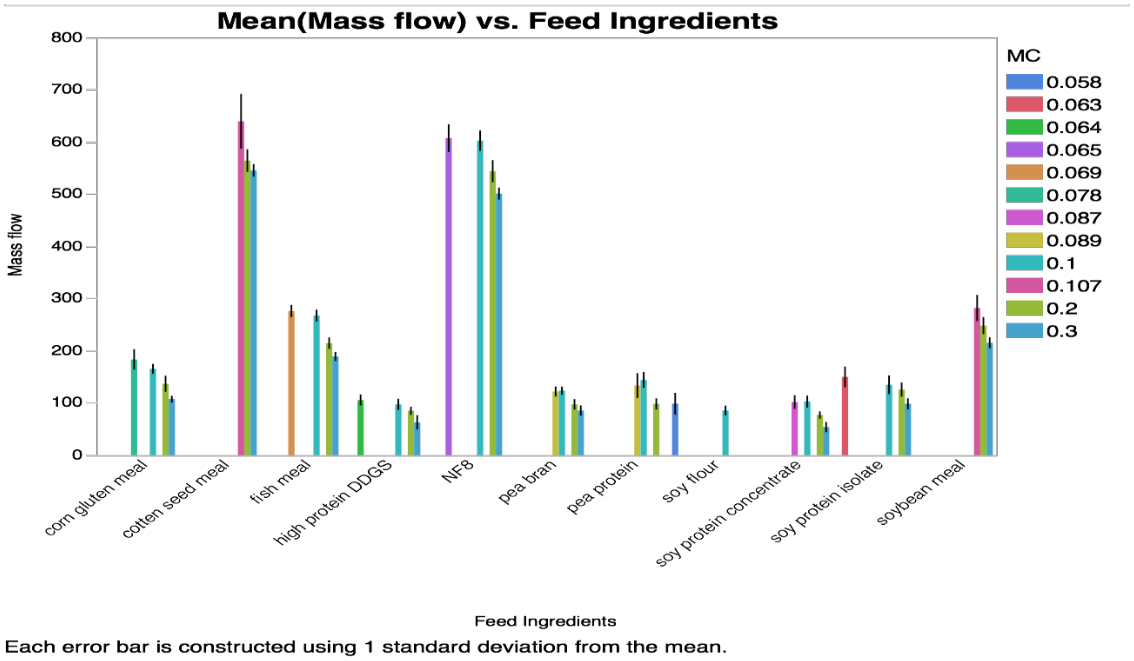


Figure 15. Bar chart for mass flow

3.7. References

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CHAPTER 4

EXTRUSION OF GLUTEN-FREE GRAINS

4.1. Introduction

Gluten is a mixture of two proteins, gliadin and glutenin. It is found in wheat, rye, and barley. In the United States, about 3 million people have celiac disease. It is because body's natural defense system reacts to gluten by attacking the lining of the small intestine. And without this lining, the body cannot absorb nutrients. Thus, this can result in serious health problems ("'Gluten-Free' Now Means What It Says" 2014).

Today, a variety of products such as pasta, ready-to-eat cereals, snacks and pet food are made using screw extrusion processes. Extrusion is defined as a process where ingredients are pushed through a die of desirable shape. In food application, extrusion processing has become increasingly important manufacturing method.

There are two major types of extruders that are single screw extruder and twin-screw extruder for food processing. This paper focused on single screw extruder. The screw is driven by a motor through a linkage and gearbox assembly. Friction between material and the barrel causes the paste to be conveyed towards the die assembly, where sufficient pressure is generated to drive the paste through the die to give an extruded product. During this process, ingredients experiences processes of heating, mixing, and shearing. Use of the single screw extruder is widely established in forming processes. There are many advantages of extrusion processing over other conventional cooking processing. Firstly, extrusion molding has a low cost compare to other modeling processing. Also, the same extruder can be used to make different types of products. Extrusion is a continuous process.

Millet, sorghum, and teff are gluten-free grains. Millet is widely grown around the world as a cereal crop for both human food and fodder. It is an important crops in the semi-arid tropics of Asia and Africa, especially in India, China, and Niger. Also, these countries are the top three in millet producing countries in the world (“Millet” 2010). This grain has relative high fiber and protein contents ("Millet, Raw Nutrition Facts & Calories" 2016). Sorghum, which now is an important crop worldwide, is native to Africa, and used for food and fodder, the production of alcoholic beverages, and biofuels. The major sorghum producing countries are the United States, Nigeria, India and Mexico ("Sorghum Maps/Stats" 2016). Sorghum has high protein and fiber contents, so it is a suitable grain for extrusion ("Sorghum Nutrition Facts & Calories" 2016). Teff is an annual cereal grain native to the African country of Ethiopia. It can be cultivated in a wide range of conditions, from marginal soils to drought conditions (("What Is Teff Grain" 2016)). With a relatively short growing season, teff produces a crop that provides grain for human food consumption and fodder for cattle. In the United States, teff largely remains an experimental crop, with a limited number of acres grown for this grain. This whole grain is high in protein, carbohydrate, and fiber ("Teff, Nutrition Facts & Calories" 2016). There was a little reference to the properties for millet, sorghum and teff extrudates. Also, there was a lack of information on how moisture affects the properties of these extrudates.

The objectives of this study were to exam the extrudate properties for millet, sorghum, and teff, and also to compared the properties of flour and raw grain after extrusion at different moisture content level (30%, 40% d.b.).

4.2. Materials and Methods

The experimental design was based on dependent variables of different kinds of grains and moisture content. Teff, millet, and sorghum were tested. One kilogram of each of the raw ingredients was ground using a laboratory mill. The particle size for sorghum, millet, and teff flour was 0.5 mm. Initial moisture content for each grain was determined using a laboratory oven at 135oC for four hours. The ingredients were mixed with appropriate quantities of water in a lab-scale mixer and stored overnight at refrigerated conditions to achieve 30% moisture content, and 40% moisture content.

4.2.1. Extrusion Processing

Each sample was processed in a single-screw extruder (model PL 2000 Plastic-Corder, Brabender South Hackencack,NJ). The raw blends were manually dropped into the hopper. The screw heat, mix, and shear forced raw blends through a die. The shape of the extrudate was determined by the die.

4.2.2. Measurement of Physical Properties

The extrudates were cooled and air-dried at room temperature for one day, then analyzed based on moisture content, color, unit density (g/cm3), expansion ratio, and bulk density.

4.2.2.1. Moisture Content

The moisture content of the dried extrudates was determined using an oven at 135 ^{o}C for 2 hours. Three measurements were made for each experimental run.

4.2.2.2. Water Activity

Water activity was measured by using a water activity meter (Series 3 TE, AquaLab, Pullman, WA, USA). Three measurements were made for each experimental run.

4.2.2.3. Unit Density

The unit density of extrudate samples was measured by cutting a piece with a length of 2 cm. They were then weighed on the balance and measured their diameters using a digital caliper. The unit density was determined as the ratio of the mass of 2 cm piece to the volume of that piece. For the volume calculation, assuming cylindrical shapes for each extrudate sample. Three measurements were made for each experimental run.

4.2.2.4. Color

A chroma meter (CR-400 Chroma meter, Konica Minolta, Ramsey, NJ, USA) was used to determine the parameters of color measurement. L* value represented brightness/darkness of the extrudate, a* value quantified redness/greenness, and b* value denoted yellowness/blueness. The color measurement can be used for customer preference and quality controlling. Three measurements were made for each experimental run.

4.2.2.5. Bulk Density

Bulk density is defined as the mass of particles that occupies a unit volume of a container. It was determined by allowing an excess of powder to flow into a specific volume cylindrical cup (Matric Cup, Seedburo, Chicago, IL, USA) until it overflows. Carefully, scraped excess powder from the top of the cup by smoothly moving the edge of the blade of a spatula perpendicular to and in contact with the top surface of the cup, taking care to keep the spatula perpendicular to prevent packing or removal of powder from the cup. Any material from the side of the cup was removed, and the mass of the powder was determined. The ratio of the mass of extrudate sample to the bulk volume was calculated.

4.2.2.6. Expansion Ratio

The expansion ratio of the extrudate was determined by using the actual diameter of the extrudates (mm) was divided by the diameter of the die (3mm).

4.2.3. Statistical analysis

The collected data were analyzed with two-way analysis of variance by using JMP software, with a type I error rate (α) of 0.05, to determine the main and interaction effects and least significant differences between treatment combinations.

4.3. Results and Discussion

4.3.1. Color

The color is an important characteristic of extruded foods. Color changes can give information about the extent of browning reactions such as caramelization, maillard reaction, the degree of cooking and pigment degradation during the extrusion process (Ilo and Berghofer, 1999).

For sorghum, the maximum (59.42) and minimum (36.84) brightness was achieved at 40% moisture content sorghum flour and 30% moisture content sorghum flour. The maximum (3.26) and minimum (2.16) redness/greenness was achieved at 40% moisture content sorghum flour, and 30% moisture content sorghum raw grain. The maximum (15.87) and minimum (-13.14) yellowness/blueness was achieved at 40% moisture content sorghum raw grain, and 30%

moisture content sorghum flour. As the moisture content was increased from 30 to 40%, the brightness of the extrudates had a significant increase, the redness had a significant increase, and the yellowness had a significant decrease for both raw grain and flour.

For millet, the maximum (74.91) and minimum (47.65) brightness was achieved at 40% moisture content millet raw grain, and 30% moisture content millet raw grain. The maximum (3.04) and minimum (1.46) redness/greenness was achieved at 40% moisture content millet flour, and 30% moisture content millet raw grain. The maximum (24.08) and minimum (-17.34) yellowness/blueness was achieved at 40% moisture content millet raw grain, and 30% moisture content millet flour. As the moisture content was increased from 30 to 40%, the brightness of the extrudates had a significant increase, and the yellowness had a significant decrease for both raw grain and flour, but redness had a significant increase only for millet raw grain,

For teff, the maximum (40.86) and minimum (22.28) brightness was achieved at 40% moisture content teff raw grain, and 30% moisture content teff raw grain. The maximum (9.74) and minimum (4.73) redness/greenness was achieved at 40% moisture content teff raw grain, and 30% moisture content teff raw grain. The maximum (13.47) and minimum (-14.82) yellowness/blueness was achieved at 40% moisture content teff raw grain, and 30% moisture content teff flour. As the moisture content was increased from 30 to 40%, the brightness of the extrudates had a significant increase and the yellowness had a significant decrease for both raw grain and flour but redness had a significant increase only for raw grain.

In general, the products cooked with high temperature have the highest values. The dark color is also developed during caramelization of sugar from the maillard reaction that why redness (a*) value is high as the temperature increases. The change in yellowness during extrusion cooking was most induced by the effects of non-enzymatic browning and pigment destruction reactions. All these differences could have been due to the shear forces generated during extrusion which accelerated the chemical reactions between amino acids and reducing sugars (maillards reaction) that take place during extrusion (Guy, 2001) and to the different temperature cooking, rolling speed and feeding speed conditions during extrusion.

Table 24. Physical properties of extrudates within each grain types at all moisture levels

		Color							
	Moisture Content (%)	L*	a*	b*	aw	Unit Density (g/cm^3)	Bulk Density (g/L)	Moisture Content (%)	Expansion Ratio
Sorghum raw grain	30	38.38 a (0.56)	2.16 a (0.03)	-10.61 a (0.23)	0.94 a (0.01)	1.14 a (0.02)	511.67 a (6.29)	28.67 a (0.01)	1.10 a (0.01)
	40	59.41 b (6.29)	2.96 b (0.49)	15.87 b (2.09)	0.94 a (0.01)	1.08 b (0.03)	553.33 b (20.36)	27.33 b (0.01)	1.01 b (0.04)
Sorghum flour	30	36.84 a (0.56)	3.13 a (0.02)	-13.14 a (0.09)	0.91 a (0.01)	1.20 a (0.01)	536.67 a (9.47)	29.00 a (0.00)	1.09 a (0.02)
	40	59.42 b (4.19)	3.26 b (0.07)	14.38 b (0.58)	0.96 b (0.01)	1.37 b (0.04)	611.67 b (8.55)	36.67 b (0.01)	0.98 b (0.01)
Millet raw grain	30	47.65 a (0.15)	1.46 a (0.01)	-14.29 a (0.06)	0.91 a (0.02)	1.22 a (0.01)	555.00 a (7.50)	27.67 a (0.01)	1.05 a (0.01)
	40	74.91 b (2.47)	2.57 b (0.08)	24.08 b (0.83)	0.94 b (0.01)	1.13 a (0.12)	646.67 b (8.78)	32.33 b (0.01)	0.99 b (0.01)
Millet flour	30	48.70 a (0.47)	2.96 a (0.07)	-17.34 a (0.32)	0.92 a (0.01)	1.19 a (0.01)	563.33 a (9.47)	26.00 a (0.01)	1.03 a (0.01)
	40	66.89 b (2.98)	3.04 a (0.51)	21.59 b (0.83)	0.96 b (0.00)	1.25 a (0.06)	646.67 b (21.55)	37.67 b (0.01)	0.97 b (0.03)
Teff raw grain	30	22.28 a (0.09)	4.73 a (0.02)	-11.28 a (0.13)	0.84 a (0.01)	1.24 a (0.04)	488.33 a (1.44)	22.33 a (0.01)	1.05 a (0.01)
	40	40.86 b (5.03)	9.74 b (0.27)	13.47 b (1.63)	0.96 b (0.01)	1.13 b (0.01)	538.33 b (23.76)	34.33 b (0.01)	0.10 b (0.01)
Teff flour	30	30.09 a (0.25)	4.88 a (0.05)	-14.82 a (0.04)	0.88 a (0.02)	1.28 a (0.08)	558.89 a (13.88)	24.33 a (0.02)	1.03 a (0.02)
	40	38.13 b (0.67)	4.95 a (0.09)	8.30 b (0.17)	0.96 b (0.00)	1.23 a (0.08)	631.11 b (11.71)	37.33 b (0.01)	0.97 b (0.01)

[a] Means with different letters in a column were significantly different ($P < 0.05$); values in parantheses are standard deviation

4.3.2. Water Activity

Water activity represents the free water in materials. With higher the water activity, the chance of rapid microbial spoilage will be greater. This will reduce the storage stability.

The maximum (0.96) and minimum (0.91) water activity of the dried sorghum extrudates were achieved at 40% moisture content sorghum flour and 30% moisture content sorghum flour. Increasing the moisture content from 30 to 40% resulted in an increase in water activity. And changing the particle size affected the water activity of the sorghum extrudates.

The maximum (0.96) and minimum (0.91) water activity of the dried millet extrudates were achieved at 40% moisture content millet flour, and 30% moisture content millet raw grain. Increasing the moisture content from 30 to 40% resulted in an increase in water activity. And changing the particle size affected the water activity of the millet extrudates.

The maximum (0.96) and minimum (0.84) water activity of the dried teff extrudates were achieved at 40% moisture content teff flour, and 30% moisture content teff raw grain. Increasing the moisture content from 30 to 40% resulted in an increase in water activity. And changing the particle size affected the water activity of the extrudates.

Chevanan et al. (2007) found that water activity of extrudates can be influenced by feed ingredient moisture content. Moisture content will impact the macroscopic and microscopic structure of the extrudates and influence the proportion of bound vs free water in the extrudates.When increasing the moisture content, the amount of free water was increased in the sample. This increased the strength of water-bond between molecular. During the extrusion process, the increasing strength of intermolecular reaction reduced the water evaporation. And resulted in the increasing of the moisture content of extrudates.

4.3.3. Unit Density

Unit density is an important property of aquaculture feeds. It dictates whether an extrudate will float or sink. The unit density of the sorghum extrudates containing 30% moisture had a significant difference comparing the extrudates containing 40% moisture. The maximum (1.37) and minimum (1.08) unit density values were achieved at 40% moisture content sorghum flour, and 40% moisture content sorghum raw grain.

The unit density of the millet extrudates containing 30% moisture did not have a significant difference comparing the extrudates containing 40% moisture for both flour and raw grain. The maximum (1.25) and minimum (1.13) unit density values were achieved at 40% moisture content millet flour, and 40% moisture content millet raw grain.

The unit density of the teff extrudates containing 30% moisture had a significant difference comparing the extrudates containing 40% moisture on only raw grain. The maximum (1.28) and minimum (1.13) unit density values were achieved at 30% moisture content teff flour, and 40% moisture content teff raw grain.

Because the extrudates all had the unit density greater than 1 g/cm3, they did not float.

4.3.4. Bulk Density

Bulk density affects the storage space required at feed production plants, aquaculture farms, and also during transportation in trucks and rail cars. The size, shape, and method of filling affect the bulk density as well. Changing the levels of the moisture content, however, did not significantly affect the bulk density of the extrudates. The maximum and minimum bulk density of 611.67 kg/L and 511.67 kg/L were observed at 40% moisture content sorghum flour, and 30% moisture content sorghum raw grain. The maximum and minimum bulk density of 646.67 kg/L and 555.00 kg/L were observed at 40% moisture content millet flour, and 30%

moisture content millet raw grain. The maximum and minimum bulk density of 631.11 kg/L and 488.33 kg/L were observed at 40% moisture content teff flour, and 30% moisture content teff raw grain.

4.3.5. Moisture Content

The moisture content of the extrudates is very important since it affects the shelf life of the products. The thermochemical and biochemical reactions occurring inside the barrel will result in changes in the nature of bound and unbound water. This will be presented in the extrudates as the total moisture content.

The maximum (36.67% d.b.) and minimum (27.33% d.b.) moisture contents of the dried sorghum extrudates were achieved at 40% moisture content sorghum flour and 40% moisture content sorghum raw grain. The moisture content of the original sorghum used before blending was 12% (d.b.), and the moisture content of the sorghum flour was 12% (d.b.). Increasing the sorghum moisture content from 30 to 40% resulted in an increase in the final moisture content of the raw grain extrudates, but the final moisture content of sorghum flour was decreased. Decreasing the particle size of sorghum resulted in an increasing in moisture content of the extrudates.

The maximum (37.67% d.b.) and minimum (26.00% d.b.) moisture contents of the dried millet extrudates were achieved at 40% moisture content millet flour and 30% moisture content millet flour. The moisture content of the original millet used before blending was 12% (d.b.), and the moisture content of the millet flour was 10% (d.b.). Increasing the millet moisture content from 30 to 40% resulted in an increase in the final moisture content of the extrudates. Decreasing the particle size of millet resulted in an increasing in moisture content of the extrudates for 40% moisture content, but the final moisture content was decreased for 30% moisture content.

The maximum (37.33% d.b.) and minimum (22.33% d.b.) moisture contents of the dried teff extrudates were achieved at 40% moisture content teff flour, and 30% moisture content teff raw grain. The moisture content of the original teff used before blending was 12% (d.b.), and the moisture content of the teff flour was 9%(d.b.). Increasing the teff moisture content from 30 to 40% resulted in an increase in the final moisture content of the extrudates. Decreasing the particle size of teff resulted in an increasing in moisture content of the extrudates.

The high temperature and shear conditions inside the extruder affect the complex interactions between water and the other chemical constituents and alter the cellular structures that result at the die exit when the water flashes into steam (Miller 1985).

4.3.6. Expansion Ratio

The expansion ratio is the amount that the product puffs upon exiting the extruder and is a very important property when it comes to extrusion of human snack foods. Expansion of extrudates can vary depending on both processing and grains composition. Starch based materials are preferred as raw materials to enhance the puffing of extruded snacks.

The maximum (1.10) and minimum (0.98) expansion ratio of the dried sorghum extrudates were achieved at 30% moisture content sorghum raw grain, and 40% moisture content sorghum flour. Increasing the moisture content from 30 to 40% resulted in a significant change in expansion ratio for sorghum.

The maximum (1.05) and minimum (0.97) expansion ratio of the dried millet extrudates were achieved at 30% moisture content millet raw grain, and 40% moisture content millet flour. Increasing the moisture content from 30 to 40% resulted in a significant change in expansion ratio for millet.

The maximum (1.05) and minimum (0.97) expansion ratio of the dried teff extrudates were achieved at 30% moisture content teff raw grain, and 40% moisture content teff flour. Increasing the moisture content from 30 to 40% resulted in a significant change in expansion ratio for teff.

In general, the expansion ratio decreased with the increase of moisture content. This is because that low moisture ingredients can reduce the drag and apply more pressure at the die, which leads to greater expansion at the exit of the die than high moisture ingredients (Ding et al., 2005; Oluwole, 2008; Rodríguez-Miranda et al., 2011).

4.4. Conclusion

Experiments were conducted using a single-screw extruder to study the effects of changing moisture content in gluten-free grains which are millet, sorghum, and teff. Quality parameters were studied on the resulting extrudates, including color, moisture content, bulk density, unit density, water activity, and expainsion ratio. Increasing the moisture content of the ingredients from 30% to 40% resulted in increased extrudate moisture content, water activity, and bulk density, but reduced expansion ratio and unit density. The aim of this study was to investigate extrusion processing of sorghum, millet and teff on a laboratory scale as a precursor to scaling-up to commercial equipment. Overall, the results indicate that moisture content has a significant effect on the extrudates properties.

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CHAPTER 5

OVERALL CONCLUSION

Today, grains are produced for three principal reasons: direct human consumption as daily food, animal feed and other uses including industrial consumption. To be served as animal feed, ingredients' handling and processing is a problem in industry. Many common manufacturing problems are related with powder flow, and all these problems can cause rejected material, machine downtime, and defective end-products. Storage, handling, production, packing, distribution, and end use can all be negatively affected by common powder flow problems. To be served as human food, the main problem is whether the processing of whole grains affects their nutrients content. For both human and animal models, processed grains often contain more nutrition value than unprocessed grains; it maybe because processing grains enhance nutrient bioavailability grains. Also, processing of grains provides shelf-stable products that are convenient and good tasting for consumers

The first part of this thesis focused on the flowability of feed ingredients. This study has shown that moisture content affected many properties of feed ingredients. For the physical properties, color values were influenced by the moisture content. And the thermal properties decreases with the increase of moisture content. For flowability properties, moisture content had effect on ABD, PBD, AoR, uniformity, compressibility and mass flow. According to these data, feed ingredients flowability generally declined with an increase in moisture content.

The second study of the thesis focused on extrusion of gluten-free grains: sorghum, millet, and teff. The results showed that increasing the moisture content of the ingredients from 30% to 40% resulted in increased extrudate moisture content, water activity, but reduced expansion ratio and unit density. The aim of this study was to investigate extrusion processing of sorghum, millet and teff on a laboratory scale as a precursor to scaling-up to commercial equipment.

Overall, moisture content has a great impact on the properties of both human food and animal feed.

CHAPTER 6

FUTURE WORK

For the first part of the thesis, only moisture content was tested as a factor influencing flowability. Based on the literature review part, there still are other factors may affect flowability. For the future work, particle size can be tested as the other factor affecting flowability. Also, when testing moisture, the storage period was not considered. Generally, increasing the moisture content will shorter the storage period. For the future work, moisture content and storage period can be conbined to find the perfect moisture content.

For the second study, in addition to moisture content, screw speed and process temperature are two other factors affecting properties of extrudates. Also, changing the moisture content of grains can affect the chemical properties and nutrition components. Thus, additional steps can go toward the change of screw speed during the process in order to study the effect on the physical can chemical properties of extrudates.