This is to certify that the
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EXTRUSION COOKING TO PRODUCE NUTRITIOUS BEAN
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of the requirements for the

M.S. degree in Food Science

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EXTRUSION COOKING TO PRODUCE NUTRITIOUS BEAN PRODUCTS

By

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ABSTRACT

EXTRUSION COOKING TO PRODUCE NUTRITIONAL BEAN PRODUCTS

By

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A laboratory co-rotating twin-screw extruder was used to study the effect of extrusion conditions on physical, chemical, and sensory characteristics of extruded light red kidney beans. Raw bean flour was extruded at 25% and 36% moisture content wet basis; screw speed of 118, 194, and 253 r.p.m; bean flour feed rate of 80 and 120g/min and extrusion barrel temperatures were 105/120°C and 115/130°C ; and die orifice was 7.00mm. Only feed rate significantly ($p=0.003$) influenced average expansion ratio with 1.22 and 1.30 for 80 g/min and 120 g/min respectively. Increasing moisture content from 25% to 36% significantly increased average bulk density from 38.86 to 39.89 g/cm^3 respectively ($p=0.05$). Water solubility index was significantly affected by feed rate ($p=0.0001$), screw speed ($p=0.0001$), and moisture content ($p=0.002$). The initial viscosity of extruded bean samples was much higher than that of raw bean samples which indicates that starch was gelatinized during extrusion cooking. Peak viscosity, hot-paste viscosity and cold paste viscosity in extruded bean samples were much lower than those in raw bean samples. Phytohemagglutinin activity reduction of extruded beans was over 90%. A comparison of thermal extrusion versus traditional cooking using charcoal demonstrated a 43 % cost reduction using extrusion.

DEDICATION

To my mother Anna Mukashuri, my wife Phiona Bamukunde, and my brother Francis Rusagara, for their moral support.

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CHAPTER 1: INTRODUCTION

Dry beans (*Phaseolus vulgaris* L.) can be an extremely beneficial component of all diets because they are high in complex carbohydrates, protein and dietary fiber, and low in fat, calories and sodium, and are cholesterol free. In the developed world where cholesterol is a major health problem, dry beans are considered as the major source of dietary fiber (USDA, 2006). Beans are one of the best sources of dietary fiber, containing both soluble and insoluble fiber. Insoluble fiber, generally thought as "roughage" that moves quickly through the digestive system, is very important because it helps promote digestion and can reduce the risk of colon cancer (Willet, 1995). Soluble fiber helps lower blood cholesterol levels, one of the main risk factors for the development of cardiovascular disease in developed countries such as the United States of America.

In developing world, dry beans are an important source of protein and calories for middle and low income families (Bliss, 1990) because animal protein is very expensive. In a country like Rwanda, animal protein is very limited and very expensive, and common beans provide up to 60% of protein needs and 25% of calories in the diet (MINIPLAN, 1988). The most common method of cooking beans in much of Africa and Rwanda is an open wood fire built on the ground (Poulsen, 1980). An open wood fire is not fuel efficient because the rate of burning cannot be controlled and much of the heat is dissipated into the surrounding atmosphere. Large quantities of wood and charcoal used to cook the beans 3-4 hrs leads to deforestation and erosion, as well as air pollution from the burning of wood. Dry beans require a long time of cooking to render the grains palatable, and to inactivate antinutritional factors such as phytohemagglutinins (lectins), protease inhibitors and amylase inhibitors. These antinutrients must be inactivated, and the starch must be gelatinized before consumption. Lack of fuel wood for cooking dry beans is a major problem facing over-populated developing countries. Besides, continued deforestation may alter local and global climate. In addition, smoke from the cooking fire is a major health hazard.

In most tropical countries, considerable deterioration of dry beans can occur during high temperature and humidity storage. The main observed deterioration includes an increase in cooking time, deterioration of texture and flavor, and loss of nutritive value. Also, lack of ideal bean storage conditions leads to increased losses of the crop due to weevils.

Low-cost extruders are seen as one of the best alternatives for dry bean cooking, especially in countries with low income, because the typical existing extrusion equipment is expensive. Extrusion is a high-temperature-short-time (HTST) cooking technique used to produce a variety of products from different food ingredients. Food extruders are generally available with segmented screws and a barrel section. Segmented screws facilitate total control over the configuration of the machine to get a combination of various process parameters. This control makes possible many functional changes and inactivation of undesirable factors technology. As a result, very little research has been published, but is sorely needed.

In Rwanda, more than 90% of the population use firewood or charcoal for cooking all types of foods. Also, increased land pressure (approximately 8,000,000 people on 26,338 sq. km) has resulted in a scarcity of wood for fuel, and current fuelwood demands far exceed the supply. Rwanda is the number one country in consumption of dry beans (*Phaseolus vulgaris* L.) in the world (ISAR, 2001). The consumption per capita is over 60 kg, one of the highest in the world (Africa average is 11.7 kg) (ISAR, 2001) and they are the only food require much firewood to cook. Using a low-cost extruder for cooking beans would reduce the amount of fuelwood and increase the amount of nutrients supplied by beans in the Rwandan diet. The extruder would have a positive impact on the environment and enhance nutritional well-being of dry bean consumers. Therefore, it is very important to calculate the energy requirement for cooking dry beans with firewood or charcoal and compare it with that used by the extruder.

Therefore, the objectives of the present research were to:

1) Assess the effect of low-cost extruder conditions on the physical characteristics of extruded light red kidney beans;
2) Determine the fate of antinutritional components, specifically lectins in the extruded bean products;
3) Determine consumer acceptability of extruded bean porridge;

4) Compare energy requirements for bean extrusion versus wood or charcoal.

CHAPTER 2: LITERATURE REVIEW

2.1. Beans in the diet of man

Beans are one of the world's most important food sources, especially in developing countries, in terms of food energy as well as nutrients (August and Klein, 1989). Common beans are a good source of proteins and are an excellent source of carbohydrates (Sathe et al., 1985). The large amount of water-soluble fiber is particularly effective in lowering cholesterol in the blood, whereas the water-insoluble fiber provides bulk, pushing food through the digestive system at a faster rate. Common beans are low in sodium. They are a good source of vitamins (thiamine, riboflavin, niacin, vitamin B6, and folic acid) and certain minerals (Ca, Fe, Cu, Zn, P, K, and Mg). Also dry beans contain about one percent of polyunsaturated fatty acids (linoleic and linolenic). (Augustin and Klein, 1989; Mahadevappa and Raina, 1978; Sathe et al., 1985)

The contribution of common beans to the diets of people is appreciable. In addition, common beans are less expensive than animal food products and have considerably longer shelf-life than many animal, fruit, and vegetable products when stored under appropriate conditions. However, dry beans have several undesirable characteristics such as long cooking times, 'beany' flavor, and the presence of enzyme inhibitors and hemagglutinins that must be removed for safe dry bean consumption. (Gupta 1987; Sathe et al., 1985).

Table 2.1.1. Major nutrients in beans and other grains

	Dry Beans	Wheat	Oats	Corn	Sorghum	Millet
Energy (kcal)	333	339	389	361	339	378
Protein (g)	23.58	13.7	16.89	6.93	11.3	11.02
Carbohydrates (g)	60.01	72.57	66.27	76.85	74.66	72.85
Dietary fiber (g)	24.9	12.2	10.6	7.3	6.3	8.5
Fat (g)	0.83	1.87	6.9	3.86	3.3	4.22
Iron (mg)	8.2	3.88	4.72	2.38	4.4	3.01
Potassium (mg)	1406	405	429	315	350	195
Folate (µg)	394	44	56	25	0	85

Source: USDA, 2006

The data provided in Table 2.1.1 are per 100 g dry basis. Compared with wheat, oats, corn, sorghum and millet, beans are a good source of dietary fiber, and B vitamins (folic acid). Dry beans also are higher in protein and minerals such as iron and potassium. Beans provide very little fat (linolenic and linoleic).

2.1.1. Nutritional importance of beans

2.1.1.1. Proteins

The most important role of legumes in the diet is as an inexpensive protein source. This role is crucial in the developing countries as beans are frequently the major source of high quality protein in the diet. Methionine is always the first limiting amino acid in legumes (Carpenter, 1981), but they are endowed with relatively high lysine levels. This lack of methionine explains beans' historical association with cereal grain. Because legumes are looked upon as a good source of protein in vegetable-based diets, much effort has been spent in investigating the protein quality of legumes. The protein efficiency ratio (PER) of raw and cooked legumes is approximately 0 and 1.2, respectively (Rockland and Radke, 1981).

2.1.1.2. Carbohydrates

Beans are rich in complex carbohydrates (Table 2.1.1), one of the nutrients that provides energy to the muscles and brain. Carbohydrate content in dry beans ranges from 50 to 60 % (Sathe et al., 1985). Dry beans have the best type of carbohydrates because they are considered to be low glycemic index making beans a suitable food for diabetics.

Monosaccharides and some oligosaccharides are present in dry beans but these make a minor contribution to the total carbohydrate. Soluble sugars are present in the range of 5.5 to 8% (Reddy et al., 1984). Those present in greatest concentration are sucrose and stachyose with raffinose and verbascose also present. Raffinose containing oligosaccharides constitute from 31-76% of the total sugar fraction in dry beans (Naivukul and D'Appolonia, 1978; Akpapunam and Markakis, 1979).

2.1.1.3. Dietary fiber

Dietary fiber constitutes 25% of the dry beans by weight twice as high as that in wheat and corn (Table 2.1.1)

The indigestible residue of dry beans is an important component and makes up from 8 to 9% to the total carbohydrate fraction (Reddy *et al.*, 1984). The most prevalent fiber components in *Phaseolus vulgaris* varieties are cellulose, hemicellulose and lignins, but pectins are also present. Dry beans contain approximately 13% water-insoluble fiber and 11% water-soluble components (Asp and Johansson, 1981).

The importance of dietary fiber in human nutrition has received a great deal of attention in recent years from scientists and consumers (Hughes, 1991; Hughes and Swanson, 1986; Olson et al., 1087; Schweizer, 1989). Numerous health benefits (Table 2.1.1) have been associated with consuming adequate amounts of dietary fiber, including lower blood cholesterol, reduced risk of heart disease (Schneeman, 1986), increased fecal bulk, decreased intestinal transit time, reduced risk of colon cancer, and improved glucose tolerance, which is especially beneficial for diabetics (Toma and Curtis, 1986).

Dietary fiber is categorized as soluble and insoluble. Soluble fibers form gels, increasing the viscosity of intestinal contents, which may affect glycemic index. Soluble fibers are generally highly fermentable and affect the animal indirectly by production of gas, short chain fatty acids (SCFA), and lactic acid as a result of fermentative digestion in the small intestine (Roberfroid, 1993). Insoluble fibers, that cannot be digested in the human digestive tract (Trowell et al., 1976) contribute to fecal bulk and ease of laxation.

2.1.1.4. Lipids

Common beans contain only 1 to 3% lipids depending on the species (Patte et al., 1982; Sathe et al., 1985). Total lipid content may vary depending on the variety, origin, location, climate, environment conditions, and the type of soil in which they are grown (Worthington et al., 1972). The majority of the fatty acids in dry beans are unsaturated (Patte et al., 1982; Sathe et al., 1985; Watt and Merril, 1963). Oleic (7 to 10%), linoleic (21 to 28%) and linolenic (37 to 54%) are the major unsaturated fatty acids, which range from 64 to 87% of total lipids. The polyunsaturated fatty acids, such as linoleic and linolenic, cannot be synthesized by animals and humans, and these two acids are required for normal growth, cell structure, functions of all tissues, and prostaglandin synthesis (Lehninger, 1975; Sathe et al., 1985). Linoleic and linolenic help to lower blood cholesterol (Mahadevappa and Raina, 1978).

2.1.1.5. Vitamins

In addition to supplying carbohydrates and proteins, dry beans are significant source of vitamins especially folic acid (0.171 to 0.579 mg per 100g), thiamine (0.86 to 1.14 mg per 100g), riboflavin (0.136 to 0.266 mg per 100g), niacin (1.16 to 2.68 mg per 100g), Vitamin B6 (0.336 to 0.636 mg/100g).

2.1.1.6. Minerals

Dry beans are also rich in minerals, such as iron, potassium, and folate (Table 2.1.1). Hosfield and Uebersax (1980) measured ash content in 34 varieties of dry beans and the average of the samples was 3.94%. The mineral content of beans should be considered in conjunction with its bioavailability (Sathe et al., 1985). Phytic acid and proteins can complex with dietary essential minerals, such as calcium, zinc, Iron, and magnesium, and render them biologically unavailable for absorption (Fritz, 1976; Martinez, 1977; Sathe et al., 1985). Physicochemical modifications of bean proteins to produce desired functional properties may alter the binding of minerals to food components, thereby influencing the mineral availability (Sathe et al., 1985).

2.1.1.7. Antioxidants in beans

Eating beans could help people reduce their risk of developing a chronic disease (Wu et al, 2004). Chronic diseases are conditions that typically take many years (10 to 30 years) to develop and include certain types of cancers, type 2 diabetes mellitus, heart disease, and other diseases of the blood system. These diseases are the most common causes of death in the United States and significantly lower the quality of life for millions (Geil and Anderson 1994).

Beans are loaded with antioxidants (Table 2.1.1.7). Antioxidants are chemicals that destroy free radicals and are highly common in many varieties of beans (Wu et al., 2004). In 2004, the USDA nutritionists analyzed total antioxidant levels using the oxygen radical absorbance capacity (ORAC) in assay in over 100 different foods, including fruits and vegetables. Among the foods analyzed, dry beans (small red, red kidney, pinto, and black beans) were surprisingly found to have high levels of antioxidants (Table 2.1.2).

Table 2.1.2. Best sources of food antioxidants: Top 20 fruits, vegetables and nuts (as measured by total antioxidant capacity per serving size)

Rank	Food item	Serving size	Total antioxidant capacity per serving size (µmol of TE[a])
1	*Small Red Bean (dried)	Half cup	13727
2	Wild blueberry	1 cup	13427
3	*Red kidney bean (dried)	Half cup	13259
4	*Pinto bean	Half cup	11864
5	Blueberry (cultivated)	1 cup	9019
6	Cranberry	1 cup (whole)	8983
7	Artichoke (cooked)	1 cup (hearts)	7904
8	Blackberry	1 cup	7701
9	Prune	Half cup	7291
10	Rasperry	1 cup	6058
11	Strawberry	1 cup	5938
12	Red Delicious Apple	One	5900
13	Granny Smith Apple	One	5381
14	Pecan	1 ounce	5095
15	Sweet cherry	1 cup	4873
16	Black plum	One	4844
17	Russet potato (cooked)	One	4649
18	*Black bean (dried)	Half cup	4181
19	Plum	One	4118
20	Gala Apple	One	3903

Source: Wu et al., 2004

*Dry beans
[a]Trolox Equivalent

1.1.3. Lectins in beans

Landsteiner and Raubitschkek (1908) reported the ability of bean seed extracts to agglutinate red blood cell from various animal sources. The name "lectin" was given to proteins responsible for this activity (Boyd and Shopleigh, 1954). Lectins are glycoproteins with the unique property of being able to bind disaccharides in a highly specific fashion. In addition to erythrocyte agglutination, the lectins can interact with other types of cells (Sgarbieri and Whitaker, 1982). Various names have been given to lectins. Lectins in dry beans are known as phytohemagglutinins. Lectins in dry beans make up 6 to 12% of the total protein, suggesting that they may play an important role in the physiology of the plant. Some of the suggested functions for the lectins are (1) acting as antibodies to counteract soil bacteria, (2) protecting against fungal attack, (3) participating in transportation or storage of sugars, and (4) playing a key role in the development and differentiation of embryonic cells (Purtzai, 1991).

1.1.3.1. Toxicity effects of lectins

Lectin's mode of action in the plant is probably related to their toxic activity in the diet. The main physiological characteristic of lectins is their specific affinity for certain sugar molecules. Most animal cell membranes contain these molecules, and the lectins can be characterized by their ability to bind to and agglutinate red blood cells (hence the name haemagglutinins). However, their toxic activity derives from their ability to attach on the same sugar moieties on intestinal cell membranes. The nature of this toxicity can range from long-term impaired nutrient uptake to serious acute food poisoning symptoms. Symptoms include nausea, vomiting, and stomach pain. Most lectin sources do not cause a problem, and they are easily denatured by the heating processes occurring in normal cooking. However, they are specific exceptions, the most well known and significant of which is red kidney beans.

Raw kidney beans are significantly toxic and must be cooked adequately before consumption. Given the wide availability of dried, raw kidney beans in the UK marketplace, and adverse TV publicity in the summer of 1981, the then department of Health and Social Security issued instructions to the food industry on the giving of general advice to purchasers of raw beans for their preparation. The form of wording suggested for labeling of beans for sale was:

"After soaking overnight and throwing away the water, these beans should be boiled briskly for at least 10 minutes and then cooked until soft otherwise they may cause stomach upsets. Never cook in a small casserole unless the beans have first been soaked and boiled this way. Do not eat raw beans" (Hutton, 2002)

Phytohemagglutinin, the toxic agent, is found in many species of beans, but it is in highest concentration in red kidney beans (*Phaseolus vulgaris* L). The unit of toxin measure is the haemagglutinating unit (hau). Raw kidney beans contain from 200,000 to 700,000 hau, while fully cooked beans contain from 200 to 400 hau. White kidney beans, another variety of *Phaseolus vulgaris* L., contain about one-third the amount of toxin as the red variety; broad beans (Vicia faba) contain about 5 to 10 % the amount the red kidney beans contain.

Toxicity of lectins in red kidney beans has been reported in the United Kingdom. Seven outbreaks occurred in the U.K. between 1976 (Noah et al., 1980). Two more incidents were reported by Public Health Laboratory Services (PHLS), Colindale, U.K. in the summer of 1988. Reports of this syndrome in the United States are anecdotal and have not been formally published.

The disease course is rapid. All symptoms usually resolve within several hours of onset. Vomiting is usually described as profuse, and the severity of symptoms is directly related to the dose of toxin (number of raw beans ingested). Hospitalization has occasionally resulted, and intravenous fluids may have to be administered. Although of short duration, the symptoms are extremely debilitating.

All persons, regardless of age or gender, appear to be equally susceptible; the severity is related to the dose ingested. In the seven outbreaks mentioned above, the attack rate was 100 %.

One of the most important nutritional problems of dry beans is low protein digestibility. Apparent protein digestibility values of different colored beans are low (48%-62%) compared with animal protein digestibility for meat (82%-86%). Possible factors that influence protein digestibility of lightly cooked beans include lectins and protease inhibitors. The toxicity of lectins is due to the lectins combining with epithelial cells of the small intestines, interfering with intestinal enzyme activity, and damaging intestinal epithelial surfaces (Kim et al., 1976; Rouanet and Resancon, 1979; King et al., 1980a and b) . Boiling for minimum of 10-12 minutes is necessary to adequately detoxify lectins (Bender and Reaidi, 1982).

2.2. EXTRUSION COOKING

2.2.1. Extrusion terminology

The names of extruder parts depend on each extruder manufacturer. In most cases the terminology is confusing and hard to understand. The following are most of the terms commonly used in the extrusion process (Riaz, 2000):

- *Feedstock*: the material or mixture to be processed in an extruder
- *Pre-conditioner*: an assembly that adjusts moisture content and temperatures of the ingredients and may partially or completely cook them before entering the extruder
- *Screw*: the member that conveys the product through the extruder
- *Shear*: a working, mixing action that homogenizes and heats the conveyed product
- *Barrel*: a pipe-like retainer in which the extruder screw(s) turn(s)
- *L/D (Length-to-diameter) ratio*: distance from the internal rear edge to the discharge end of the barrel, divided by the diameter of the bore
- *Die plate*: Final assembly for shaping the product as it leaves the extruder (Die holes may be drilled directly into the plate for shaping the product and may be made of hard-wearing material).

2.2.2. Single-Screw extruders

Single-Screw extruders may be regarded as friction pumps, since they rely entirely on friction between the material being processed and the barrel wall to convey materials (Purvis 1987, Starer 1996). Thus they rely on drag flow for conveyance. The mass of the material being processed must stick to the barrel wall in order to be forwarded, and the higher the friction forces, the more efficient the conveyance is.

Single-Screw extruders consist of three sections: feed, transition, and metering. The extrusion screw sequentially conveys and heats food ingredients and works them into a continuous plasticized mass while rotating in a tightly fitting barrel. The screw can be designed either a single piece or as a splined shaft that accepts screw sections of varying configurations to increase versatility and reduce the cost of replacing worn sections (Harper, 1989).

2.2.3. Twin-Screw extruders

Twin-Screw Extruders consist of two screws of equal length placed inside the same barrel for its entire length (Martelli 1983). Twin-Screw extruders are classified according to the position of the screws in relation to one another and to the direction of screw rotation (IFT, 1989; Riaz, 2000). Therefore, twin-screw extruders can be (1) counterrotating and corotating twin-screw extruders. These categories of twin-screw extruders can be further subdivided into intermeshing and non-intermeshing. In intermeshing twin-screw extruders, the flights of one screw engage or penetrate the channels of the screw while in non-intermeshing twin-screw extruders each screw turns without interference from the other.

2.2.4. Benefits of extrusion cooking

Extrusion is a processing technology used to produce foodstuffs such as breakfast cereals, snack foods, baby foods, pet foods, modified starches, etc. By controlling variables such as temperature, moisture, and screw speed in the extruder, food ingredients undergo physical and chemical changes such as starch gelatinization and protein denaturation. These molecular transformations convert food material into a visco-elastic dough under the presence of heat, moisture, shear, and pressure.

2.2.4.1. Starch gelatinization

Starch granules undergo gelatinization and melting by the action of heat and moisture on hydrogen bonding among tightly packed polysaccharide chains in the granule structure. Under conditions of excess water, hydrogen bonding in the less ordered amorphous regions of the granule is disrupted first, allowing water to associate with free hydroxyl groups. This is marked by polymer chain mobilization and can be called glass transition, Tg. Swelling is the result, and further opening of the granule structure to the action of water occurs. Melting of the crystalline fraction results in complete disappearance of birefringence, which is irreversible.

As starch is heated to gelatinization temperature, the heat energy begins to dissociate the more weakly bonded regions within the starch granules, water moves into the granule and it begins to swell. The swelling continues as the temperature is raised. Shorter of the linear molecules actually diffuse out of the swollen granule and into the surrounding liquid. However, the longer linear chains wander through the granule among the bushy amylopectin molecules and act to keep the molecule together and prevent complete solubilization. As the granules take up water and swell, they occupy more space and friction is created between granules. The starch paste becomes thicker, the consistency reflecting the resistance to stirring of the mass of swollen particles. The greater the granule swelling the higher will be the viscosity. However, swollen granules are fragile and are deformed and fragmented by swelling with the consequent thinning of the mixture (Schultz et al., 1969)

The final collapse of the granule is marked by release of remaining hydrated, gelatinized contents into the cooking medium. Viscosity of the medium increases rapidly until a majority of the granules are completely collapsed, which results in a set back in viscosity.

The gelatinization process allows greater susceptibility of starch to enzymatic hydrolysis and, subsequently, higher starch digestibility.

2.2.4.2. Protein denaturation and digestibility

The nutritive value of a protein depends on the ease with which it can be digested. Many factors including the presence of protease inhibitors can reduce the amount of protein for intestinal absorption. The heat generated during extrusion cooking improves the digestibility of proteins by inactivating enzyme inhibitors and denaturing the protein, which may expose new sites for enzyme attack.

Alteration from the naturally ordered conformation of a protein molecule to a randomly structured molecule is called denaturation (Orten and Neuhaus, 1970). Most proteins are sensitive to changes in pH, ion concentration and temperature. The highly native protein is easily disrupted as weak cross-linkages are broken. The polypeptide chains may unfold and the helix becomes disordered. Denaturation does not include breaking of the peptide linkage in a hydrolysis process. Hydrolysis of proteins, except when carried out by enzymes, requires extreme conditions of heat and acidity and alkalinity.

2.2.5. Low-cost extrusion cooking

Low-cost extrusion cooking has been studied with encouraging success (Harper and Jansen, 1981) and could offer the long-term solution the malnutrition problem among children in developing countries, for example. Africa. Childhood malnutrition is a serious health problem in several countries of the world. In a country such as Tanzania, in East Africa, 200,000 children die annually under the age of five as a result of inadequate protein, energy, and/micronutrients (Mosha and Bennink, 2004). However, most of studies (Harper and Jansen, 1981) were on soybean and did not include foods local to the developing countries such as root/stem tubers and dry beans.

Low-cost extrusion cooking has been suggested as a suitable alternative for mass production of pre-cooked, nutritious cereal and legume foods are shelf-stable (Harper and Jansen, 1985). Extrusion cooking technology is still limited in developing countries. Developing countries can benefit from low-cost extruders in the following ways. (Moquet et al, 2003).

1. Women in the countryside can save time they use gathering firewood to cook beans;
2. Low-cost extruders can be used to process local foods such as corn, cassava, potato, beans into nutritious snacks. The snacks can be ground into powder that can be used to prepare nutritious porridge that can prevent malnutrition, especially among children;
3. Low-cost extruders are suitable for countries of low income as they are cost-effective and require less technology skills.

In most developing countries, extrusion cooking is not very popular in food processing enterprises because its full potential has not been well recognized (Dedeh and Saalia, 1997). One of the major reasons why adoption of extrusion cooking for processing of ready-to-eat foods and infant flours is very limited in poor countries is that the present extruders are designed for large scale production, thus requiring very high investment and technical knowledge (Moquet et al., 2003). Even the so-called low-cost extruders, that were designed for the production of complementary foods around 1980s by the University of Colorado (Harper, 1985; Harper and Jansen, 1985; Said, 2000), are too costly and their production capacity is too high (approximately 55,000 U.S. dollars for an extruder with production capacity of 1 ton an hour). These extruders are thus not affordable for developing countries. Therefore, the development of a small and simple low-cost extruder (about 22,000 dollars with production capacity of about 100 kg an hour) would be of great potential interest for countries with low income.

CHAPTER 3: MATERIALS AND METHODS

3.1. Raw material

Whole dry light red kidney beans (*Phaseolus vulgaris* L.), harvested in 2005 and having ~13% moisture content (appendix 6), were purchased from Bayside Best Beans, LLC (Sebewiang, Mich., U.S.A.). The beans were hand-sorted to remove splits, wrinkled seeds, and any debris and stored at 4°C until needed for extrusion processing.

3.2. Extrusion experiments (Objective 1)

Before extrusion dry light red kidney beans were ground with a hammer mill (Model D comminuting Machine, The W.J. Fitzpatrick Company, Chicago USA) to pass through mesh No. 50 US standard. Extrusion runs of raw ground red kidney beans were carried out in duplicate using a low-cost (less than $20,000) laboratory co-rotating twin-screw extruder model JS30A manufactured in China by Qitong Chemical Industry Equipment Co, Ltd. The screws are 30 mm in diameter and the barrel has a L/D of 14. A full factorial design was used. Raw light red kidney bean flour was extruded at 25% and 36% moisture content wet basis; screw speed was 118, 194 or 253 r.p.m; feed rate of bean flour was 80 or 120g/min and extrusion barrel temperatures were 105 and 120^{o}C (temperature profile 1) and 115 and 130^{o}C for temperature profile 2 (Table 3.2.1) where 120^{o}C and 130^{o}C are nearest the die end of the extruder. The die was a plate with one 7-mm diameter circular hole. Moisture content was determined using the formula in appendix 5.

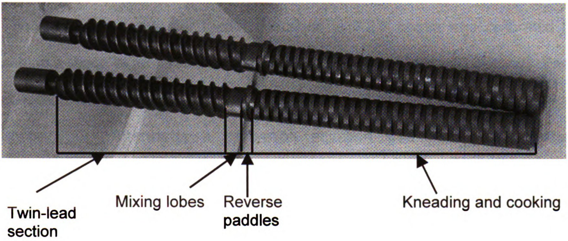
Table 3.2.1. Experimental design

Sample Number	Barrel Temperature (°C)	Moisture Content (%)*	Screw Speed (rpm)	Flour Feedrate (g/min)
1	120/105	25	118	80
2	120/105	25	184	80
3	120/105	25	253	80
4	120/105	25	118	120
5	120/105	25	184	120
6	120/105	25	253	120
7	120/105	36	118	80
8	120/105	36	184	80
9	120/105	36	253	80
10	120/105	36	118	120
11	120/105	36	184	120
12	120/105	36	253	120
13	130/115	25	118	80
14	130/115	25	184	80
15	130/115	25	253	80
16	130/115	25	118	120
17	130/115	25	184	120
18	130/115	25	253	120
19	130/115	36	118	80
20	130/115	36	184	80
21	130/115	36	253	80
22	130/115	36	118	120
23	130/115	36	184	120
24	130/115	36	253	120

*Moisture content was calculated using the formula in appendix 5

Table 3.2.2. Extruder specification

Screw diameter	30mm
Screw length	425mm
Motor	4 kw
Screw Speed	70-258 rpm
Output	Up to 12 kg/h
Heating power	1.8 kw



JS30A extruder is a twin-screw extruder. The 425 mm length solid twin screws with fixed configuration are divided into four segments. The first segment is a twin-lead section in the feeding zone. It is followed by mixing lobes and 30° reverse paddles. The next segment towards the die end that is used for kneading and mixing has uniform configuration of 90° mixing lobes.

3.2.1. Fabrication of feeder

The feeder used throughout the study was designed in the shop of the Department of Biosystems Engineering, Michigan State University. Motor and auger were purchased from Grainger (Lansing MI) while other parts like hopper and general assembling of the parts were done in the shop of the Department of Agricultural and Biosystems Engineering of Michigan State University.

3.2.2. Calibration of feeder

The single-screw extruder feeder described in 3.2.1 above was calibrated by setting a range of feed rates and weighing feed material every 30 seconds. Each collection was done 5 times. The feeder had a coefficient of variation (CV) of about 3%. Afterwards a calibration equation was made for extrusion experiments.

3.2.3. Calibration of water pump

Calibration of water pump was done in a similar way as the extruder feeder (3.2.2). Water was collected at different pump rates every 30 seconds and weighed. Each collection was done five times. A calibration equation was obtained for extrusion.

3.2.4. Estimation of degree of fill

Degree of fill is affected by changing screw speed and feed rate. Extruding at different conditions such as screw speed and feed rate may affect the degree of fill and shear and amount of mixing on the material being processed. Lower degree of fill allows more mixing. This may influence the quality characteristics of extruded products. To estimate the degree of fill of the extruder used for all runs, we measured the volume of the twin screws. Briefly the screws were submerged in 2000 volumetric cylinder and the volume of water displaced was taken as the volume of screws which was 0.000384 m^3. The volume of the screws was then used in the computation of void volume of the extruder. Percent fill was calculated as follows:

$$\% \text{ fill} = \frac{\dot{m}\bar{t}}{vd} \times 100$$

Where

$\dot{m}$ = mass flow rate of dough ($\dot{m}_{flour}$ + $\dot{m}_{water}$) (kg/s)

$\bar{t}$ = residence time, s

v = void volume of the extruder (m^3) was 2.02×10^{-4} m^3

d = dough density (kg/m^3) was 1100 kg/m^3

For the dough density measurement, the method used by Schmid et al., 2005 was used. Briefly, a sample of dough was taken near the entrance of the extruder die, wrapped in a pre-weighed plastic wrap and then weighed. After recording the weight, the dough was place in a 100 mL graduated cylinder filled with 30 mL distilled water. Dough volume was recorded as the volume of water displaced by the dough. The density of the dough was calculated as the weight of the dough (kg) divided by the dough volume (m^3).

3.2.5. Residence Time Distribution

Average retention time is very important during extrusion cooking. Residence time distribution is a measure of the length of time the material spends in an extruder barrel. Residence time distribution in an extruder is a useful means of determining optimal processing conditions for mixing, cooking, and shearing reactions during the process. From knowledge of RTD function one can estimate the degree of mixing, the residence time of mass flow, and the average total strain exerted on the mass during its transition and thus provide a clearer picture of how an extruder behaves as chemical reactor (Fichtali and Van de Voort, 1989). Residence time distribution, like degree of fill, is also affected by feed rate and screw speed.

3.2.5.1. Preparation of dyed flour to measure Residence Time Distribution

Twenty grams of extruded bean flour was mixed with 8 mL of water-based red dye #1080-0500 (Craft Store, Cordova, TN) by weight. The dye was poured on the flour and mixed until the dye was completely absorbed. The mixture was the let to dry at room temperature until sufficient moisture had evaporated for the sample to be milled. The dye-flour mixture was coarsely ground using a mortar and a pestle.

3.2.5.2. Residence time sample collection

Mean residence times were determined using a tracer (red dye) described in 3.2.4.1. At each extrusion run, approximately 4.0 g of the residence time dye was added instantaneously to the barrel hopper. Time in seconds was recorded from when the dye was added until color was seen coming out through the die. Samples were then collected every five seconds from the time color appeared in the extrudate until the there was no more color visible in the bean extrudate. A strand was collected prior to color injection to represent the color value at time zero. The samples were placed in aluminium pans in sequence and allowed to dry at room temperature for 24 hr until they were dried. A coffee grinder (Sunbeam Corporation, Maitland, FL) was used to grind each strand. Each sample in the amount of approximately 2.0 g was then placed into a round disc with a 3.5 cm diameter and 0.5 cm height. A hunterLab D25 L color meter (Hunter Associates Laboratory, Reston, VA) measured the a* value (redness) of the ground samples. Results were reported as color minus control color. A white tile (Standard No. C2-30954) was used to standardize the colorimeter. Redness values were recorded and were used to represent the intensity color (t) of red color at exit time t.

3.2.5.3. Color concentration calibration curve

The idea of color-concentration curve for residence time distribution was developed by Peng et al., (1994) and was applied for all residence time samples in this study. Unlike the linear "standard curve" typically used for High Performance Liquid Chromatography (HPLC), the calibration curve for concentration versus color is non-linear. At high concentrations, there is a color saturation effect, where large increases of concentration cause only minimal changes in color readings. Seven batches of flour were prepared by mixing 5, 10, 25, 75, 100, 150, and 200 mL dye with 300g bean flour. A spray bottle was used to spray the dye onto the flour in aluminium pan. Sprayed flour was allowed to sit overnight so that the flour could fully absorb the dye. The flour mixtures were then placed in the dryer at approximately 80°C. After drying to a state that could be extruded, the samples were extruded at 80g/min feed rate; 25% moisture content and 118 rpm screw speed. Each of seven batch was extruded separately and after a steady state was attained, samples for color reading were collected. Samples were placed in aluminium pans and allowed to dry for 4 hours in the oven at 80°C. A coffee grinder was used to grind samples and color readings were taken in triplicate. Color was measured using a Hunter Color Difference Meter (D25 DP 9000 System Hunter Color Associates Lab., Reston, VA). Color readings (a^*) were plotted against dye concentration to obtain a calibration curve. This relationship was then applied to all residence time data to estimate mean residence time. This calibration curve is used to convert all extrudates color values to color concentration, c. Normalized concentration E(t) was calculated according to Levenspiel (1999):

$$E(t) = \frac{c(t)}{\int_0^\infty c(t)dt} \cong \frac{ci}{\sum_i ci\Delta ti}$$

The normalized concentration, E(t), was used to calculate mean residence time, $\bar{t}$

$$\bar{t} = \int_0^\infty tE(t)dt \cong \frac{\sum_i tiCi\Delta ti}{\sum_i ci\Delta ti}$$

3.2.6. Specific mechanical energy

Efficiency is always a major concern for engineers. Food extrusion is an energy efficient process because a substantial amount of the mechanical energy from the extruder motor is dissipated during the viscous flow within the extruder barrel. Specific mechanical energy (SME) is a measure of the viscous energy dissipation per unit mass of dough (Mason and Hosneney, 1986). This energy originates from the direct current motor supply which provides the required torque to turn screws at a given screw speed. A portion of total power supplied to the shaft is used to push dough along the barrel against back pressure generated at the die (Mohamed et al., 1990). The remaining power is transferred into the dough via fluid friction. Therefore, specific mechanical energy is calculated as the total power supplied to the shaft (kW), divided by the mass flow rate.

3.2.7. Physical characteristics of bean extrudates (Objective 1)

3.2.7.1. Expansion ratio

After drying extrudates at room temperature for 24 hours, the average diameter of 5 randomly selected extrudates were measured for each treatment using a vernier caliper. Per sample, five strands were randomly selected and three measurements were taken along the product. The ratio of the mean diameter of the extrudates to the die diameter of 7 mm was calculated as the expansion ratio.

3.2.7.2. Bulk density

The bean extrudate pieces that were approximately 0.5 cm long of extrudate were placed in a 100 mL graduated measuring cylinder. The graduated cylinder with extruded bean pieces was tapped gently on a flat surface before weighing. The bulk density was calculated as weight per unit volume, as:

$$\text{Bulk density} = \frac{\text{g of sample per 100mL}}{\text{100mL}}$$

Duplicate determinations were made for each sample.

3.2.7.3. Water Absorption Index

The determination of Water Absorption Index was determined according to the method reported by Mason and Hoseney (1986), Gomez and Aguilera (1983) and Anderson *et al.*, (1969). Briefly, 20 g of extruded bean extrudate was mixed in 20 mL of distilled water at 30°C and centrifuged at 1000 x *g* for 15 min. The supernatant was dried in an oven at 130°C for 2 hours. Taking two measurements per sample, Water Absorption was calculated as the increase in weight of the sediment (gel) formed after decanting the supernatant.

$$\text{WAI} = \frac{\text{(weight of sediment + centrifuge tube)} - \text{(weight of centrifuge tube)}}{\text{Sample dry weight}}$$

3.2.7.4. Water Solubility Index

The supernatant from the water absorption determination was decanted in a pre-weighed moisture dished and evaporated to constant weight in the oven. Water

Solubility Index was calculated as a percentage of soluble material using the following equation:

$$\% \text{ WSI} = \frac{(\text{weight of dish + dried supernatant}) - (\text{weight of dish})}{\text{Sample dry weight}} \times 100$$

3.3. Starch gelatinization

Sample preparation for Rapid Visco Analyzer

After extrusion, the extrudates were dried in a tray drier at 60°C for overnight to obtain dry samples having moisture content of approximately 5 %. Extrudates were then ground in a coffee grinder so that they could pass through a 80-mesh United States Standard sieve and used for the determination of pasting characteristics.

Viscosity measurements

The pasting profile was determined using a RVA (Newport Scientific, Narabeen, Australia) according to the manufacturer's instructions using the following profile: a 2 min hold at 25°C followed by a target temperature of 95°C at 7 min., holding at 95°C to 10 min and cooling back to 25°C at 15 min and holding to complete profile at 20 min. A 3-g sample (14% moisture dry basis) was mixed with 25 mL of distilled water and transferred to the aluminium sample holder can (Walker et al., 1988; Deffenbaugh & Walker, 1990).

The parameters that were obtained from RVA included:

a) Initial viscosity (IV), i.e. the viscosity obtained at 25°C at the beginning of RVA study.
b) Peak Viscosity (PV), i.e. the highest viscosity shown by the paste in the peak formed by joining the inflection points of the base line viscosity curves during the heating phase.
c) Hot-paste viscosity (HPV), i.e. the viscosity of the paste at the end of the heating phase at 95°C
d) Cold-paste viscosity (CPV), i.e. the viscosity of the paste at the end of the cooling phase, namely at 25°C.

The area under the peak occurring during the heating phase of the pasting curve exhibited by the extrudated samples, relative to that of raw beans (as 100%), represented the ungelatinized or uncooked part, which after subtraction from 100 yielded the extent of gelatinization (Newport Scientific, Narabeen, Australia).

3.4. Phytohemagglutinin assay (Objective 2)

Boniglia et al., (2003) identified lectins (phytohemagglutinins) in kidney beans as a major antinutrient factor. Phytohemagglutinins are proteins present in a variety of legume seeds including dry beans (*Phaseolus vulgaris* L.) Lectins are believed to have antinutritional properties by interfering with growth and utilization of dietary nutrients (Puztai, 1977). Active phytohemagglutinins are also believed to cause food poisoning.

For all treatments including raw dry beans (control), samples were extracted according to the method of Boniglia and others (2003). Briefly, 1-g samples of finely ground extruded beans (0.5 mm mesh size) were extracted in 20 mL of PBS (phosphate buffer solution, 10 mM, pH 7.2 containing 150 mM NaCl) by stirring overnight using a magnetic stirrer at room temperature. After centrifugation (10,000 X g, 35 min, 10 °C), the supernatant was collected and the pellets were re-extracted twice in 10 mL PBS, stirred as above for 2 h at room temperature and centrifuged as above. The clear supernatant was collected and stored at 4 °C until further analysis.

The detection of active phytohemagglutinin activity (PHA) in bean samples was performed by ELISA, according to the method of Boniglia and others (2003). Microtiter plates, coated overnight at 4 °C with 0.1 mL of porcine thyroglobulin (8 ng/μL in 50 mM carbonate-bicarbonate buffer, pH 9.8), were washed twice with PBT (phosphate buffer 10 mM, pH 7.2 containing 0.05% Tween 20) and once with PBS (phosphate buffer 10 mM pH 7.2 containing 150 mM NaCl). Remaining plastic reactive sites were blocked by incubation (1 h, 37 °C) with PBS supplemented with 0.5% bovine serum albumin (BSA). The wells were then washed as described above and loaded in triplicate with 0.1 mL sample extracts diluted 1:50 in PBS. After 1 h at 37 °C, the wells were washed, loaded with 0.1 mL rabbit anti-PHA IgG diluted 1:5000 in PBS containing 0.25 BSA (PBSB) and incubated for 1 h at 37 °C. After washing, 0.1 mL alkaline phosphatase-conjugate monoclonal anti-rabbit IgG diluted in PBS (1:10000) was added to each well and incubated for one more h at 37 °C. The wells were washed twice with PBT and once with PBS followed by 0.1 mL of P-nitrophenyl phosphate for color development. After 1 h at 37 °C, the reaction was stopped by the addition of 50 μL of 3M NaOH and the absorbance read at 405 nm (Benchmark Microplate Reader; BioRad, Hercules, Calif, U.S.A.).

3.5. Sensory evaluation of extruded bean porridge (Objective 3)

Sensory evaluation of extruded bean porridge was carried out at the National University hospital located in the southern of province of Rwanda. 75 panelists comprised mostly of adult low-income women who evaluated bean porridge and compared it with a local porridge known as *sosoma*. *Sosoma* is a blend of corn, sorghum, wheat, and soy and is fed to undernourished populations. Only panelists that could sign the consent statement were selected. The MSU Biomedical, Health Sciences Intuitional Review Board, approved the study protocol (appendix 4). The panelists were asked to read and sign a consent statement and were compensated with a free bottle of soda at the end of sensory exercise for their participation in the study. All evaluations were conducted at room temperature (24 ± 1 °C) on the same day in the hospital kitchen of the Faculty of Medicine of the National University of Rwanda.

Extruded bean porridge was prepared the same morning the sensory evaluation was carried out. Extruded bean porridge was prepared approximately in the ratio of 1:1:8(w/w) for extruded bean powder, sugar, and water respectively. On the same morning of sensory evaluation, approximately 40-g samples of extruded bean porridge were placed in 85-g clear plastic cups that were labeled with three-digit random codes (723 and 829 for sosoma and extruded bean porridge respectively) and kept at room temperature before serving to the panelists. The hospital nurses were trained to assist the panelists on how to fill out the sensory questionnaire. Samples were presented in random order and panelists were asked to rate their liking for color, texture, sweetness, flavor and overall acceptability on a 1-9 hedonic scale (9=like extremely, 8=like very much, 7=like moderately, 6=dislike slightly, 5=neither like nor dislike, 4=dislike slightly, 3=dislike moderately, 2=dislike very much, 1=dislike extremely) (Meilgaard and others 1999). Questionnaires were prepared and provided to the panelists using SIMS Sensory Evaluation Software, version 6.0 (Sensory Computer Systems, Morristown, N.Y., U.S.A.). Panelists' responses were entered manually in a computer for analysis using. A score of 5 or below was considered a limit of acceptability for all sensory attributes tested.

3.6. Calculation of energy and cost consumption by extruder (Objective 4)

The energy and cost consumption by the extruder was calculated using the following parameters:

1. Total feed rate (kg/hr)
2. Power meter reading (kW)
3. Cost of 1 kWhr

Specific Mechanical Energy (SME) (kJ/kg) was calculated by dividing averaged power reading by total feed rate. Specific Mechanical Energy (kWh/ton) was calculated by multiplying SME (kJ/kg) by 3.6. The cost of SME (kWh/ton) was calculated by multiplying the SME (kWh/ton) by the cost of 1 kWh. Energy and cost consumption by extruder was calculated for both United States and Rwanda (Table 4.4).

3.7. Statistical analysis

All data were analyzed either by Analysis of Variance (ANOVA) using JMP IN software, version 5.1 (SAS Institute, Inc., Cary, N.C., U.S.A.) or Microsoft excel (plots).

CHAPTER 4: RESULTS AND DISCUSSION

4.1. Estimation of degree of fill

Figure 4.1 shows the effect of screw speed on the degree of fill at 25% and 36% moisture. Increasing screw speed while keeping mass flow rate constant significantly (p=0.0234) decreased the degree of fill at 36% moisture content. At 25% percent moisture, increasing screw speed did not significantly (p= 0.0900) decrease the degree of fill. Because moisture content has a nominal effect on the mean residence time (Altimore and Ghossi, 1986), increasing moisture content at constant flour feed rate increased total mass flow rate which increased the degree of fill (figure 4.1).

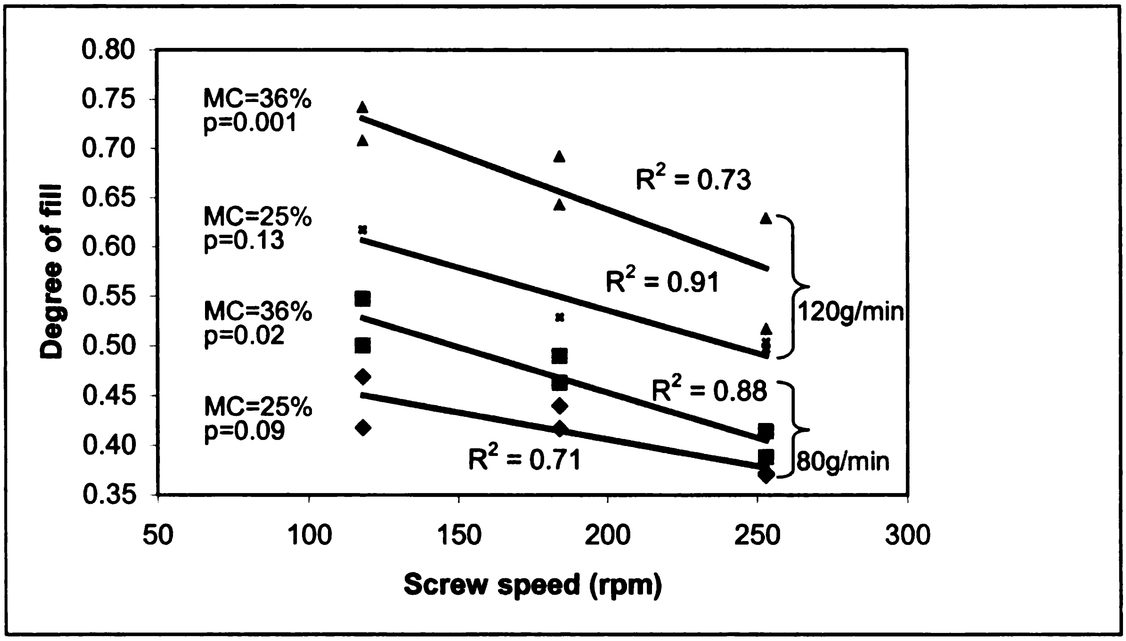


Figure 4.1 Effect of screw speed on the degree of fill

Higher fill levels result in a shorter and tighter residence time distribution (RTD) and less shear, and lower fill levels are associated with wider RTD and more shear (Suparno, 2004). Fill level approximations help explain why different processes benefit from comparative fill level percentages. For lower barrel temperature, the lines are reversed because mean residence times are reversed.

4.2. Residence Time Distribution Analysis

4.2.1. Color Concentration Calibration Curve

Figure 4.2 below shows a relationship between color reading and dye concentration. The curve was approximately linear up to a*=15 at cconcentration of approximately 20 mL dye/300g flour. At higher concentration, the curve was nonlinear.

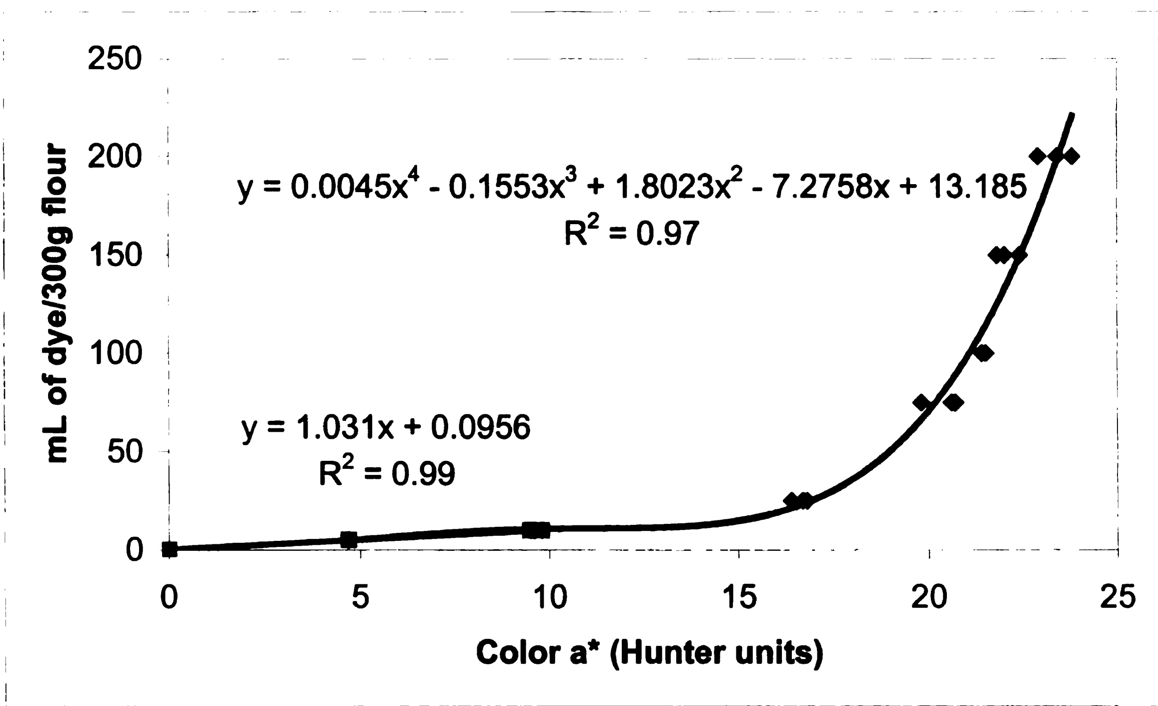


Figure 4.2. Calibration curve for color concentration versus Hunter color values (a*) for extruded light red kidney bean flour

Figure 4.2 above shows the data points dye concentration versus Hunter color values for samples extruded at 36% moisture content; flour feed rate of 120 g/min; screw speed of 253 rpm; and barrel temperature of 120 (zone 1 near die end)/105 (zone 2 near feed zone). Two trend lines were used to fit data points at lower and higher concentrations. One trend line did not pass through data points at higher concentrations. The calibration curve was used for all extrusion runs to convert all Hunter a* color to color concentration for determination of mean residence time.

Importance of residence time

Each particle experiences a different residence time. This affects gelatinization, protein denaturation, product texture, flavor, color, pathogen destruction (food safety), expansion, viscosity, water solubility index, water absorption index, inactivation of antinutritional factors. Shear history is affected most by feed rate and screw speed (Altimore and Ghoss, 1986).

Effect of Screw Speed on the residence time

Screw speed is one of the process parameters which has a strong effect on Residence Time Distribution (RTD) and Mean Residence Time (MRT). Screw speed determines the amount of time the material resides in the extruder barrel. According to figure 4.3 below, increasing screw speed decreased mean residence time. Screw speed is one of the variables determining the amount of time the material resides in the extruder. When all factors, for example, feed rate, moisture content are held constant, when screw speed is increased, the residence time is reduced. This effect has been validated by Ainsworth et al., (1997), Yeh and Jaw (1998), Ollet and et al., (1989), Gogoi and Yam (1994). Altimore and Ghossi, (1986) also reported shorter mean residence times when screw speed was increased at constant throughput. Increasing screw speed also shortens residence time distribution curve. De Ruyck (1997) also reported that increasing screw speed decreases mean residence time.

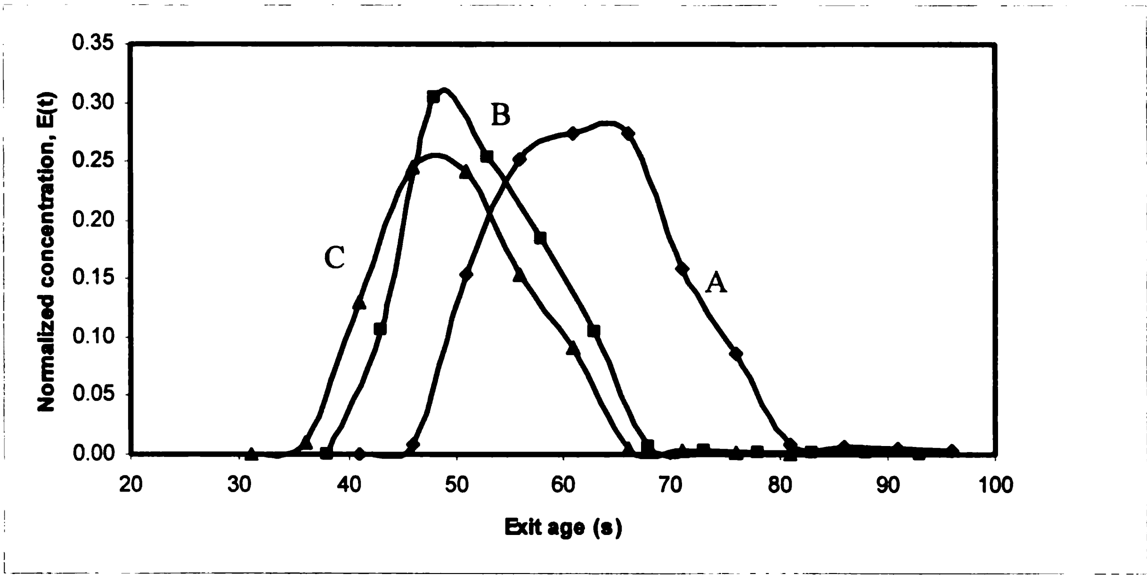


Figure 4.3 A representative of the effect of screw speed on Residence Time Distribution

*Exit age is the time measured from when the color tracer was dropped into the extruder entrance (hopper) until color appeared at die exit.

A: Screw speed = 118 rpm; Feed rate = 80 g/min; Moisture = 25 %;
Mean Residence Time = 70.6s (sample 3, Table 3.2.1)
B: Screw speed = 184 rpm; Feed rate = 80 g/min; Moisture = 25 %;
Mean Residence Time = 66.3s (sample 2, Table 3.2.1)
C: Screw speed = 253 rpm; Feed rate = 80 g/min; moisture = 25 %;
Mean Residence Time = 57.0s (sample 1, Table 3.2.1)

Effect of feed rate (throughput)

Feed rate is the input rate of the material into the extruder. It is another process variable which has a pronounced effect on residence time. Mean Residence Time and Residence Time Distribution have been reported to decrease with increase in feed rates (De Ruyck, 1997), Yeh et al., 1992. As figure 4.3 shows, the influence of throughput on the residence time is dramatic. As shown by the figure, at the lower feed rates where the extruder is less filled, there is less tendency for the extruder to provide positive conveyance. According to the present study the effect of throughput was more pronounced than that of screw speed (appendix Table A.3). Ainsworth and others (1997) also reported that increasing throughput decreased mean residence time than screw speed. When throughput is increased there is more material going through the extruder with time, leading to a decrease in the time the material will stay in the extruder, thus decreasing residence time.

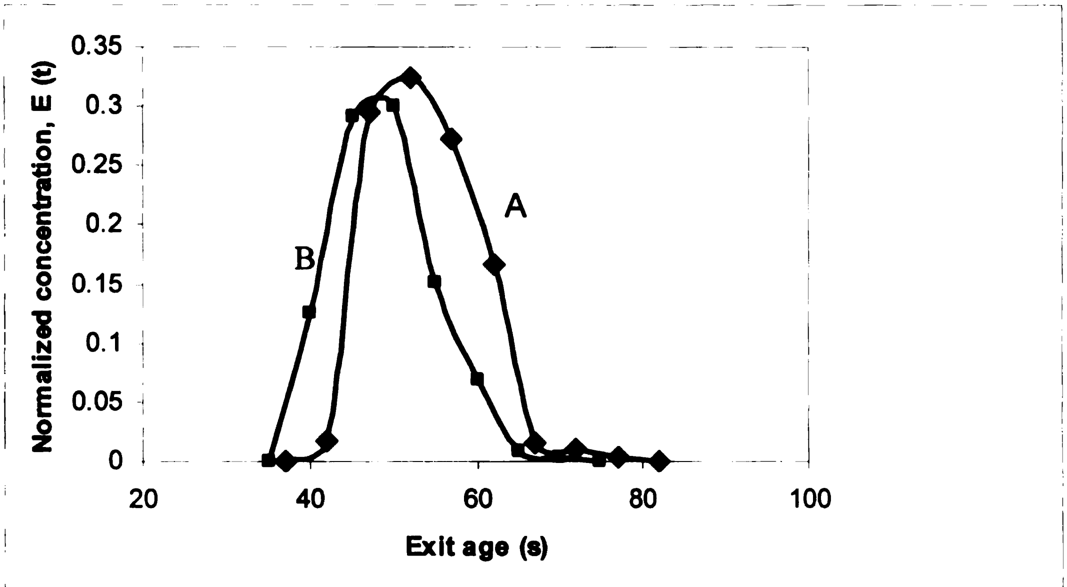


Figure 4.4. A representation of the effect of feed rate on Residence Time Distribution

A: Feed rate = 80 g/min; Screw speed = 253 rpm; Moisture = 25 %; MRT=57.0s (sample 3, Table 3.2.1)
B: Feed rate = 120 g/min; screw speed = 253 rpm; Moisture = 25%; MRT=50.4s (sample 6, Table 3.2.1)

When the feed rate is increased there will be more material going into the extruder with time, reducing mixing leading to a decrease in the time the material will stay in the extruder, thus decreasing the residence time.

Effect of Moisture content on residence time distribution

Moisture content of the feed material is another process variable that affects the residence of the dough inside the extruder. Generally, for the present study increasing moisture content slightly resulted in wider residence time distribution. Gogoi and Yam (1994), Altomare and Ghossi (1986) reported that moisture content has a nominal effect on the mean residence time. In their study, increasing moisture from 10% to 28.4% only raised the residence time from 21 to

24.5 seconds. However the effect is not as pronounced as for feed rate and screw speed.

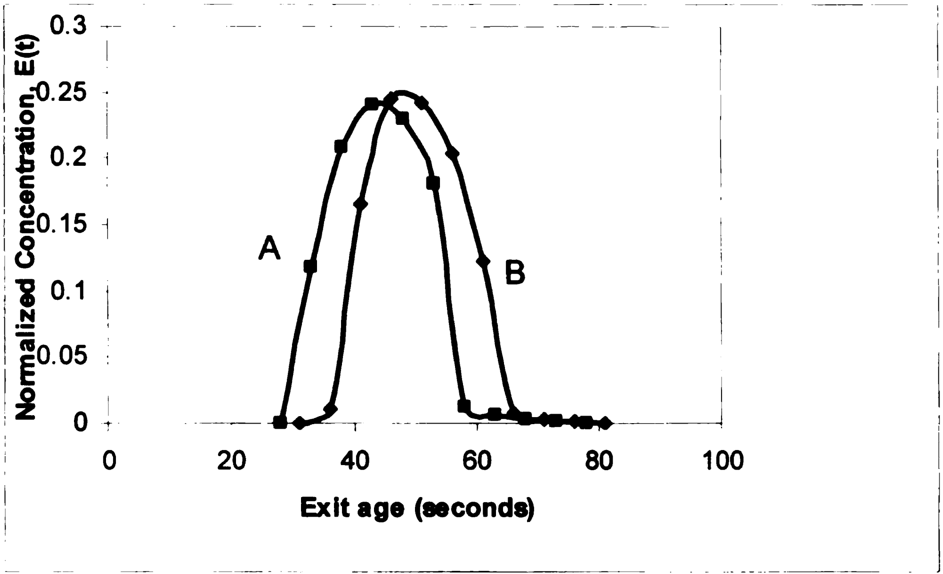


Figure 4.5. Effect of moisture content on residence time distribution at barrel temperature 120/105°C

A: Feed rate = 120 g/min; Screw speed = 253 rpm; Moisture = 36 %; MRT=44.2s (sample 12, Table 3.2.1)
B: Feed rate = 120 g/min; screw speed = 253 rpm; Moisture = 25%; MRT= 50.4s (sample 6, Table 3.2.1)

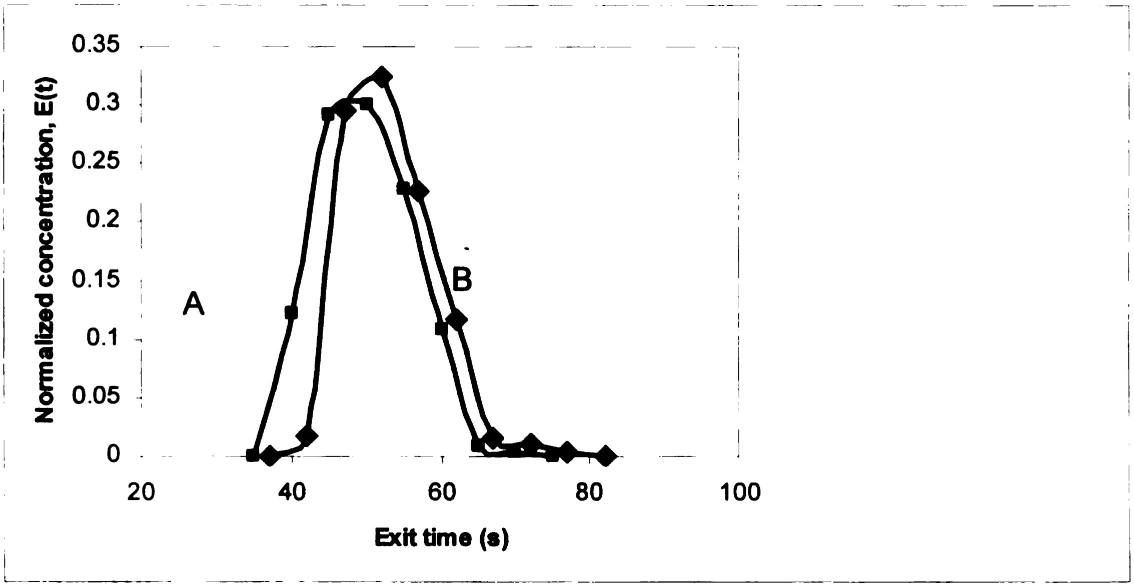


Figure 4.6. Effect of barrel temperature on residence time distribution at moisture content = 36%

A: Feed rate = 80 g/min; Screw speed = 253 rpm; Moisture = 36 %; MRT=49.8s at barrel temperature 120/105°C (sample 9, Table 3.2.1)
B: Feed rate = 80 g/min; screw speed = 253 rpm; Moisture = 36%; MRT= 53.2s at barrel temperature 130/115°C (Table 3.2.1)

4.3. Specific Mechanical Energy

Effect of screw speed on specific mechanical energy

At a constant feed rate, increasing screw speed resulted in an increase in specific mechanical energy (SME) input (figure 4.6). As a consequence, there was a simultaneous increase in the product temperature (PT) at the extruder die.

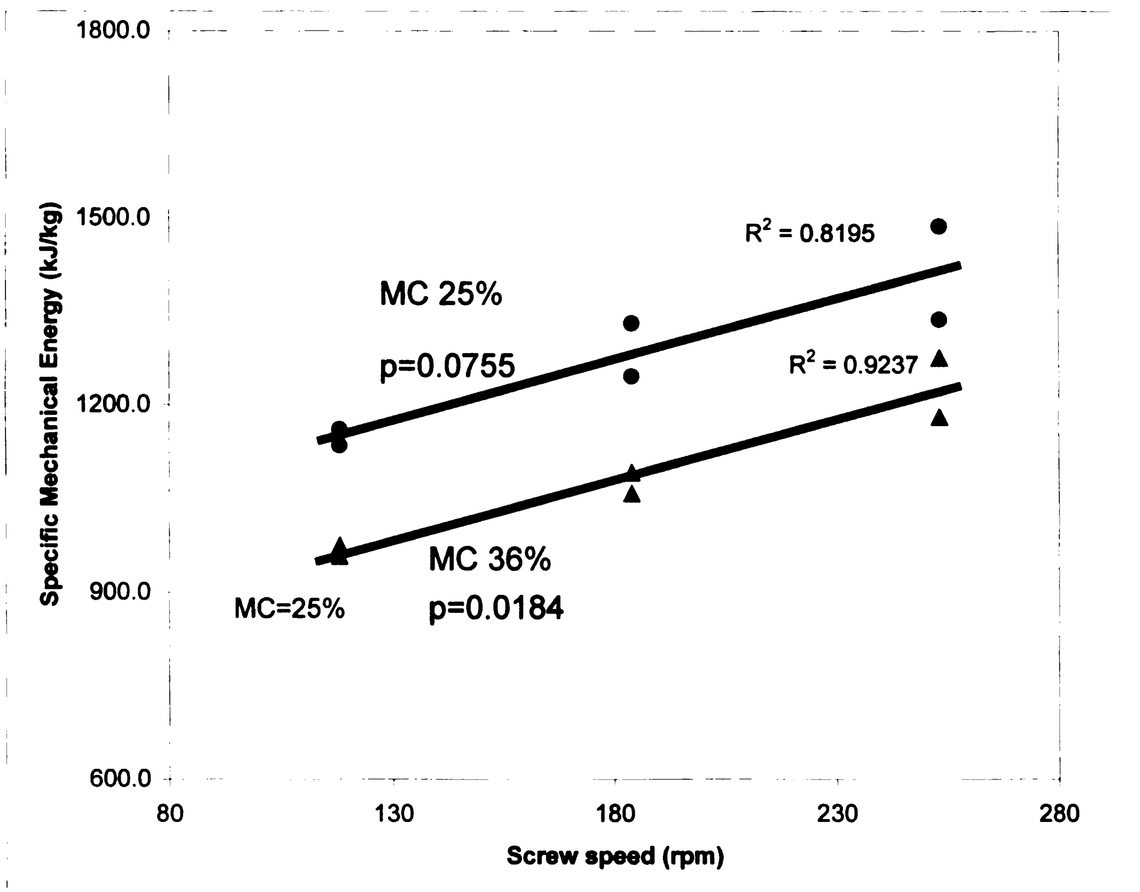


Figure 4.6. Effect of Screw speed on specific mechanical energy at constant flour feed rate = 80g/min at two moisture contents

From figure 4.6 above, it is clear that the specific mechanical energy increases with increase in screw speed and decrease in total feed rate. It can therefore be implied that the specific mechanical energy will be lowest when the mean residence time will be the lowest.

4.4. Physical characteristics of bean extrudates

4.4.1. Expansion ratio

The expansion ratio is an important characteristic of extruded products. Highly expanded products have softer texture. Expansion ratio is a measure of cross sectional area of the extrudate. Expansion takes place due to sudden exit of molten mass from the restricted die from very high pressure to atmosphere giving improved texture to the extrudate. The results of expansion ratio are shown in Table 4.1 below. For all the extrusion variables studied, only feed rate significantly (p=0.003) increased expansion ratio. This effect may be due to fully developed flow at the die that caused some expansion. Moisture content (p=0.13), screw speed (p=0.10), and product temperature (p=0.4245) did not significantly affect expansion ratio. This lack of effect was probably due to the presence of high level of protein in light red kidney beans which reduced expansion. The high levels of disulfide and sulfhydryl groups in legumes may affect the physical properties of extruded bean products. Iwe and Ngoddi (1998) reported the same results. Berrios and Pan (2001) reported that the fine-ground bean flours produced extrudates with significantly higher expansion ratio than the extrudates from medium- and coarse-ground raw material flours. Therefore, the course-ground flour used as a raw material may be one of the factors that caused low expansion indices of extruded light red kidney beans. Also, extrudates with high protein content tend to have low expansion ratio and high bulk density (Anderson, 1998). This may be the cause of toughening in high protein extrudates such as beans. Expansion ratio of dry beans (100 %) is very low. Addition of sodium carbonate to the bean flour before extrusion increases expansion ratio (Berrios and Pan, 2001).

4.4.2. Bulk density

Bulk density, expressed as g/cm^3, is also a measurement of expansion ratio of the extrudate. Edwards et al. (1994) indicated that bulk density considers sample weight and the three dimensional changes of the extrudate resulting from expansion at the die. Bulk density is inversely proportional to expansion ratio. The effect of extrusion variables on bulk density is shown in table 4.3. According to our results, there was significant difference in bulk density for product moisture content (p=0.05). Bulk density was higher for 36% moisture content. This is possible because at higher moisture there is lower expansion ratio. High moisture may have reduced pressure at the die that is believed to increase expansion. There was no significant difference in bulk density for feed rate (p=0.84) and screw speed (p=0.23). Although not significantly different (p=0.23), bulk density increased slightly with increase in screw speed (from 118 to 253 rpm). Ferdinand et al. (1990) reported lowering moisture content lowered bulk density. He also reported that bulk density decreased with increasing screw speed.

Table 4.1. Expansion ratio and bulk density under different extrusion conditions

Sample number	Barrel Temperature (°C)	Feed rate (g/min)	Moisture content (%)	Screw speed (rpm)	Bulk density (g/cm^3)	Expansion ratio
1	120/105	80	25	118	39.7±2.90	1.23±0.032
2	120/105	80	25	184	38.6±2.57	1.30±0.023
3	120/105	80	25	253	38.6±0.78	1.35±0.035
4	120/105	120	25	118	41.0±1.29	1.26±0.071
5	120/105	120	25	184	40.4±0.95	1.34±0.006
6	120/105	120	25	253	40.0±0.81	1.29±0.011
7	120/105	80	36	118	40.7±0.57	1.18±0.044
8	120/105	80	36	184	40.7±0.50	1.19±0.002
9	120/105	80	36	253	38.8±0.57	1.22±0.003
10	120/105	120	36	118	40.2±0.99	1.32±0.142
11	120/105	120	36	184	40.2±0.76	1.36±0.114
12	120/105	120	36	253	40.7±1.19	1.35±0.110
13	130/115	80	25	118	40.5±0.49	1.27±0.037
14	130/115	80	25	184	39.3±0.66	1.21±0.006
15	130/115	80	25	253	37.4±1.40	1.25±0.066
16	130/115	120	25	118	36.7±0.40	1.24±0.101
17	130/115	120	25	184	36.9±1.01	1.22±0.002
18	130/115	120	25	253	37.2±0.85	1.37±0.001
19	130/115	80	36	118	39.4±0.81	1.14±0.092
20	130/115	80	36	184	40.3±0.61	1.15±0.002
21	130/115	80	36	253	39.1±1.20	1.21±0.084
22	130/115	120	36	118	40.1±0.85	1.24±0.062
23	130/115	120	36	184	40.1±0.71	1.24±0.021
24	130/115	120	36	253	38.4±1.53	1.31±0.026

Bulk density and expansion ratio are the average of 2 replicate values±standard deviation

4.4.3. Water Absorption Index (WAI)

The effect of extrusion variables: feed rate, product temperature, screw speed, and moisture content moisture using a 7.0 mm die on Water Absorption Index and Water Solubility Index are shown in Table 4.2. Feed rate ($p=0.15$), moisture content ($p=0.78$) and screw speed ($p=0.74$) did not significantly affect water absorption index. Although there was no significant difference, water absorption index decreased with decrease in feed rate (80g/min) and increase in moisture content (36%). Colonna and Mercier, 1983 reported the same results. However, this is contrary to what Njoki & Faller (2001) observed for extruded plantain/corn/soy blend. Increasing screw speed did not have a significant difference ($p=0.74$) on water absorption index. However, water absorption index increased slightly with increase in screw speed (118 to 253 rpm). Lower water absorption index at lower screw speed may be attributed to severe degradation of starch granules as a result of long residence time. The water absorption index increased with increasing screw speed. This was probably caused structural modification of fiber. Badrie and Mellows (1991) reported changes from a more sheet-like micro-structure to a more disrupted appearance when shear was increased.

4.4.4. Water Solubility Index

The water solubility index is related to the presence of soluble molecules, which is related to dextrinisation (Colonna *et al* 1989). Table 4.2 shows the effect of barrel temperature, feed rate, screw speed, and moisture content on water solubility index. Increasing flour feed rate significantly (p=0.0001) increased water solubility index. The average water solubility indices for 80 and 120 g/min feed rate were 18.12 and 20.51 respectively. The increased water solubility index under high feed rate is probably due to fully developed flow along the die which also increases starch break down. Chang et al., 1998 reported the same findings when they studied the effect of extrusion variables on rheological properties of cornmeal. The average solubility indices for 25 and 36 % moisture contents were 21.26 and 17.36 respectively. Increasing extrusion moisture to 36 % decreased product temperature and shear. This resulted in lower solubility index. Colonna et al. (1984) reported that lower solubility indices for higher moisture and low temperature extrusion conditions. The same results were reported by Sebio and Chang (2000) when they extruded yam flour. Increasing screw speed from 118 to 253 rpm significantly increased (p=0.0001) water solubility index although residence time was reduced. Increased solubility was probably due to sufficient starch and/or fibre degradation during extrusion cooking. Hashimoto and Grossman (2003) reported the same results when they extruded cassava bran/cassava starch blend. Diosady et al. (1985) concluded that degradation of starch is exclusively due to the product of the shear stress in the active zone of the extruder barrel. Product properties depend mostly on the molecular transformations, for example, disruption of starch granules, depolymerization of amylose and amylopectin; these transformations are generated in the various parts of the extruder by pressure, shearing and residence time (Colonna et al. 1989).

Table 4.2. Effect of extrusion variables on Water Absorption and Solubility Indices

Sample number	Barrel Temperature (°C)	Bean flour (g/min)	Moisture content (%)	Screw speed	WAI	WSI
1	120/105	80	25	118	5.33±0.37	18.92±0.28
2	120/105	80	25	184	5.35±0.21	19.08±0.17
3	120/105	80	25	253	7.86±0.10	20.16±0.11
4	120/105	120	25	118	5.79±0.48	20.62±0.14
5	120/105	120	25	184	6.52±1.07	22.42±0.37
6	120/105	120	25	253	5.68±0.80	23.08±1.07
7	120/105	80	36	118	4.61±0.71	16.02±0.48
8	120/105	80	36	184	4.88±1.51	15.30±0.20
9	120/105	80	36	253	4.95±0.22	17.18±1.64
10	120/105	120	36	118	6.54±0.67	16.34±0.20
11	120/105	120	36	184	8.44±1.09	17.88±0.23
12	120/105	120	36	253	4.88±0.01	19.72±0.57
13	130/115	80	25	118	5.38±0.55	18.14±0.28
14	130/115	80	25	184	4.41±0.37	20.84±0.57
15	130/115	80	25	253	5.37±0.85	21.56±0.28
16	130/115	120	25	118	5.94±1.73	22.02±0.59
17	130/115	120	25	184	5.39±0.58	24.54±0.14
18	130/115	120	25	253	5.68±0.83	23.76±0.28
19	130/115	80	36	118	5.05±0.06	16.56±0.61
20	130/115	80	36	184	5.06±0.22	17.86±0.31
21	130/115	80	36	253	6.19±1.56	16.10±0.20
22	130/115	120	36	118	4.97±0.15	16.08±0.60
23	130/115	120	36	184	6.11±0.46	18.92±0.74
24	130/115	120	36	253	5.68±0.54	20.90±0.20

Water absorption and solubility indices are average of 2 replicate values±standard deviation

4.5. Starch gelatinization

Gelatinization is an important physico-chemical change associated with the cooking of starchy materials. Pasting properties of raw beans and extruded samples are presented in figure 4.7, 4.8, and 4.9. The initial viscosity of extruded samples was higher than that for raw beans. This was expected because extruded samples are already gelatinized, which enables them to hydrate faster and to a greater extent than raw sample. The viscosity of extrudate pastes decreased with increasing temperature, in contrast to that of raw bean sample. This behavior is not unexpected. Heating slurries of completely gelatinized materials is known to cause a decrease in viscosity leading to the thinning of starch slurry (Schwiezer et al., 1986).

Ungelatinized starch cannot absorb water at room temperature, and its viscosity as measured by the Rapid Visco-Analyzer (RVA) is nearly zero. Gelatinized starch, however, absorbs water rapidly to form a paste at room temperature without further heating. The viscosity of the paste depends to a large extent on the degree of gelatinization of the starch granules and the extent of their molecular breakdown (El-Dash et al. 1983). The gelatinized starch is characterized by lack of gelatinization peak, by a continuous decline in viscosity for temperatures between 50 and 95°C, and by progressive increase in viscosity during the cooling cycle.

The rise in viscosity at the end of cooling phase, that is, the difference between the cold paste viscosity (CPV) and hot paste viscosity (HPV), gives an indication of gelling properties due to retrogradation of starch molecules, especially amylose and amylopectin. The final viscosity of extrudates was lower than that for raw bean sample. This indicates that starch in extruded beans had undergone thermal and mechanical degradation to an extent that was not conducive to retrogradation and the slurry remained thin. Cia et al., (1995) also reported the same trend for wheat extrudates.

Effect of screw speed on starch gelatinization

The effect of screw speed on pasting properties is illustrated in figure 4.7. The cold-paste viscosity, that is, the viscosity of the paste at the end of cooling phase of the extruded at 184 r.p.m. was higher than the viscosity of the sample extruded at 253 r.p.m. The explanation for this phenomenon is that under high screw speed there was more shear to break down starch granules that resulted in sufficient gelatinization. The same results were reported by Guha et al. (1998) when studying the effect of barrel temperature and screw speed on rapid viscoanalyzer pasting behavior of rice extrudate. This demonstrates that the proportion of partially cooked starch was slightly higher in samples extruded under low shear. Shear is therefore a significant contributor to starch gelatinization.

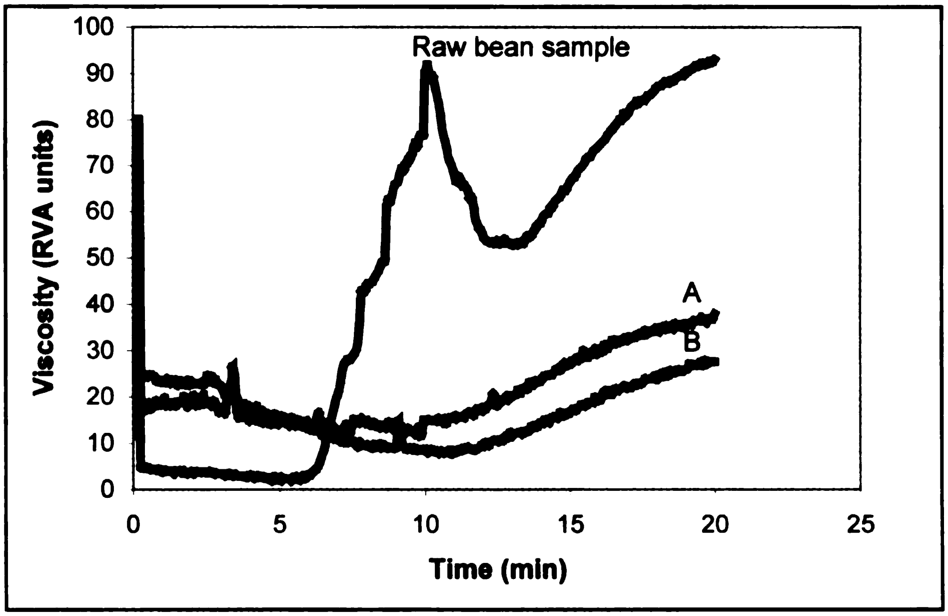


Figure 4.7. A representative set of curves showing the effect of screw speed on starch gelatinization of raw and extruded light red kidney beans.

Temperature was 25° from 0 –7 min; 95° from 8 –10 min; and
25° from 11 –15 min

A: Screw Speed = 253 rpm; Feed rate = 80 g/min; Moisture Content = 25%
B: Screw Speed = 184 rpm; Feed rate = 80 g/min; Moisture Content = 25%

Effect of feed rate on starch gelatinization

The final viscosity of the sample extruded at a feed rate of 120 g/min was lower (more gelatinized) than the sample extruded at 80 g/min (figure 4.8). There is a possibility that increasing feed rate increased pressure at the die which, resulted in mechanical and thermal degradation of starch crystalline structure.

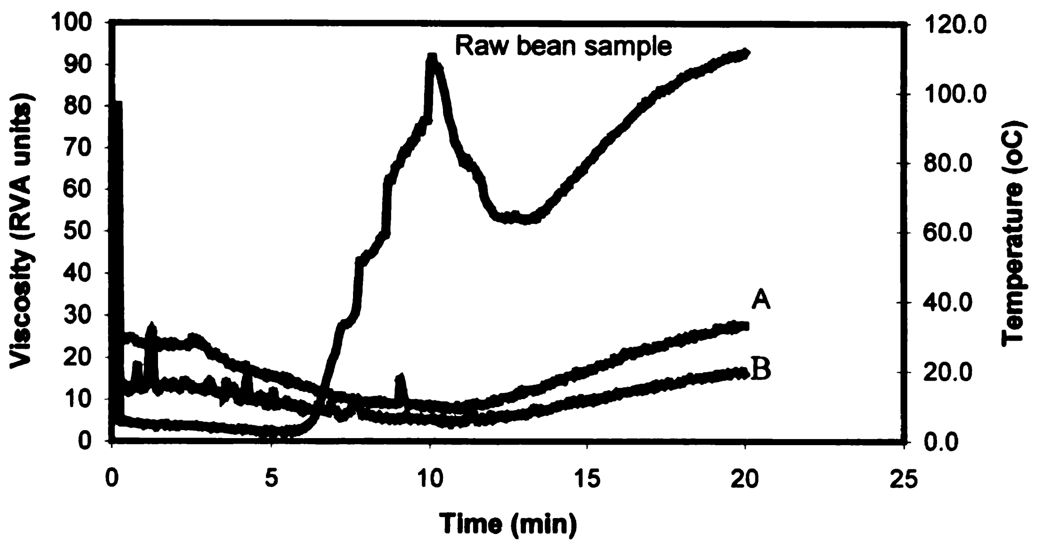


Figure 4.8. A representative set of curves showing effect of feed rate on gelatinization in extruded and raw light red kidney beans.

Temperature was 25° from 0 – 7 min; 95° from 8 – 10 min; and 25° from 11 – 15 min

A: Screw Speed = 253 rpm; Feed rate = 80 g/min; Moisture Content = 25%
B: Screw Speed = 253 rpm; Feed rate = 120 g/min; Moisture Content = 25%

Effect of moisture content

The final paste viscosity was higher for samples extruded at higher feed moisture (figure 4.9). The final paste viscosity is a measure of starch retrogradation, which in extruded products, depends on the modifications that occur in the structure of granules and molecules. The sample extruded at 25% moisture content was characterized by a low degree of retrogradation, while the sample extruded at 36% moisture content resulted in high degree of gelatinization. It is possible that increasing feed moisture to 36% percent reduced product temperature that to some extent reduced starch gelatinization.

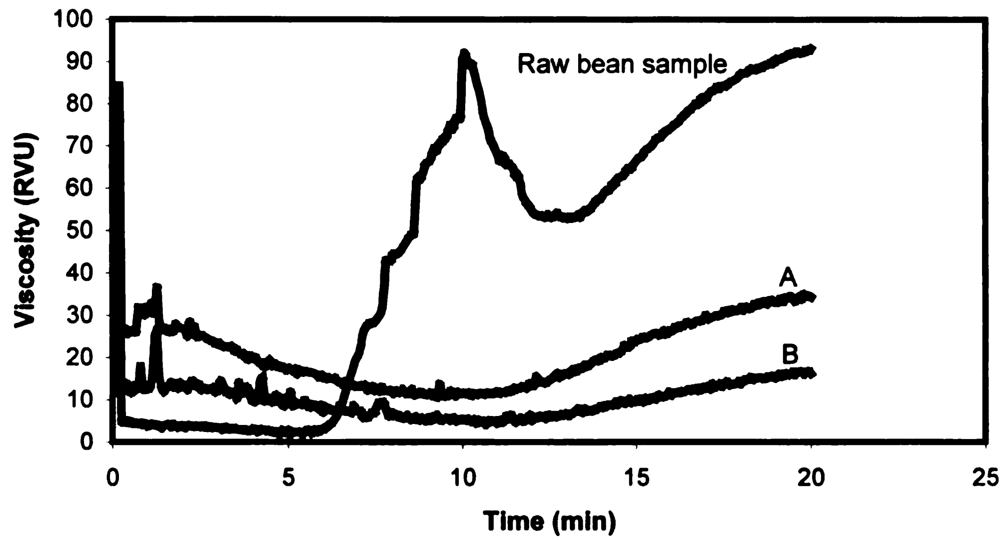


Figure 4.9. A representative set of curves showing effect of moisture content on starch gelatinization in extruded and raw light red kidney beans.

Temperature was 25° from 0 – 7 min; 95° from 8 – 10 min; and
25° from 11 – 15 min

A: Screw Speed = 253 rpm; Feed rate = 80 g/min; Moisture Content = 25%
B: Screw Speed = 253 rpm; Feed rate = 120 g/min; Moisture Content = 25%

4.6. Sensory evaluation of extruded bean porridge

Extruded bean porridge that was used in this study was prepared by extruding beans at 36% moisture content wet basis. The flour extruded at low moisture content formed lumps in the porridge making it look unattractive. This may be caused by severe degradation of starch extruded under high shear. The idea of carrying out sensory evaluation came after preliminary evaluation by people including Rwandan natives at Michigan State University, who evaluated extruded bean porridge as delicious. A group of 70 trained panelists comprised mostly of adult low income women at the National University of Rwanda, evaluated extruded bean porridge and compared it with a local common porridge known as *Sosoma*. Sosoma, considered to be a highly nutritious porridge by Rwandans, is a blend of corn, sorghum, wheat, and soy.

Panelists liked extruded bean porridge. Frequency distribution of sensory score for sosoma and extruded bean porridge for color, texture, flavor and overall acceptability are shown in figure 4.10. A copy of the sensory questionnaire is presented in appendix (Table A.1 and A.2 in English and Kinyarwanda respectively).

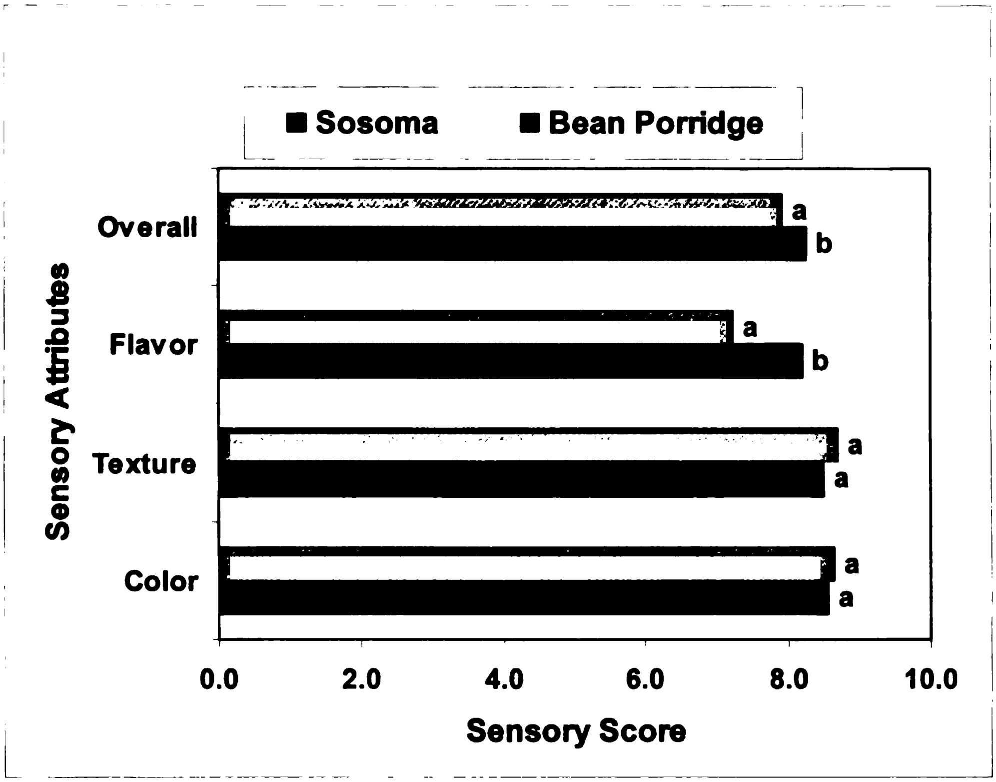


Figure 4.10 Sensory evaluation of sosoma and extruded bean porridges. Lower numerical values represent higher degree of acceptance Means with different letters are significantly different ($p \leq 0.05$)

There was no significant difference ($p \leq 0.05$) for color and texture. However, some panelists liked sosoma flavor more than extruded bean porridge. In general, panelists liked both porridges because all samples evaluated scored lower than 5 (the lower the sensory score the higher the degree of acceptance) for the sensory attributes tested. A score of 5 corresponds to neither like nor dislike. In other words, a score above 5 means the panelists did not like product while any score below 5 means the panelists like the product. Since this is completely a new product and 100 % beans, the sensory results from this study show that extruded bean porridge is a promising product.

4.7. Lectins as active phytohemagglutinins (PHA) activity

The PHA activity in dry beans was 0.55 ng/ µL. There was a significant reduction between control (raw dry beans) and extrudated samples. Lectin activity in terms of phytohemagglutinating activity (PHA) in light red kidney beans was effectively reduced by all extrusion processing conditions used in this study (see Table 4.3 below). There was a significant difference ($p=0.0031$) between control (raw dry beans) and extrudated samples. Extrusion conditions reduced phytohemmaglutinin activity in all extruded samples by over 90%. This shows that extrusion temperature was high enough to inactivate PHA activity. However, there was no significant difference in phytohemagglutinin retention for feed rate ($p=0.6873$), moisture ($p=0.3910$) and screw speed ($p=0.9753$). The explanation for this phenomenon is that lectins in extruded samples were inactivated at a temperature lower than the product temperature at the die. Our result confirm with Coffey and others (1992) who reported complete inactivation of lectins at 93°C (wet heat) for 2 hr. Myer et al. (1981) and Myer and Froseth (1983) reported 90 % reduction of lectins in red kidney bean and soybean mixes extruded at barrel temperatures of 140°C.

Table 4.3. Percent reduction of lectins in light red kidney extruded at different conditions

Run	Barrel Temperature (°C): Zone 1 (nearest die)/Zone 2	Product temperature at die (°C)	Bean flour (g/min)	Screw Speed (rpm)	Moisture content (%), wet basis	PHA retention (ng/µL)
Raw beans	N/A	N/A	N/A	N/A	N/A	0.550±0.094
1	120/105	123.0	80	118	25	0.040±0.017
2	120/105	127.3	80	184	25	0.054±0.003
3	120/105	130.0	80	253	25	0.052±0.005
4	120/105	124.0	120	118	25	0.055±0.006
5	120/105	129.3	120	184	25	0.055±0.003
6	120/105	128.3	120	253	25	0.042±0.004
7	120/105	119.3	80	118	36	0.044±0.004
8	120/105	118.0	80	184	36	0.051±0.004
9	120/105	117.3	80	253	36	0.047±0.004
10	120/105	126.0	120	118	36	0.041±0.003
11	120/105	129.4	120	184	36	0.042±0.001
12	120/105	124.0	120	253	36	0.051±0.004
13	130/115	126.0	80	118	25	0.052±0.002
14	130/115	123.2	80	184	25	0.044±0.003
15	130/115	135.1	80	253	25	0.047±0.004
16	130/115	137.2	120	118	25	0.054±0.003
17	130/115	135.5	120	184	25	0.049±0.003
18	130/115	127.2	120	253	25	0.053±0.014
19	130/115	123.3	80	118	36	0.052±0.003
20	130/115	124.8	80	184	36	0.037±0.006
21	130/115	126.6	80	253	36	0.030±0.009
22	130/115	127.8	120	118	36	0.037±0.013
23	130/115	127.0	120	184	36	0.038±0.006
24	130/115	126.1	120	253	36	0.047±0.005

PHA retention is a mean of triplicate values±standard deviation

4.8. Calculation of energy requirement by the extruder

Efficiency has always been a major concern for engineers. Extrusion cooking is an energy efficient process because a substantial amount of the mechanical energy from the extruder motor is dissipated during the viscous flow within the channels of the extruder screws (Harper, 1980). Table 4.4 shows the total energy and cost (US dollars) that was used for all extrusion runs.

Table 4.4. Energy and cost consumption for the extruder

Sample Number	Total feed rate (kg/hr)	Screw speed	Power(kW)	SME (kJ/kg)	SME (kWh/ton)	Cost*/ton in US dollars	Cost**/ton in Rwanda
1	5.534	118	1.83	1193.1	4294.7	386.52	1073.66
2	5.534	184	2.04	1329.9	4787.5	430.87	1196.87
3	5.534	253	2.43	1584.1	5702.7	513.25	1425.68
4	7.934	118	1.74	754.2	2715.2	244.37	678.80
5	7.934	184	2.05	888.6	3199.0	287.91	799.74
6	7.934	253	2.53	1096.7	3948.0	355.32	987.00
7	5.905	118	1.64	912.1	3283.6	295.53	820.91
8	5.905	184	1.98	1101.2	3964.4	356.80	991.10
9	5.905	253	2.39	1329.3	4785.3	430.68	1196.33
10	8.305	118	1.57	580.8	2091.0	188.19	522.75
11	8.305	184	2.30	850.9	3063.3	275.69	765.82
12	8.305	253	2.53	936.0	3369.6	303.26	842.40
13	5.534	118	1.72	1121.3	4036.5	363.29	1009.11
14	5.534	184	2.41	1571.1	5655.8	509.02	1413.95
15	5.534	253	2.72	1773.1	6383.3	574.50	1595.83
16	7.934	118	1.86	806.2	2902.5	261.22	725.62
17	7.934	184	2.48	1075.0	3870.0	348.30	967.49
18	7.934	253	2.78	1205.0	4338.1	390.43	1084.53
19	5.905	118	1.76	978.9	3523.9	317.15	880.98
20	5.905	184	2.23	1240.3	4465.0	401.85	1116.24
21	5.905	253	2.59	1440.5	5185.8	466.72	1296.44
22	8.305	118	1.82	673.3	2424.0	218.16	605.99
23	8.305	184	2.12	784.3	2823.5	254.12	705.88
24	8.305	253	2.67	987.8	3556.0	320.04	889.01

*based on $0.09/kWh
**based on $0.25/kWh

The most important extrusion variable that affected the power used by the extruder was screw speed. Increasing screw speed increased energy requirement from the motor. As an example of estimating energy requirements, the lowest-cost extruded product was at 118 rpm; 36% moisture content; 8.3

kg/hr total feed rate and the cost per ton was approximately $188 in the United States or $522 in Rwanda (sample no.10 Table 4.4).

Figures 11 below shows percent of operating expenses (electricity, raw beans, labor, and packaging) required to produce 1 kg of extruded bean flour in Rwanda and United States.

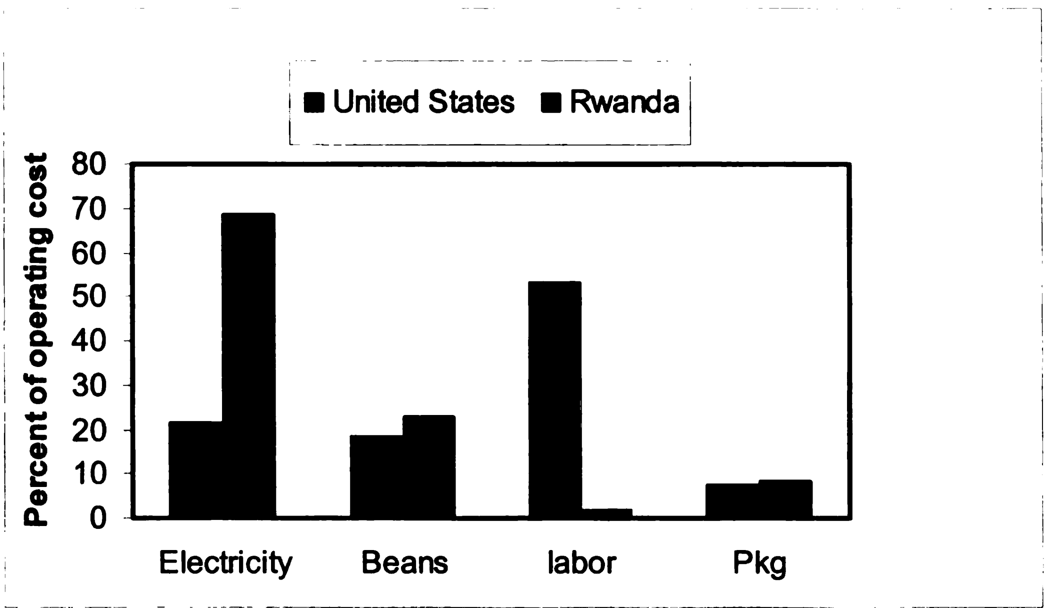


Figure 11. Percent of total operating expenses to produce 1 kg of extruded bean flour in United States and Rwanda

The total operating costs to produce 1 kg of extruded bean flour were estimated to be $1.37 in the United States and $1.20 in Rwanda. The most expensive operating cost is labor and electricity for the United States and Rwanda respectively.

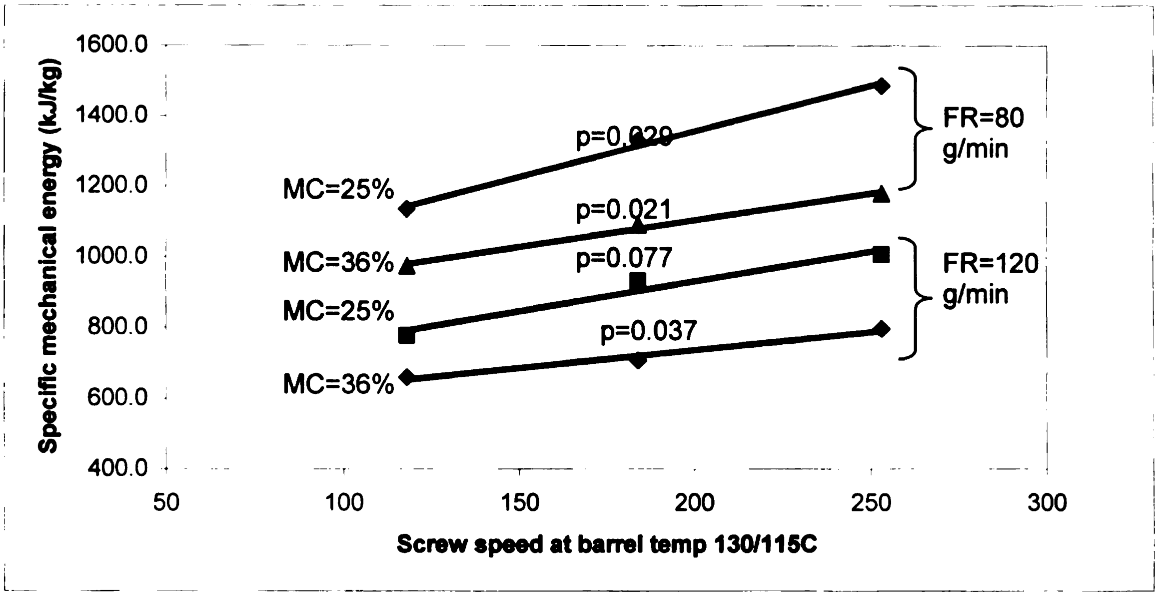


Figure 4.12. Effect of screw speed on SME at different moisture contents and feed rates at barrel temperature 130/115°C

Cost of charcoal and firewood in Rwanda

Charcoal and firewood are the main source of energy for cooking dry beans and other food stuff in Rwanda. A bag of charcoal costs FRW 5,000 (USD 9.00) and is not available all the time. This bag of charcoal can last for 10 days if you are cooking 2 kg of beans, an amount that feeds a typical Rwandan family per day. Therefore, to cook 20 kg of dry beans, Rwandans spend $9.00. For 1 ton (1000 kg) Rwandans would pay around $450.00. Using charcoal is more expensive (table 4.5) compared to using a low-cost extruder (Table 4.5, $ 197-$482/ton), and there are several advantages linked to extrusion processing. Extrusion cooking is a High-Temperature-Short-Time so one does not need to spend hours on a simmering pot of beans. This reduces the amount of smoke produced by cooking fires which are detrimental to human health and can also cause global warming problems. Extruded beans are shelf-stable and are ready-to-eat. This prevents loss of beans by bean weevils during storage. Extrusion technology can be used to make novel extruded bean-based products. Using extruders in Rwanda may reduce the amount of trees cut for firewood and charcoal making. This in turn would reduce soil erosion and increase agricultural yields. Reduction in tree cutting would also protect natural habitats.

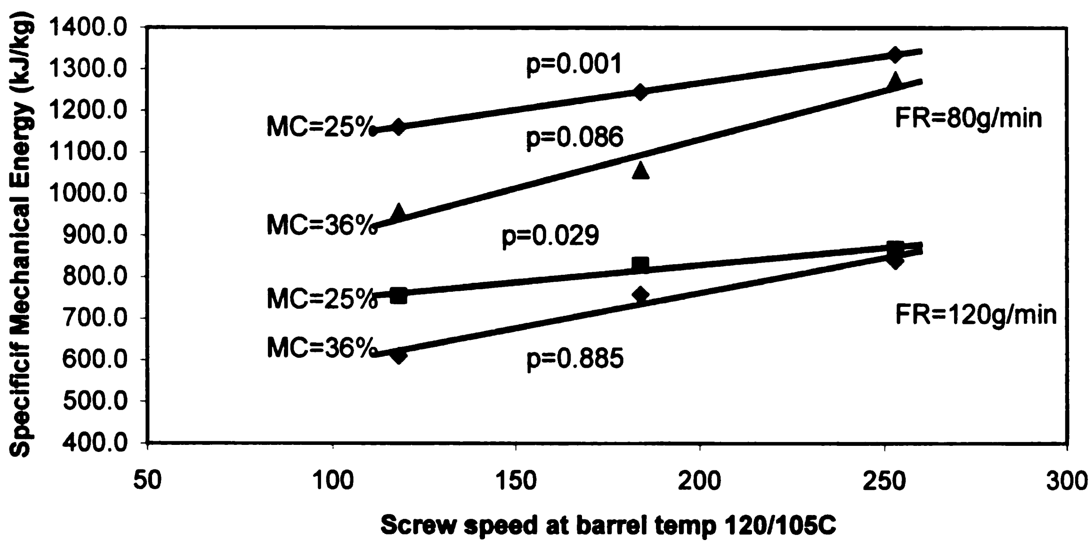


Figure 4.13. Effect of screw speed on SME at different moisture contents and feed rates at barrel temperature 120/105°C

Increasing barrel temperature from 120/105°C to 130/115°C did not have a significant effect ($p=0.1496$) on specific mechanical energy (figures 4.11 and 4.12). The extrusion parameters screw speed ($p=0.0001$); feed rate ($p=0.0001$); and moisture content ($p=0.0001$) significantly affected specific mechanical energy. Increasing screw speed increased power dissipated by the extruder motor that increased specific mechanical energy. Increasing flour feed rate and moisture content increased total mass flow rate that decreased specific mechanical energy.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

In developed countries, extrusion processing has become on of the important new technologies that is assuming an increasing role in the food industry in an effort to provide an unprecedented array of novel products to satisfy consumer preferences, especially in the ready-to-eat cereals. Little work on extrusion has been done on dry beans. Much work on extrusion processing has been accomplished using expensive extrusion equipment with high production capacity. This type of extrusion equipment is not suited to the context of developing countries. Therefore, the use of low-cost extrusion would be of great potential interest for countries with low income.

In the present study physical, chemical and sensory characteristics of extruded light red kidney beans were investigated. Raw ground bean flour was extruded at 120 and 130°C barrel temperature; 25 and 36% moisture content wet basis; screw speeds of 118, 184 and 253 r.p.m; and flour feed rate of 80 and 120 g/min.

Degree of fill increased with increase in mass flow rate and decreased with increase in screw speed. This was expected because higher fill levels result in a tighter residence time distribution (RTD) and less shear, and lower fill levels are associated with wider RTD and more shear.

Feed rate is the one of the extrusion variables that had a pronounced effect on residence time most. Mean residence time and residence time distribution decreased with increase in feed rate.

In general extrusion variables did not significantly affect expansion ratio of extruded light red kidney beans. Low expansion ratio may be attributed by the presence of high protein in dry beans.

Flour feed rate, screw speed and moisture content did not significantly affect water absorption index (WAI). However, percent water solubility index was affected only by feed rate, and moisture content.

According to Rapid Visco Analyzer pasting curves, starch was completely gelatinatized under all conditions studied. However, more gelatinatization was observed in samples extruded under low screw speed and moisture content.

There was significant reduction of phyohemagglutinins (lectins) in extruded beans compared to raw beans.

Sensory evaluation results show that extruded bean porridge is promising. Rwandans who evaluated the product liked it very much compared to sosoma, a wheat-corn-sorghum-soy-based porridge.

The cost of energy for running an extruder appeared to be low under increased mass flow rate and screw speed. Cooking dry beans using an extruder is up to 43% less expensive than using charcoal and firewood, and there are many advantages associated with extrusion technology. These advantages may include reduced environmental degradation.

5.1. Conclusions

1. The results from our experiments indicate that the low-cost Chinese extruder resulted in total starch gelatinization, which is required if the flour is to be used as instant flour;

2. Extrusion conditions inactivated phytohemagglutinins in light red kidney beans by over 90%;

3. The cost of using extruder to cook dry beans was estimated to be approximately 43% lower than using charcoal;

4. Extrusion cooking technology may result in products with extend shelf-life because of the reduced moisture (approx. 5%) compared to raw beans (approx. 14%) stored in open conditions;

5. Using extrusion cooking technology in Rwanda may prevent environmental degradation caused by deforestation and erosion.

5.2. Recommendations for future research

1. The present study is characterized by less expanded products. Future research should focus on running extrusion experiments on an extruder with bigger motor using smaller dies, for example, less than 4mm under low moisture (<25% wet basis);

2. Conduct bean extrusion runs with other types of foods, for example, corn, tapioca, wheat, oats. This may improve the texture and overall acceptance of extruded bean based products;

3. "Beany" flavor is one of the factors that limit consumption of dry beans. Extrusion is believed to create new flavor in extruded beans. Future research should investigate the effect of extrusion variables on the reduction of "beany" flavor;

4. Dry bean is of the legumes loaded with antioxidants. Further research studies should investigate the effect of extrusion cooking variables on phytochemical (antioxidant) bioavailability and stability in dry beans;

5. Investigate the effect of extrusion on beans with dried fruits and vegetables to make vegetable snack;

6. Conduct sensory evaluation studies of extruded bean porridge for Americans;

7. Our results show that extrusion cooking inactivated phytohemmaglutinin activity was inactivated by at least 90%. Studies should be conducted by normalizing extruded beans by canned beans to find out if the remaining percentage is a residual or not.

APPENDICES

Appendix 1. Water pump calibration

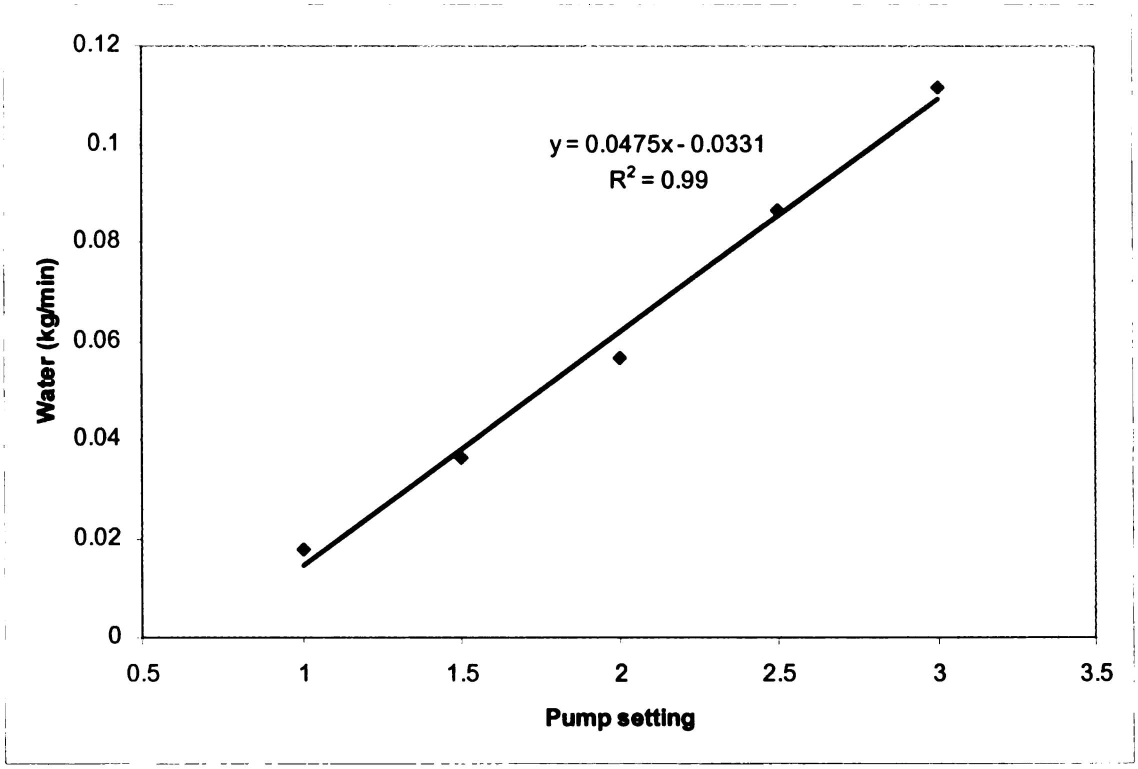


Figure A.1. Standard curve for water pump used in all extrusion runs

Appendix 2. Screw speed calibration curve

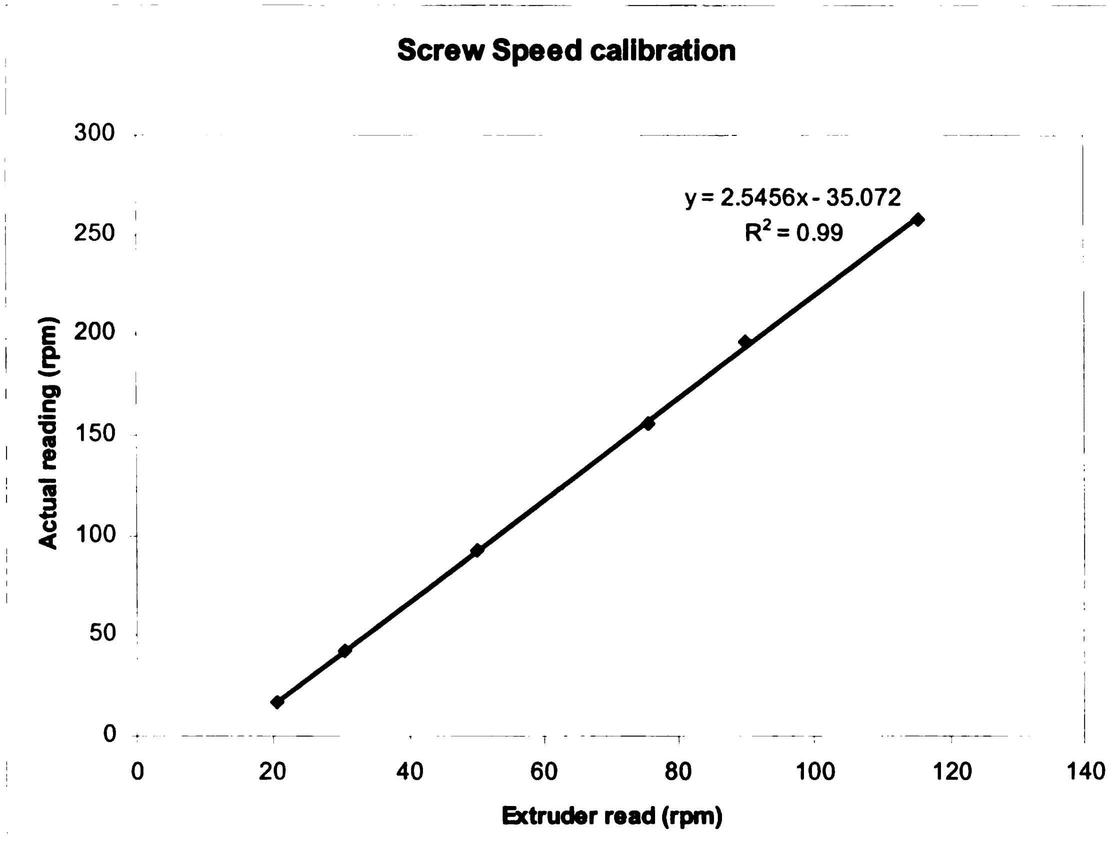


Figure A.2. Standard curve for screw speeds used in all extrusion runs

Appendix 3. Extruder feeder calibration

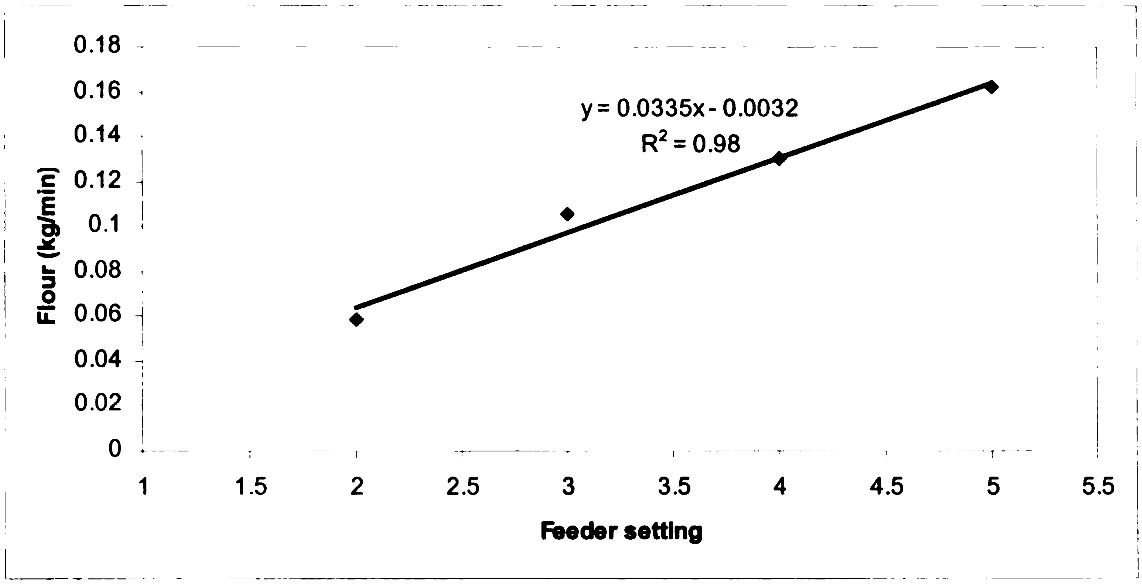


Figure A.3. Standard curve for extruder feeder calibration

Appendix 4. Consent form for extruded bean porridge

<u>Consent Form-Consumer Panel:</u> Evaluation of extruded bean products (porridge)

Dear Participant:

Several Michigan State University researchers are investigating consumer perceptions of bean porridge made from extruded dried beans. We would like you to take about 15 minutes (including the time you spend reading this letter) to help us evaluate 2 samples of porridge. We are asking for volunteers, over the age of 18, taste these samples. *If you have a known food allergy* dried beans and sugar, *please do not volunteer for this study.*

If you meet the above requirements, we would like you to look at and taste the bean products. You will be give 2 samples to look at, taste and answer questions related to the product quality. If you agree to taste these and provide your evaluation based on the survey questionnaire, please sign the consent form below. You will be given a bottle of soda and/or food treats that are worth less than $5 for your evaluation and completion of the survey.

If you believe there is a potential of an **allergic reaction upon sniffing and tasting**, notify the on-site sensory evaluation coordinator and/or principle investigator immediately. You will be released from participating in this study. Please note if you are injured as a result of your participation in this research project, Michigan State University will assist you in obtaining emergency care, if necessary, for your research related injuries. If you have insurance for medical care, your insurance carrier will be billed in the ordinary manner. As with any medical insurance, any costs that are not covered or in excess of whatever are paid by your insurance, including deductibles, will be your responsibility. Financial compensation for lost wages; disability, pain or discomfort is not available. This does not mean that you are giving up any legal rights you may have. You may contact George Nyombaire with any questions (08432228).

Your response is confidential and we will protect your confidentiality to the full extent of the law. We have no way to connect you, as an individual, to this completed survey form. You are free to not answer any question you choose, but please try to answer every question. We are not able to use incomplete responses nor are we able to provide the incentive for incomplete responses.

If you have any questions during your reading this consent form, or during or after your participation, please do not hesitate to contact the on-site sensory evaluation leader and/or the principle investigator. Feel free to contact George Nyombaire, the principle investigator, via phone at 08432228 or <u>nyombair@msu.edu</u> for any inquiry you might have due to your participation in our study.

In case you have questions or concerns about your role and rights as a research participant, please feel free to contact Dr. Peter Vasilenko, Ph.D., Director of Human Research Protections, (517)355-2180, fax (517)432-4503, e-mail irb@msu.edu, mail 202 Olds Hall, Michigan State University, East Lansing, MI 48824-1047.

PLEASE NOTE UPON YOUR SIGNING THIS CONSENT FORM, YOU VOLUNTARILY AGREE TO PARTICIPATE IN OUR STUDY. YOUR SIGNATURE INDICATES YOU HAVE READ THE INFORMATION PROVIDED ABOVE AND THAT YOU HAVE HAD AN ADEQUATE OPPORTUNITY TO DISCUSS THIS STUDY WITH THE PRINCIPLE INVESTIGATOR AND HAVE HAD ALL YOUR QUESTIONS ANSWERED TO YOUR SATISFACTION. YOU WILL BE GIVEN A COPY OF THIS CONSENT FORM WITH YOUR SIGNATURE FOR YOUR RECORDS UPON YOUR REQUEST.

SIGNED ______________________________________ DATE____________

Appendix 5. Formula for calculating moisture for extrusion runs

$$MC = \frac{\dot{m}_{flour} MC_{flour} + \dot{m}_{water}}{\dot{m}_{flour} + \dot{m}_{water}}$$

Where MC = Moisture Content wet basis, decimal

$\dot{m}_{flour}$ = Mass Flow Rate of flour (g/min)

MC_{flour} = Moisture Content of Flour, wet basis, decimal

$\dot{m}_{water}$ = Mass Flow Rate of water (g/min)

Appendix 6. Flour moisture determination

Bean flour moisture was determined by drying 2 g of bean flour in a convection oven at 135oC for 2 hours. Percent moisture was determined as loss of moisture/weight o wet sample multiplied by 100.

Appendix 7: Sensory evaluation questionnaire for extruded bean porridge (Kinyarwanda)

IGERAGEZWA KUBIKOMA BYUBWOKO BUBIRI

Soma kuri buri gikoma hanyuma usubize ibibazo bikurikira (hitamo igisubizo kikubereye).

Nimero y'igikoma # ➔	723	829
A. Ukuntu ukunze ibara ryigikoma? 9—Ndarikunze birenze 8—Ndarikunze cyane 7—Ndarikunze bigereranije 6—Ndarikunze buhoro 5—Sindikunze kandi sindyanze 4—Ndaryanze buhoro 3—Ndaryanze bigeraranije 2—Ndaryanze cyane 1—Ndaryanze birenze	9 8 7 6 5 4 3 2 1 *Hari ikindi wumva wavuga*	9 8 7 6 5 4 3 2 1 *Hari ikindi wumva wavuga* ....
B. Ukuntu ukunze igikoma mukanwa? 9—Ndagikunze birenze 8—Ndagikunze cyane 7—Ndagikunze bigereranije 6—Ndagikunze buhoro 5—Sinkikunze kandi sinkyanze 4—Ndacyanze buhoro 3—Ndacyanze bigereranije 2—Ndacyanze cyane 1—Ndacyanze birenze urugero	9 8 7 6 5 4 3 2 1 *Hari ikindi wumva wavuga*	9 8 7 6 5 4 3 2 1 *Hari ikindi wumva wavuga* ....
C. Agahumuro? 9—Ndagakunze birenze 8—Ndagakunze cyane 7—Ndagakunze bigereranije 6—Ndagakunze buhoro 5—Sinkakunze kandi sinkanze 4—Ndakanze buhoro 3—Ndakanze bigereranije 2—Ndakanze cyane 1—Ndakanze birenze urugero	9 8 7 6 5 4 3 2 1 *Hari ikindi wumva wavuga*	9 8 7 6 5 4 3 2 1 *Hari ikindi wumva wavuga* ....

D. Ukuntu ukunze igikoma muri rusange? 9—Ndagikunze birenze 8—Ndagikunze cyane 7—Ndagikunze bigeraranije 6—Ndagikunze buhoro 5—Sinkikunze kandi sinkyanze 4—Ndacyanze buhoro 3—Ndacyanze bigeraranije 2—Ndacyanze cyane 1—Ndacyanze birenze urugero	**9** **8** **7** **6** **5** **4** **3** **2** **1** ***Hari ikindi wumva wavuga***	**9** **8** **7** **6** **5** **4** **3** **2** **1** ***Hari ikindi wumva wavuga*** ....

Appendix 8: Sensory evaluation questionnaire for bean porridge (English)

Please evaluate the bean porridge samples and answer the following questions (circle the appropriate response).

Sample # ➔	723	829
A. How do you like the texture ? 9--Like Extremely 8--Like Very Much 7--Like Moderately 6--Like Slightly 5--Neither Like nor Dislike 4--Dislike Slightly 3--Dislike Moderately 2--Dislike Very Much 1--Dislike Extremely	9 8 7 6 5 4 3 2 1 *Comments*..............	9 8 7 6 5 4 3 2 1 *Comments*.............. ....
B. How do you like the sweetness? 9--Like Extremely 8--Like Very Much 7--Like Moderately 6--Like Slightly 5--Neither Like nor Dislike 4--Dislike Slightly 3--Dislike Moderately 2--Dislike Very Much 1--Dislike Extremely	9 8 7 6 5 4 3 2 1 *Comments*..............	9 8 7 6 5 4 3 2 1 *Comments*.............. ....
C. How do you like the flavor? 9--Like Extremely 8--Like Very Much 7--Like Moderately 6--Like Slightly 5--Neither Like nor Dislike 4--Dislike Slightly 3--Dislike Moderately 2--Dislike Very Much 1--Dislike Extremely	9 8 7 6 5 4 3 2 1 *Comments*..............	9 8 7 6 5 4 3 2 1 *Comments*.............. ....

D. How do you rate the OVERALL acceptability? 1--Like Extremely 2--Like Very Much 3--Like Moderately 4--Like Slightly 5--Neither Like nor Dislike 6--Dislike Slightly 7--Dislike Moderately 8--Dislike Very Much 9--Dislike Extremely	**9** **8** **7** **6** **5** **4** **3** **2** **1** ***Comments***..............	**9** **8** **7** **6** **5** **4** **3** **2** **1** ***Comments***.............. ....

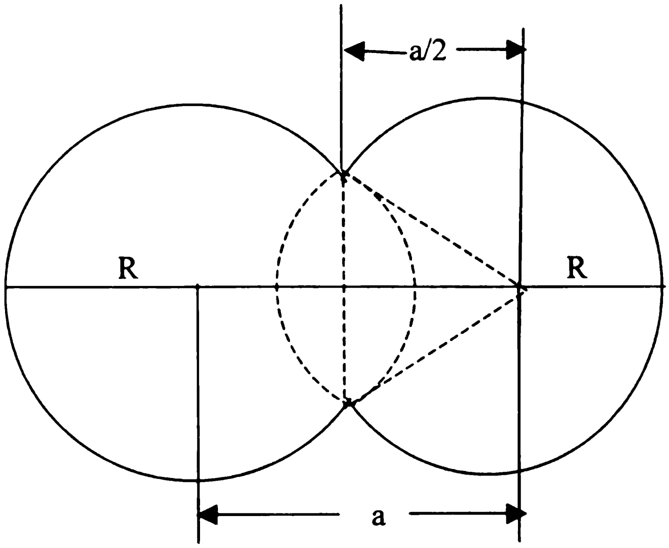
Appendix 9: Extrusion variables with mean residence time

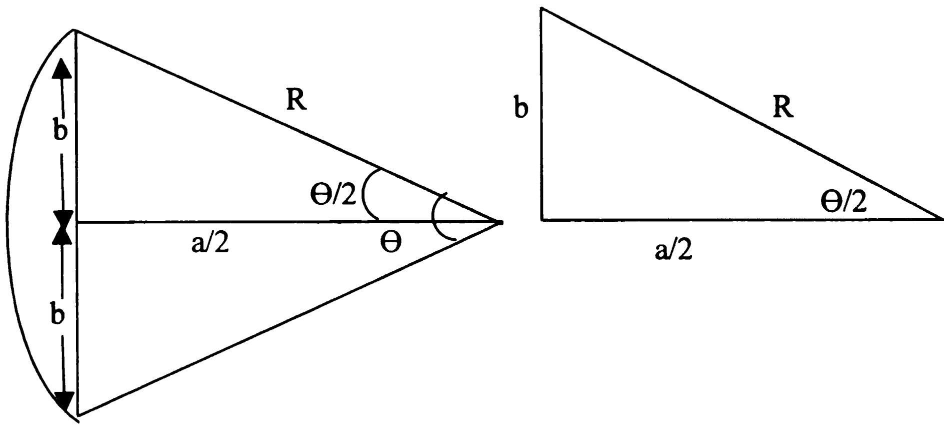
Sample Number	Barrel Temperature (°C)	Moisture Content (%)	Screw Speed (rpm)	Flour Feedrate (g/min)	Mean Residence time (s)
1	120/105	25	118	80	70.7
2	120/105	25	184	80	66.4
3	120/105	25	253	80	57.0
4	120/105	25	118	120	62.6
5	120/105	25	184	120	52.7
6	120/105	25	253	120	50.0
7	120/105	36	118	80	64.2
8	120/105	36	184	80	59.4
9	120/105	36	253	80	49.8
10	120/105	36	118	120	60.5
11	120/105	36	184	120	58.3
12	120/105	36	253	120	44.2
13	130/115	25	118	80	62.3
14	130/115	25	184	80	62.7
15	130/115	25	253	80	56.0
16	130/115	25	118	120	61.8
17	130/115	25	184	120	52.9
18	130/115	25	253	120	49.7
19	130/115	36	118	80	65.4
20	130/115	36	184	80	62.9
21	130/115	36	253	80	53.2
22	130/115	36	118	120	63.0
23	130/115	36	184	120	58.5
24	130/115	36	253	120	53.4

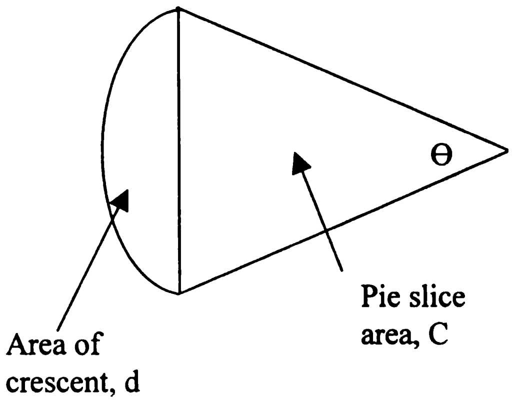
Appendix 10: Extrusion variables with extruder percent fill

Sample Number	Barrel Temperature (°C)	Moisture Content (%)	Screw Speed (rpm)	Flour Feedrate (g/min)	Percent fill
1	120/105	25	118	80	46.9
2	120/105	25	184	80	44.0
3	120/105	25	253	80	37.9
4	120/105	25	118	120	61.8
5	120/105	25	184	120	52.9
6	120/105	25	253	120	50.4
7	120/105	36	118	80	50.0
8	120/105	36	184	80	46.3
9	120/105	36	253	80	38.8
10	120/105	36	118	120	70.8
11	120/105	36	184	120	64.3
12	120/105	36	253	120	51.7
13	130/115	25	118	80	41.8
14	130/115	25	184	80	41.7
15	130/115	25	253	80	37.2
16	130/115	25	118	120	61.7
17	130/115	25	184	120	52.9
18	130/115	25	253	120	49.7
19	130/115	36	118	80	54.7
20	130/115	36	184	80	49.0
21	130/115	36	253	80	41.4
22	130/115	36	118	120	74.2
23	130/115	36	184	120	69.2
24	130/115	36	253	120	62.6

Appendix 11: Calculation of void volume of twin-screw extruder JS30A







Appendix 11 con't"

$$\cos\frac{\theta}{2} = (a/2)/R$$

$$\frac{\theta}{2} = \cos^{-1}(a/2)/R$$

$$\frac{b}{R} = \sin\left(\frac{\theta}{2}\right)$$

Area of triangle = ½ (b)(a/2)
Area of two triangles = (b a/2)
Pie slice area, C = $\Theta R^2/2$
Area of crescent, d = ½(ΘR^2 – ba)

Diameter of extruder screw, D = 30 mm
Radius of extruder screw, R = 15 mm
Diameter of extruder barrel, P = 56.5 mm
Length of extruder screw, L = 425 mm
Volume of 2 screws = 0.0003838 m^3
Volume of barrels = barrel volume * Screw length
Void volume = Volume of barrels – Volume of 2 screws

Appendix 12: Analysis of variance tables

Analysis of Variance for Bulky density

Source	Degree of Freedom	Sum of Squares	Mean Square	F Ratio
Model	4	10.99	2.75	1.90
Error	19	27.48	1.45	Prob > F
Total	23	38.46		0.15

Analysis of Variance for Expansion Ration

Source	Degree of Freedom	Sum of Squares	Mean Square	F Ratio
Model	4	0.05	0.013	4.72
Error	19	0.05	0.0027	Prob > F
Total	23	0.10		0.008

Analysis of Variance for Water Absorption Index

Source	Degree of Freedom	Sum of Squares	Mean Square	F Ratio
Model	4	2.79	0.69	0.74
Error	19	17.90	0.94	Prob > F
Total	23	20.69		0.57

Analysis of Variance for Water Solubility Index

Source	Degree of Freedom	Sum of Squares	Mean Square	F Ratio
Model	4	145.46	36.36	31.48
Error	19	21.95	1.16	Prob > F
Total	23	167.40		0.001

Appendix 12 con't''

Analysis of Variance for Phytohemagglutinins

Source	Degree of Freedom	Sum of Squares	Mean Square	F Ratio
Model	4	0.00027	0.000069	1.63
Error	19	0.00081	0.00043	Prob > F
Total	23	0.0011		0.21

References

Akpapunam, M.A. and Markakis, P. 1979. Oligosaccharides of 13 American cultivars of cowpeas (Vigna sinensis). J. Food Sci. 44: 1317.

Altomore, R.E., and Ghoss, P. 1986. An Analysis of residence time distributions in a twin screw-screw cooking extruder. Biotech Progress. 2(3): 157-163.

Anderson R A, Conway H F, Pfeifer V F, Griffin E L. 1969. Gelatinization of corn grits by roll- and extrusion-cooking. Cereal Sci Today 14, 4-12.

Anderson, A.K. 1998. The Impact of Twin-Screw Extrusion Processing on Physical and Biochemical Properties of the Major Components of Wheat Flour. Ph.D. Dissertation, Michigan Sate University.

Asp, N. G. and Johansson, C. G. 1981. Techniques for measuring dietary fiber: aims and comparisons of different techniques. In "The analysis of dietary fiber in food." P173 -189. Mariel Dekker Publishers, New York, N.Y.

Augustin, J. and Klein, B.P. 1989. Nutrient composition of raw, cooked, canned, and sprouted legumes, in *Legumes, Chemistry, Technology and Human Nutrition*, Matthews, R. H., Ed., New York.

Augustin, J., Beck., C.B., Kalbfleish, G., and Kagel, L.C. 1981. Variation in the vitamin and mineral content of raw and cooked commercial *Phaseolus vulgaris* classes, Food Technol: 35-37.

Bender, A. L. and G. B. Reaidi. 1982. Toxicity of Kidney Beans (Phaseolus vulgaris) with particular reference to lectins. J. Plant Foods 4: 15-22.

Bjorck, I. L. and Asp, N. 1983. The effects of extrusion cooking on nutritional value- A literature review. Journal of Food Engineering: 281-308.

Bliss, F. A. and J. W. S. Brown. 1983. Breeding common bean for improved quantity and quality of seed protein. In: Janick, J. (ed.). Plant Breeding Reviews 2. AVI Publishing Co. , Westport, CN, USA. 59-102

Bliss, F. A. and J. W. S. Brown. 1990. Breeding common bean for Improved Quantity and Quality of Seed Protein. In: Janick, J. (ed.). Plant Breeding Reviews 1. AVI publishing Co., Westport, CN, USA. 59-102.

Boniglia C, Feedele E, Sanzini E. 2003. Measurement by ELISA of active lectins in dietary supplements containing kidney bean protein. J. Food Sci 68: 1283-6.
Boyd, W. G. and Shopleigh, E. 1954. Specific precipitating activity of plant agglutinins (lectins), Science. 119-419.

Camire and Krumhar, K. 1990. Chemical and nutritional changes in food during extrusion. Critical Reviews in Food Science and Human Nutrition, 29 (1), 35-56.

Camire, M., Camire, A., Krumhar, K. 1990. Chemical and nutritional changes in foods during extrusion. Critical reviews in Food Science and Human Nutrition, 29 (1), 35 – 56.

Carpenter, K.J. 1981. The nutritional contribution of dry beans (Phaseolus vulgaris) in perspective. Food Tech. 34: 77-78.

CIAT. 1981. Potential for field beans in East Africa: Proceedings of a Regional Workshop held in Lilongwe, Malawi. 9-14 March 1980. pp 226.

Coffey DG, Uebersax MA, Hosfield GL, Bennink MR. 1992. Stability of red kidney bean lectin. J Food Biochem 16: 43-57.

Dedeh,S.S., and Saalia, F.K. 1997. Extrusion of Maize-Cowpea Blends in a Modified Oil Expeller. J Sci Food Agric 73, 160-168.

Fichtali J, Van De Voort FR. 1989. Fundamental and practical aspects of twin-screw extruder. Cereal Foods World 34(11): 111-119.

Fritz, J. C. 1976. Bioavailability of mineral nutrients, Chem. Tech. 6: 643.

Gomez M H, Aguilera J M. 1983. Changes in the starch fraction during extrusion cooking of corn. J Food Sci. 48, 378-381.

Gupta, Y. P., Antinutritional and toxic factors in food legumes: a review, Plant foods Hum. Nutr., 37, 201, 1987.

Harper, J., and Jansen, G. 1985. Production of nutritious pre-cooked foods in developing countries by low-cost extrusion technology. Food reviews international, 1(1), 27-97.

Harper, J.M. 1978. Extrusion Processing of food. Food Technol. 32: 67.

Harper, J.M. and Jansen, G.R. (1981). Nutritious Foods Produced by Low Cost Technology. Summary Report of Cooperative Activities between Colorado State University and the office of International Cooperation and Development, USDA, 1974-80. pp 1-72. Ft. Collins, Colorado: Colorado State University.

Hosfield, G. and Uebersax, M. 1980. Variability in physical-chemical properties and nutritional components of tropical and domestic germplasm. J. Amer. Soc. Hort. Sci. 105(2) : 246 – 252.

Hughes, J. S. and Swanson, B. G. 1989. Soluble and insoluble dietary fiber in cooked common beans (*Phaseolus vulgaris*) seeds, Food microstruct. 8-15.

Hughes, J. S. 1991. Potential contribution of dry bean dietary fiber to health, Food Technol. 45-122.

Huton, T. 2002. Food Chemical Composition: dietary significance in food manufacturing. Key topics in Food Science and Technology No.6. Campden & Chorleywood Food Research Association Group.

IFT. Innovative Food Trend. 1989. Single- and Twin-screw extruders in food processing. Food Technol. 43: 164.

ISAR. 2001. Annual Report.

Jaffe, W.G. 1973. Factors affecting the Nutritional Value of Beans. In: M. Milner (Ed.) Nutritional Improvement of Food Legumes by Breeding. Protein Advisory Group of the United Nations System, New York. P. 43-48.

Kim, Y. S. , E. J. Brophy., J. A. Nicholson. 1976. Rat intestinal Brush Border Membrane Peptidases. J . Biol. Chem. 251: 3206-3212.

King, T. P., A. Pusztai., and E. M. W. Clarke. 1980b. Kidney Bean (*Phaseolus vulgaris*) Lectin-induced Lesions in Rat Small intestine, 1: Light Microscope Studies. J. Comp. Pathol. 90: 585-595.

Landsteiner, K. and Raubitschkek, L., Beobachtungen uber Hamylose and Haemagglutination, Zbl. Bakt. Abt. II., 45, 96, 1908.

Levenspiel, O. 1999. Chemical Reaction Engineering. 3rd ed. New York, NY: Wiley. 668 pp.

Mahadevappa, V. G. and Raina, P. L. 1978. Nature of some Indian legume lipids, *J. Agric. Food Chem.*, 26, 1241.

Martelli, F. G. 1983. Twin-screw extruders. In Twin Screw Extrusion – A Basic Understanding, p.7. Van Norstrand Rheinhold Co., Inc., New York.

Martinez, W. H.1977. Other Antinutritional Factors of Practical importance in Evaluation of proteins for Humans, Bodewell, C.E., Ed., AVI Publi., Westport, CT.

Mason W, R, Hoseney R C. 1986. Factors affecting the viscosity of extrusion-cooked wheat starch. Cereal Chem. 63, 436-441.

MINIPLAN. 1988. Consomation Alimentaire en Milieu Rural. Volume 4: Enquette Nationale sur le Budget et la consummation des ménages. p 46.

Mohamed, I.O. , Ofoli, R.Y., and Morgan, R.G. 1990. Modeling the average shear rate in a co-rotating twin-screw extruder. J. Food Proc. Engineering. 12:227-246

Mosha, T. C. E. and Bennink R.M. 2004. Protein quality of drum-processed cereal-bean-saradine composite supplementary foods for preschool-age children. J Sci Food Agric 84:1111-1118.

Mouquet C., Salvignol B., Hoan N., Monvois J., Treche S. 2003. Ability of a "very low-cost extruder" to produce instant flours at a small scale in Vietnam. Food Chemistry 82, 249-255.

Myer, R.O., Coon., C.N., Froseth, J.A. 1981. The nutritional value of extruded beans in chick diets. Poult. Sci. 61:2117.

Myer, R.O., and Froseth, J.A. 1983. Extruded mixtures of beans and soybeans as protein sources of barley-based swine diets. J. Anim. Sci. 57:296-306

Naivukul, O. and D'Appolonia, B. L. 1978. Comparison of legumes and wheat flour carbohydrates. I. Sugar analysis. Cereal Chem. 55: 913.

Olson, A., Gray, G.M., and Chiu, M. C.1987. Chemistry and analysis of dietary fiber, Food Technol., 41, 71, 1987.

Orten, J. M. and O. W. Neuhaus. 1970. Biochemistry, 8th edition. St. Louis: Mosby.

Patte, H. E., Salunkhe, D. K., Sathe, S. K., and Reddy, N. R.1982. Legume Lipids, CRC Crit. Rev. Food Sci. nutr. 17- 97.

Peng, J., Huff, H. E., and Hsiel, F. 1994. An RTD determination method for extrusion cooking. J. Food Processing and Preservation. 18: 263-277.

Poulsen. G. 1978. Man and Tree in Tropical Africa: three essays on the role of trees in the African environment. International Development Research Centre. Ottawa, Canada. p. 31.

Purvis, I. 1998. Extruders. Tortilla and Snack Food Symposium, Am. Assoc. of Cereal Chem. Cereal Foods World 43: 73.

Reddy, N.R., Pierson, M.D., Sathe, S.K., Salunkhe, D. K. 1984. Chemical, nutrition and physiological aspects of dry bean carbohydrates. A review. Food Chem. 13:25-68.

Reddy, S.J. , Pubols, M. H., and McGinnins, J. 1979. Effect of gamma irradiation on nutritional value of dry field beans (Phaseolus vulgaris) for chicks. J. nutr. 109: 1307-1312.

Riaz, M. N. 2000. Introduction to Extruders and their Principles. In M. N. Riaz (Ed.), Extruders in Food Applications (pp 5-7). Texas: Technomic publishing Co.

Roberfroid, M. 1993. Dietary fiber, inulin, and oligofructose: A review comparing their physiological effects. Crit. Rev. Food Sci. Nutr. 33: 103 – 148.

Rockland, L.B., and Radke, T.M. 1981. Legume protein quality. Food Tech. 34: 79-82.

Rounanet, J. M. and P. Besancon. 1979. Effets d'un Estrait de Phytohemagglutinines sur la croissance, la Digestabilite de l'Azote et l'Activite de l'invertase et de la (Na+ K+) ATpase de la Muquese intestinale, chez la Rat. Ann. Aliiment. 33: 405.

Said, N.W. 2000. Dry extruders. In M.N. Riaz (ed.), Extruders in food applications (pp 51-62). Texas: Technomic publishing Co.

Sathe, S. K., Deshpande. S. S., and Salunkhe, D. K.185. Dry beans of Phaseolus: a review. II. Chemical composition: carbohydrates, fiber, minerals, vitamins, and lipids, *CRC Crit. Rev. Food Sci. Nutr.,* 46: 1389.

Schneeman, B.O. 1986. Dietary fiber: physical and chemical properties, methods of analysis and physiological effects. Food Technol., 40: 104.

Schultz, H. W., R. F. Cain, and R. W. Wrolstad. 1969. Carbohydrates and Their Roles. Westport, Conn. : Avi Publishing Company.

Sgarbieri, V. C. and Martins-Whitaker., J. R.1982. Physical, chemical and nutritional properties of common bean (*Phaseolus vulgaris*) protein, Adv. Food Res., 28-93.

Starer, M. S. 1996. When to consider twin-extruder for making a pet food. Cereal Foods World 41: 822.

Suparno, M. 2004. Modeling thermal and mechanical effects of extrusion on thiamin retention in extruded wheat flour. M.S. Thesis. Michigan State University.

Toma, R. B. and Curtis, D. J.1986. Dietary fiber: its role for diabetics, Food Technol. 40, 118.

Trowell, H., Southgate, D. A. T., Wolever, T. M. S., Leeds, A.R., Gassull, M.A., and Jenkis, D. J. A.1976. Dietary fiber redefined, Lancet. pp 967.

Worthington, R. E., Hammons, R. O., and Allison, J. R. 1972. Varietal differences and seasonal effects on fatty acid composition and stability of oil from 82 peanut genotypes, J. Agric. Food Chem., 20, 727.

Wu, X., Beecher, G. R., Holden, J. M., Haytowitz, D.B., Gebhardt, S. E., Prior, R. L. 2004. Lipophilic and Hydrophilic Antioxidant Capacities of Common Foods in the United States. J. Agric. Food Chem. 52: 4026-4037.

Young, I. S., Woodside, J. V.2001. Antioxidant in health and disease. J. Clin. Pathol.54, 176 – 186.