Physico-chemical properties of chickpea flour obtained using roller milling and extrusion pre-cooking

by

Randall Clade Martin

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Major Professor
Dr. Sajid Alavi

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Abstract

Chickpea is a high protein pulse that is gaining popularity in U.S. and international markets. This research focused on an integrated approach to process raw chickpeas grain into precooked chickpea flour with improved functionality and flavor for downstream applications such as baked products. This was achieved by conducting bench-top milling and extrusion studies, followed by scaling-up to pilot milling and extrusion, and physico-chemical characterization of the flour and evaluation of its functionality in baked cracker applications. The approach involved processing techniques, such as roller milling and extrusion, which are not typically used for pre-cooked chickpea flour but have the potential of improving efficiency and quality. The first chapter of this thesis covers the bench-top milling and extrusion trials as a proof of concept at a smaller scales. The second chapter describes the pilot-scale roller milling process and evaluation of milling efficiency. The third and final chapter covers the pilot-scale extrusion process and evaluation of the resultant pre-cooked flour, including physical and sensory properties of crackers baked using the flour.

Two varieties of chickpea were evaluated, Kabuli and Desi. Raw ‘Kabuli’ chickpeas were obtained as whole seeds, while ‘Desi’ chickpeas were obtained as split and de-hulled seeds. Benchtop roller mills were used to mill the chickpeas to a coarse meal and a fine flour. A benchtop extrusion trial was conducted using the chickpea meal and flour. The extruded product was reground into a precooked flour that was evaluated for physico-chemical properties and baked into crackers for physical and sensory testing. The benchtop milling information was used for scaling-up to a pilot flour mill. Again, the chickpeas were milled to a coarse meal and fine flour, and a flow sheet was developed. The chickpea meal obtained for each variety was then extruded on a pilot-scale twin-screw extruder under varying in-barrel moistures to obtain three

distinct processing intensities. The extruded product was reground to flour and evaluated for physico-chemical properties and functionality in baked cracker application.

The results of this research include four bench-top and two pilot-scale milling flow sheets for processing the two varieties of chickpeas into coarse meal and fine flour using roller mills and found that whole Kabuli seeds mill more efficiently than split Desi seeds (+9.3%). The bench-top data translated extremely well to pilot-scale, which showed the benefits of small-scale milling and extrusion research before scale-up. The extrusion pre-cooking resulted in enhanced flour functionality (final viscosity increased 500-1500cP) than commercial samples. Dough made with precooked flour sheeted easier than those made with raw flour. Crackers baked using pre-cooked flour also had a reduced hardness in comparison to raw flour (>400g). Pre-cooking resulted in a significantly lower gritty texture. Beany flavor of the crackers was not significantly reduced but the cooking process did not increase any rancid or negative flavors. This research provides the food industry with novel value-added milling and extrusion processing techniques for chickpeas flour for improving efficiency and functionality.

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Chapter 1 - Introduction and Overview

Brief introduction of topics

Chickpeas are a sustainable plant-based protein source. The high levels of protein have helped chickpeas become and important crop in world markets. Chickpeas have been grown and consumed for hundreds of years and are used in a variety of foods. Traditional methods for processing chickpeas have involved large amounts of water, energy and time. To increase the inherent sustainability of chickpeas, new processes need developed.

Two major varieties of chickpeas are available on the market, Kabuli and Desi. These varieties vary in size, composition, and hull structure. The differences in variety can lead to processing differences and thusly both were studied. This research did not study a comprehensive list of chickpea samples, but the research can be used as the foundation for modifying the process for varietal differences.

This research focused on using existing equipment to tackle the challenges of chickpea milling and precooking. Roller milling was proposed as a de-hulling and size reduction method due to the increased particle size control and separation. Roller mills have been used primarily on grains and been extensively studied. However, chickpeas have not been heavily researched with roller milling systems.

Precooking methods have primarily been done in batch processes that require large amounts of water and energy, such as with pressure cooking. Extrusion precooking was proposed as a more efficient cooking process due to the fact that it is continuous and requires less water than traditional cooking. Another benefit of extrusion cooking is that it can be changed and altered to create varying processing levels.

Objectives for Chapter 2

Chapter 2 focused on proving the methods proposed at a smaller benchtop scale. Benchtop milling trials focused on creating flow sheets for the two chickpea varieties, as well as two focuses, meal and flour. The chickpea meal and flour were then extruded to observe particle size and extrusion parameter effects. A post-extrusion grinding method was developed and the flour was evaluated for functionality and baked into crackers. The crackers would then be evaluated using instruments and sensory panelists to observe differences. The benchtop sensory work helped to streamline testing for pilot scale samples.

Objectives for Chapter 3

Chapter 3 focused on expanding what was learned from the benchtop milling trials. Only meal was targeted as a meal flow sheet would be more difficult to produce than a flour flow sheet. This was because the separation of hull could not be done solely based on size separation. Compositional differences were compared with benchtop trials to confirm trends and to observe differences between samples. Flowability was also measured on the final products to foresee any possibly challenges.

Objectives for Chapter 4

Chapter 4 focused on expanding what was learned from the benchtop extrusion trials. Both variety and processing intensity (In-Barrell Moisture) were evaluated. Raw and precooked flours were evaluated on pasting properties, functionality, and baked into crackers. Once again the crackers were evaluated using instrumental and sensory testing. The crackers were compared against commercially available samples to compare the novel extrusion process against commercial precooking processes.

Chapter 2 - Optimization of benchtop milling and extrusion of chickpeas (*Cier arietinum*) into a precooked flour

Abstract

The desire for sustainable protein sources has brought a new focus on legumes. The chickpea is a legume that is growing in popularity in the food market because of its nutritional value, sustainability and cost compared to animal proteins. Chickpea digestibility can be improved through cooking, which removes anti-nutritional factors such as trypsin inhibitors. Traditional cooking processes involve cooking either whole or split seeds through boiling or roasting. Milling studies have been done on chickpeas, however the focus has been with dehulling and splitting on attrition mills. In this study, chickpeas were dehulled and ground to a coarse meal (300-750 microns) and a fine flour (<150 microns) using a bench top roller milling system. The meal and flour were then extruded on a benchtop extruder and reground to create a precooked chickpea flour. The precooked flour was evaluated using rapid visco analyzer (RVA) and baked into gluten free crackers. The benchtop milling yields were substantially higher yields for flour (92-96%) as compared to meal (67-79%). The extrusion precooked flour resulted in lower RVA peak and final viscosities than the raw flour (200.8-718.3 cP versus 888.3-1159 cP, respectively), and led to crackers with reduced hardness (0.65-0.69 kg-f versus 1.3 kg-f).

Key Words: Chickpea, roller milling, extrusion, baking, precooked flour

Practical Applications:

This research has shown how milling equipment designed for wheat, roller mills, can be used to process chickpeas. The milling equipment was shown to process whole and split chickpeas. The authors created 4 flow sheets that can process chickpeas into flour and meal for multiple downstream applications. The meal and flour can go directly into food applications or can be processed further through extrusion. The extrusion process impacted the starch through cooking and shear to improve functionality. The extruded material can then be reground into precooked flour that behaves differently than raw chickpea flour. This benchtop work can be used as the foundation to extend these processes to pilot and later commercial scale. This research could increase the usage of chickpeas by utilizing existing technology to create better ingredients.

2.1 Introduction

Chickpeas have become increasingly popular in today's food markets for many reasons consumers find important. Chickpeas are nutritious, with a lower glycemic index than most grains, such as wheat or corn (Foster-Powell et al., 2002). Chickpeas can be used as complementary proteins as they are lacking in the amino acid tryptophan, where most cereals such as wheat are lacking in threonine and lysine (Candela et al., 1997). Most chickpea varieties are composed of 23-26% protein, 37-39% carbohydrates, 3-5% lipids and 5-13% fiber all in dry basis (d.b.) .) (Gil et al., 1996). Another reason for the chickpea's growing popularity is that it is a sustainable ingredient. Chickpeas are nitrogen fixers and do not require any additional fertilizer to grow (Sinclair and Serraj, 1995).

Chickpeas are an important food grown around most of the world (Gil et al., 1996). Raw chickpeas are typically sold as whole seeds, split seeds or flour. There are several varieties of chickpeas in the world market today as they can grow in many regions. Two chickpea varieties have been selected for this research, Kabuli and Desi. These varieties differ in several ways. Desi chickpeas have a thicker and darker hull or bran (approximately 14% bran by weight) and Kabuli chickpeas have a thinner and lighter hull (approximately 5% bran by weight) (Ravi and Harte, 2009). Kabuli chickpeas also tend to be slightly larger than desi chickpeas and have a higher, almost double, 100 seed weight (Ravi and Harte, 2009). Both varieties are common and readily available commercially.

Some drawbacks of chickpeas are that they contain anti-nutritional factors such as trypsin inhibitors and can bring beany flavors that consumers do not typically desire in all products (Sreerama et al., 2010) and (Mohammed et al., 2014). Thermal treatments are needed to eliminate or reduce these anti-nutritional properties and enhance the flavor. Typical thermal processing methods for chickpeas involve long cooking times, large water usage or high energy requirements. Some typical processing methods are dry roasting, soaking and boiling. Other traditional uses with chickpea flour have been cooking them in slurries to create thick pastes.

Milling equipment used to dehull chickpeas have been either dahl mills, designed to split the seeds, or hammer mills to grind the seeds into flour (Ravi and Harte, 2009). This milling process involved hydrating the chickpeas and removing the hull by pitting or scratching with abrasive forces. The dehulled chickpeas were then dried in an oven before grinding. This process uses large amounts of water to hydrate the chickpeas between 18-35% moisture (w.b.), depending on the process. It also requires large amounts of thermal and mechanical energy for drying and grinding.

One of the focuses of this research was to mill chickpeas more efficiently using roller mills. Previous data focused on milling with attrition mills to dehull and split the chickpea seeds (Wood et al., 2008) however research has not been done with roller mills. Particle size can be better controlled using roller mills versus hammer mills. Roller milling of the product can also reduce water usage by removing the hulls without soaking or excessive moisture that would need to be subsequently removed. The roller mills flowsheets were designed for two products, meal and flour.

Extrusion processing was tested in this research as it is known to be energy, water and time efficient (Bouvier and Campanella, 2014)Extrusion cooking requires less water and energy by using mechanical energy instead of thermal and often using high pressures. The goal of the extrusion cooking process was to eliminate trypsin inhibitors, reduce the beany flavors to improve consumer acceptance and improve end flour functionality. After extrusion the material was then ground with a hammer mill to create a precooked chickpea flour that is more nutritious (greater digestibility), has a reduced beany flavor and creates doughs that sheet or roll easier than raw flour. Both the raw and precooked flour were evaluated for composition, particle size and pasting properties. This precooked flour was then used to make crackers that were evaluated on both texture and flavor.

2.2 Materials and Methods

2.2.1 Materials

The two varieties of chickpeas used for this study were whole Kabuli seeds and split and de-hulled Desi seeds. Both varieties were grown in the northern part of the United states. A commercial precooked chickpea flour (not extrusion precooked) was used as control. A hard-red winter wheat flour (Hal Ross Flour Mill, Manhattan, Kansas, U.S.A) was used to evaluate and compare pasting properties.

2.2.2 Proximate analysis

Proximate analysis of ground samples was done by SDK laboratories (Hutchinson, KS, USA) in duplicate. The crude protein (AOAC 976.06) was measured by combusting samples and analyzing the amount of nitrogen in the sample. Crude protein for chickpeas was calculated using N x 6.25 (Tavano et al., 2016). Crude fiber (AOAC 962.09) was determined after digestion of sample with sulfuric acid and sodium hydroxide and then combusted. Crude fat by acid hydrolysis (AOCS Ba 3-38) was measured by extracting oil with petroleum ether and given as a percentage of original sample weight. Total starch (AOAC 979.10) was measured by digesting starch with enzymes and the glucose level was measured through spectrophotometry. Whole chickpea moisture contents were determined using a laboratory oven at 105oC for 72 hours (ASAE S352.2). Moisture contents of ground samples were determined using a laboratory oven at 135oC for 2 hours (AACC44-19.01). Tests were also performed in duplicate.

2.2.3 Seed Measurements

Diameter of the whole chickpeas was measured with digital calipers. Measurements were taken perpendicular and parallel to the cotyledons and averaged. The overall diameter was calculated by measuring 10 seeds. The weight of 100 seeds was measured in triplicate with new seeds each time and averaged to get the 100 seed weight.

The bulk density was calculated by measuring the volume of 100g of seeds in a graduated cylinder using the formula below. Tests were done in triplicate.

$$BD = Sm/Sv \qquad \text{Equation (1.1)}$$

Where BD is bulk density, Sm is seed mass and Sv is seed volume.

True density was calculated using the water displacement method. Water was added to a graduated cylinder and recorded. Then a known mass of seeds was added to the cylinder and the displacement of the water was read quickly so the seeds would not have time to absorb any of the water. The displacement of the water was recorded as volume and true density was determined using Equation 2. This test was performed in triplicate.

$$TD = Sm/Wv \qquad \text{Equation (1.2)}$$

Where TD is True density, Sm is seed mass and Wv is volume of water displaced by the seeds.

2.2.4 Tempering

Chickpeas were combined with room temperature purified water to the desired moisture content of 11% wet basis (w.b.) and placed in a clear plastic bag that was agitated for 2 minutes until moisture was not visible in the bag. The bag was then sealed again in a second bag to ensure no moisture interaction from the environment, and allowed to rest for the duration of the tempering. The bag was rotated and agitated halfway through the tempering time to ensure equal hydration.

2.2.5 Milling

Benchtop stainless steel roller mills (Ross Machine & Mill Supply Inc., Oklahoma City, Oklahoma, USA) were used to mill the chickpeas. Number of break rolls and reduction rolls varied for each process and can be found in the flow sheets for each milled product in Figures 2.2 through 2.5. All rolls were 9 inches (22.86 cm) in diameter, 5 inches (12.7 cm) long and belt driven. The process flows were designed to remove the exterior hull in as large a piece as possible so it could be sifted and separated by particle size. Further milling reduced the endosperm to the desired particle size. Samples were sifted after each milling step with a 1-kg capacity gyratory sifting box (Great Western Manufacturing, Leavenworth Kansas, USA) and weights were recorded for each sieve. Sieve type and micron opening was recorded in the flow sheets. Samples were milled in triplicate and yields averaged.

Roll characteristics can be found in Figures 2.2-2.5. As the particles get smaller through the 2nd and 4th break rolls the corrugations get finer to more efficiently grind the particles. The spiral increased from the first break to the other breaks to create more shear forces to help remove the hull from the endosperm and reduce the particle size. The speed differential between the pair of rollers was higher for the break system to create more shear forces and lower for the reduction or middlings system to have more compressive force. The labels for the roll passages are consistent with where these passages would be in a commercial mill.

The information in Figure 2.1 can be used to interpret the other flow sheets. The sieve information includes the material of the sieve as well as the micron size of the screen. In this example 16-gauge wire was used with openings of 1180 microns. The screen material can be altered to better accommodate the flow of a mill with stronger materials used in higher throughput areas. However, screen material was not a factor considered in this research.

2.2.6 Particle Size analysis

Particle size analysis on final flour and meal streams was done using an Alpine jet sieve analyzer (e200LS, Hosokawa Alpine, Germany) or a Ro-Tap sieve (RX-29, W.S. Tyler, Mentor, Ohio, U.S.A.). Samples were measured in triplicate.

2.2.7 Extrusion Precooking Process

Only Desi samples were extruded to ensure differences between meal and flour were limited to particles size as there was no hull in either sample. Milled Desi samples were extruded on a lab scale co-rotating twin screw extruder (Leistritz M18, New Jersey, USA). Milled Desi meal was hydrated to 16% and 10.7% moisture (w.b.). A Desi flour sample was also extruded at 16% moisture. Chickpea samples were compared to a cornmeal control hydrated to 16% moisture. Moisture levels were chosen based on previous testing using this extruder found 16% to be ideal and 10.7% would be a higher mechanical energy process. Flour was not hydrated to 10.7% because it would lead to flow problems in the extruder. Samples were all fed at 36g/min. Heating of the barrel was held constant through treatments using 6 electric zones at 30, 60, 80, 90, 100, 110^{o}C. Parameters recorded were die temperature, piece density, net torque, and moisture loss through extrusion. Piece density was calculated based on average of 10-piece dimensions and weights. The net torque for each treatment was calculated using the motor load data from the control panel and expressed in N-m units. Moisture loss through extrusion was determined from comparing the moisture content of the raw material and extrudate. Screw configuration was kept constant and shown in Figure 2.6 with a Length/Diameter ratio of 30/1.

2.2.8 Post Extrusion Grinding

After extrusion extrudates were ground using a model 4 Wiley mill (Thomas Scientific, New Jersey, USA) with a mesh opening of 0.5mm. The ground samples were sifted to separate flour using a 150-micron screen. Particles larger than 150 microns were reground in two passes of a lab scale roller mill (Ross Machine & Mill Supply Inc. Oklahoma City, Oklahoma, USA) with a roll gap of 0.003 and 0.001 inches respectively. The final product was a precooked flour with 100% of the particles below 150 microns.

2.2.9 Rapid Visco Analysis (RVA)

The standard RVA method (AACC Method 76-21.02) was used to analyze pasting properties of raw and precooked chickpea flours. The chickpea flours were also compared to a HRW wheat flour. The method was included hydrating 3.5 g samples with water added to obtain a solids level of 14% (w.b). The samples were constantly mixed, and the temperature was increased to 95°C before cooling to 50°C.

2.2.10 Cracker Baking

The cracker formula consisted of equal parts dry mix and water for pre-cooked flours and 2 parts dry mix to 1 part water for raw flours. The difference in water ensured a consistent dough viscosity amongst samples to allow sheeting. The dry mix included 61.4% chickpea flour, 20.46% potato flakes, 10.91% waxy pre-gelled corn starch, 3.94% corn oil, 2.05% oat fiber, 0.49% monocalcium phosphate, 0.41% sodium bicarbonate and 0.34% salt. A commercial chickpea flour, that was not precooked with extrusion, was used as comparison. The only independent variable of the formula was the type of chickpea flour used.

A wheat cracker control was also baked using the same HRW wheat flour used in the RVA analysis. The formula for the wheat cracker included 65.57% wheat flour, 22.95% water, 6.56% vegetable oil, 3.28% sugar and 1.64% salt. This formula was based off a typical wheat cracker and does not contain many of the ingredients that the chickpea cracker formula includes. This change in formulas was due to differences associated with gluten development in the wheat samples.

Dough was mixed using a stand mixer with a paddle attachment and combined for 4 minutes on low to medium speed until the dough was evenly mixed and had a smooth exterior surface. The dough was sheeted without laminating and cut using a rotary cutter into 0.5-inch-wide by 2-inch-long crackers (0.5 by 50.8 mm). Raw cracker dough was consistently checked to ensure 10 pieces had a consistent thickness and weighed 10.6 ± 0.5 grams. A two-stage baking process was used in a convection oven (Oshikiri, Fujisawa-City, Japan) with two separate heating decks and no steam addition. The crackers were first baked for 2.5 minutes at 232°C and then they were moved to another oven at 135°C for 17 minutes. This two-stage system mimics a tunnel oven system with different heating zones, typically used in industry.

2.2.11 Cracker Texture

The texture analysis was measured on a TAXT2i texture analyzer (Texture Technologies, Hamilton, MA, USA) with a three-point bend test designed to evaluate the cracker's snap force or hardness. An aluminum rounded blade with a diameter of 2mm was used. The crackers were supported on a rig at each end with a gap of 20 mm in between. The pretest speed was set at 1mm/s, the test speed was set at 1mm/s, and the post-test speed was set at 10mm/s. Crackers made with raw chickpea flour, precooked chickpea flour and HRW wheat flour were tested. Hardness was recorded as the peak force during breaking. Crackers were sampled with 20 replicates each.

2.2.12 Cracker Sensory Analysis

A descriptive analysis was done on crackers made with raw chickpea flour, precooked chickpea flour, wheat control and commercial control crackers. Controls used included Original Wheat Thins™ (Nabisco, East Hanover, NJ, USA) and Saltines™, also from Nabisco. Individual analysis of the crackers was done in duplicate using 5 highly trained panelists. Seven pieces of crackers were served in 3.25 oz containers. The crackers were ranked on attribute intensity scores ranging from 0-15 with 0.5 increments. Panelists were provided cucumber slices and deionized water for palate cleansing between samples. Textural attributes recorded were hardness, fracturability, initial crispness, sustained crispness, flakiness, denseness, cohesiveness of mass, moistness of mass, tooth packing, residual particles, powdery, gritty and desire to clear throat. The flavor attributes recorded were oil heated, overall beany, doughy, toasted, leavening, cardboard, musty, overall grain, starchy, wheat like, bran, stale, sweet aromatics, sweet, salt, metallic, bitter and astringent. Aftertastes were recorded for overall beany, leavening, overall grain, salt, metallic, sweet and bitter. Definitions of each attribute can be found in Tables 1.1 and 2.1.

2.2.13 Statistical Analysis

Statistical analysis was performed using a two-way ANOVA test conducted with a 95% confidence level using SAS software 9.4. Pair-wise differences were analyzed with a general linear model (GLM) and least square mean comparison. Significantly different values were denoted with different lower-cased letters.

2.3 Results and Discussion

2.3.1 Chickpea seed characteristics

Comparing the whole Kabuli seeds in this research to literature, Table 2.3, showed that the seeds tested were slightly smaller than those found in literature. The whole Kabuli seeds tested had a 7.73 ± 0.57 mm seed diameter, 37.28 ± 0.43g 100 seed weight, 74.33 ± 1.53 mL 100g seed volume, 0.78 ± 0.01 g/mL bulk density and 1.35 ± 0.03 g/mL True Density. All factors measured excluding bulk and true density were lower than previous research (Ravi and Harte, 2009). However, these differences were not substantial and could be attributed to differences in growing conditions. Only split and de-hulled Desi seeds were analyzed in this research. It is important to note the diameter and 100 seed weight differences between Kabuli and Desi seeds as the milling processes would need to be adjusted if whole Desi seeds were used.

2.3.2 Milling Flow Sheets

Flow sheets for each process are outlined in Figures 2.2-2.5. These flow sheets were simplified to show the flow of material. Additional sieves were used to reduce overloading of material on each sieve however the flow of material was not altered. Roll passages that were identical such as the smooth roll sections of 2M, 3M, and 4M were condensed in the flow sheets but actually represent individual passages. Additional screens could be used in the meal streams to create coarse and fine meals however that was not the focus of this research.

Kabuli flour was produced using process 1 and is shown in Figure 2.2. The whole seeds were first broken on the 1st break (1BK) passage into smaller pieces through the rollers with a roll gap of 0.07 inches (1.778 mm). Any larger roll gap would not grind the seeds sufficiently and any smaller gap would cause the seeds to bounce off the rollers without being ground. Particles larger than 1180 microns were sent to the second break (2BK) passage. Particles between 630 and 1180 microns were sent to the third break (3BK) passage. Particles between 150 and 630 microns were sent to the first reduction or middlings rolls (1M) passage. Particles less than 150 microns were separated as flour.

The 2BK passage had a smaller roll gap of 0.025 inches (0.635 mm) and is the first step that separates bran. Particles larger than 2000 microns were considered coarse bran and were removed from the system. Particles of 2BK between 630 and 2000 microns were sent to the 3BK passage. Particles between 150 and 630 particles were sent to the 1M passage. Again, flour less than 150 microns was separated.

The 3BK roll gap was further reduced to 0.016 inches (0.406 mm) to ensure reduction in size of the endosperm while maintaining the larger bran size. Particles larger than 1180 microns were separated as fine bran and removed from the system. Particles between 630 and 1180 microns were sent to the fourth break (4BK) passage. Particles between 150 and 630 microns were sent to the 1M passage. Again, flour was separated below 150 microns.

The 4BK passage had a roll gap of 0.006 (0.1524 mm) inches. Fine bran above 240 microns was removed from the system. Particles between 150 and 240 microns were sent to 1M. Lastly, flour was separated less than 150 microns.

The first reduction passage into flour 1M is where most of the flour of the system was produced. The roll gap was set to 0.003 inches (0.0762 mm) and particles larger than 425 microns were removed as an inseparable mixture of bran and endosperm labeled shorts. Particles from the 1M passage between 150 and 425 microns were passed to the second reduction passage (2M), and flour was removed below 150 microns. The 2M and following passages had roll gaps set at 0.001 inches (0.0254 mm) which was the tightest the rolls could be positioned without creating flakes of endosperm. The 2M, and 3M passages followed the same separating procedure as 1M with particles between 150 and 425 microns continuing to the next passage. The 4M passage differed by separating discolored pieces from soft and green chickpeas above 150 microns as feed and finally separating the last amount of flour.

Kabuli meal was produced using process 2 shown in Figure 2.3. The goal was to optimize meal; however, flour was still produced as a coproduct. This flow sheet mainly differed by the roll gaps and sieve separations. The same number and types of passages were used as in Figure 2.2. The four break passages roll gaps were 0.06, 0.03, 0.015, and 0.010 inches (1.5, 0.762, 0.381, 0.254 mm) respectively. The sieve separation for each break passage was constant but the designated streams were different for each passage. For 1BK and 2BK, particles larger than 1041 microns were sent to the next subsequent break passages and particles between 750 and 1041 microns skip a passage (i.e. from 2BK to 4BK). This ensured particles received adequate grinding at each passage and did not slip between the roll gaps. For all break passages, particles between 300 and 750 microns were separated from the system as meal. The two sieves, 300 and

630 could be used to separate a fine and coarse meal if desired however for this research the meal streams were combined. Particles for all break passages below 150 microns were separated from the system as flour. The 3BK passage particles larger than 1041 microns were separated as coarse bran. The 4BK particles larger than 1041 microns were pieces of green or soft chickpeas that were called feed. Particles of the 4BK between 750 and 1041 microns were separated as fine bran. Although the system was not designed for flour production a small amount was produced and there were particles between 150 and 300 microns created through the break system that needed further grinding to flour. The reduction system used the same roll gaps as the Kabuli flour flow sheet of 0.003, 0.001, 0.001 and 0.001 inches (0.0762, 0.0254, 0.0254 and 0.0254 mm) respectively. Little or no bran was observed in these stages therefore no bran separation was needed. Each reduction passage sent particles larger than 150 microns to then next passage and particles smaller than 150 microns were deemed flour. The 4M passage recirculated on itself due to the low number of particles above 150 microns and no bran observed.

Desi Flour was produced using process 3 shown in Figure 2.4. This flow sheet differed from the Kabuli flour flow sheet show in Figure 2.2. As bran separation was not needed for the dehulled and split seeds, grinding could be more aggressive. The break system only required 2 passages with smaller roll gaps for 1BK and 2BK of 0.008 and 0.006 inches (0.2032 and 0.15424 mm). This was both due to the high intensity of the grinding and the smaller seed size. Multiple screens were used to determine the grind intensity of the break system however all particles from 1BK above 240 microns were sent to 2BK. For both 1BK and 2BK particles between 150 and 240 microns were sent to 1M, and a small amount a flour was collected below 150 microns. For the 2BK passage particles larger than 750 microns were separated from the system as feed. These particles were from green and soft chickpeas. All other particles from 2BK, except for flour, were sent to 1M. The reduction/middlings system (1-4M) followed the same roll gaps as previous flow sheets. The largest particles of 2M and 4M were removed as feed if any green or discolored seeds were present. A cleaning system in a commercial mill should be able to remove all these seeds with a color sorter however one was not used for these benchtop trials.

Desi meal was produced using process 4 shown in Figure 2.5. The break system was less aggressive than the Desi flour flow sheet and was used to maximize the meal production and minimize any flour. However as before some small particles were created and further processed in the reduction system. The break system used roll gaps of 0.018, 0.015, 0.012 and 0.08 inches (0.4572, 0.381, 0.3048 and 0.2032 mm) respectively. The roll gaps differed from process 2 by having a more intense grinding action on 1BK with the other break passages similar as with the Kabuli meal. The sieve separation of the break system separated meal from the system between 300 and 750 microns. The extra screens between that range could be used to separate finer and coarser meals as well as observe the grinding intensity. However, for this research all meal streams were combined for further testing. Particles from the break system larger than 750 microns were passed to the next passage until 4BK when it was removed as green seed or feed. Flour was removed from the break system below 150 microns and particles larger than flour and smaller than meal were sent to the 1M passage. Only 3 reduction passages were needed due to the lack of bran and lower quantity of flour produced.

2.3.3 Process Yields

2.3.3.1 Overall Comments

Milling yields for each process are shown in Table 2.6. These yields differed than those in Table 2.5 because these account for process loss to give a better picture of the process. All process losses were similar except for an increase with process 3. The shorts and feed streams were small and primarily contain discolored chickpea seeds. In a larger scale operation, a color sorter could be used to remove these discolored seeds and therefore remove them before grinding.

2.3.3.2 Process 1 vs. Process 2

Comparing the Kabuli processes, 1 and 2, besides the change in focus, the endosperm yields (meal + flour) were similar. Process 1 was more efficient than process 2 by producing more of the target product, flour and meal respectively. This was expected as flour was still produced in the break passages even though the roll gap was larger to keep the particles in the meal size range of 300-750 microns. Process 1 had a numerically, but not significantly larger percentage of hull removed than process 2. Bran separation was efficient at approximately 5-6% because previous research found Kabuli hull to be 5% of the total seed (Ravi and Harte, 2009). The proximate analysis data showed an increase in crude fiber for the meal stream of process 2 than the flour in process 1. Since the bran yields were similar for process 1 and 2 but the fiber was different, this showed that endosperm was present in the bran fraction.

2.3.3.3Process 3 vs. Process 4

Comparing the Desi processes, 3 and 4, the endosperm yields (meal + flour) were similar. This was expected as these processes were simpler than processes 1 and 2 due to the lack of hull. The process loss as mentioned before was larger for process 3 than process 4. This could be due to the flour being “stickier” than meal and sticking to the sides of the milling and sifting equipment.

2.3.3.4 Process 1 vs. Process 3

Comparing process 1 and 3 for flour production showed significantly higher yields for the split Desi seeds than the whole Kabuli seeds in process 1. This again was expected however, both processes were efficient with flour yields greater than 90%. The process loss was higher for process 3 showing evidence that desi seeds could have differences in flow properties.

2.3.3.5 Process 2 vs. Process 4

When comparing process 2 and 4 for meal production, a significant increase in meal yield and significantly lower flour yield for the split Desi seeds was found. These data showed that process 4 was more efficient at producing meal than process 2. This was expected as no bran or hull had to be removed from these seeds and therefore made the milling process simpler with less separation.

2.3.3.6 Process 1 Tempering Trials

Tempering experiments were conducted only for Kabuli seeds as Desi seeds were already dehulled and did not require tempering. Initial comparisons were done comparing no tempering (8.5% MC), 11% MC, and 13% MC. Tempering was tested for both meal and flour flowsheets for Kabuli seeds and found to increase bran separation as compared to no tempering, however it reduced yields for meal flow sheets. Any level of tempering tested lowered meal yields by approximately 5%. The tempering increased bran strength but softened the endosperm and therefore more flour was created instead of meal. Further tempering trials, comparing time, were only completed for process 1 because it was a flour focused process. The results of the 11% MC trials are shown in Table 2.5. Hydrating to 13% led to seeds that were too soft and were crushed by the rollers instead of broken. This showed a narrow range of effective tempering for chickpeas.

The yields in Table 2.5 do not account for process loss to make a better comparison of the tempering. The coarse bran, fine bran, shorts/feed, and flour percentages in Table 2.5 combined equal 100%. Process loss cannot easily be controlled and mostly comes from the sifting process. However, loss was still compared. Significantly high flour yields were found for both the 6- and 12-hour tempering times. The 24-hour trial had the lowest flour yield as well as a larger production of shorts/feed. The 24-hour trial also had the largest amount of loss. The increased flour yield in the 6- and 12-hour trials came from lowered shorts and feed production. Tempering for 12 hours was chosen based on the lower process loss. The effect of tempering on process loss is unknown but it could affect the flow properties of the flour that could cause it to be more or less “sticky”.

2.3.4 Proximate Analysis

2.3.4.1 Process 1

Proximate analysis results showed the effective removal of the bran or hull of the chickpeas as shown in Table 2.4 comparing the raw material whole seeds to the process 1 flour. The crude fiber was significantly reduced while all other compositions, except ash, increased slightly accommodating for the change in fiber. The significant yet small change in ash content of the flour from process 1 compared to whole Kabuli seeds showed that ash content was not an accurate predictor of hull contamination in the flour. This showed a major difference in comparison with wheat milling. The bran and shorts of process 1 were composed mainly of fiber with significant amounts of protein and starch. Previous research found the chickpea hull is primarily fiber (Soni and Sarita, 2014). Previous research (Sreerama et al., 2010) showed chickpea bran had a protein level of approximately 7%. The higher levels of protein and starch showed evidence of some endosperm remaining in the bran and shorts stream. The significant increase of fat in the dehulled flour than whole seeds or bran/shorts streams showed that fat was distributed mainly in the endosperm. This was confirmed previously that found less than 2% fat in the bran (Sreerama et al., 2010) There was a significant increase in the total starch content of process 1 flour at approximately 7% most likely attributed to the hull removal.

2.3.4.2 Process 2

The Kabuli meal had protein levels consistent with the whole seeds and had a significantly smaller total starch content. This lower starch content could be that areas of endosperm with less protein are easier to breakdown and form more of the flour fraction. This has been reported previously that the outer layer of the endosperm had higher protein levels while the center of the endosperm consisted of more starch (Wood et al., 2011). The crude fiber however was not reduced to the same level as seen in process 1. This showed more hull contamination in the meal than was in the flour of process 1. This was expected as it became increasingly difficult to separate the meal and hull pieces solely on size. Use of a purifier and air separation could be used on a commercial system and would be expected to remove these larger bran pieces. Unfortunately, a benchtop scale purifier was not available for this research. The ash content increased significantly in the meal streams while the fiber content was reduced. This further emphasized that ash content was not primarily found in the hull and therefore cannot be used as a quality measurement.

2.3.4.3 Process 3

With the limited removal of streams in process 3 major changes in the proximate analysis were not expected. Small reductions were seen in crude protein, crude fiber, fat and ash. However, a significant increase from 42.25% to 51.75% in total starch was observed between the split seeds and flour, respectively. This large increase in total starch was unexpected as 0.014%, shown in Table 2.6, of the material was removed as feed.

2.3.4.4 Process 4

Protein levels in meal were similar to the split desi seeds. Comparing Desi meal and flour there were significantly higher levels of protein and significantly lower levels of total starch in the meal as compared to the flour. This difference reinforced that protein was not distributed evenly across the endosperm. The starch granules that are not held together with as much protein will break off easier and create smaller particles that will be part of the flour stream. These effects are also seen in milling differences between hard and soft wheats (Hoseney, 1986) as well as in corn milling differences between the floury and horny regions of endosperm (Hoseney, 1986).

2.3.5 Particle Size Distribution

2.3.5.1 Process 1

A bimodal distribution of the Kabuli flour can be seen in Figure 2.7 showing two peaks at 53 microns and 150 microns. The bimodal distribution could reinforce the reasoning that protein was not distributed evenly in the chickpea endosperm similar to corn. Another explanation could be the first peak was from flour that came from the break system and the larger peak came from the reduction or middlings system. The second hypothesis was more likely true due to the fact that a bimodal distribution was found in all flour streams even those from processes focused on meal. If there were sections of increased protein in the endosperm it could be assumed that it would be primarily found in the meal stream and not the flour.

2.3.5.2 Process 2

A bimodal distribution was found again in the Kabuli flour from process 2 shown in Figure 2.8. This time the first finer peak at 53 microns was larger than the more coarse second peak around 125 microns. However, there were a larger number of particles between in the second and broader peak than the thinner first peak. This further reinforced that the initial peak was coming from the flour produced in the break system. Kabuli meal ranged from 200 to 800 microns. This larger range was attributed to the sieve analysis and if more sieves were used the distribution would not be as broad.

2.3.5.3 Process 3

The bimodal distribution trend seen in Kabuli flour (Figure 2.7) can be seen again in the Desi Flour shown in Figure 2.9. The first peak was smaller than the one observed from process 1. Process 3 had a shorter break passage and therefore would result in less flour from the break passage. This again reinforced that the bimodal distribution was caused by where the particles come from in the process.

2.3.5.4 Process 4

A bimodal flour distribution was still found in process 4, shown in Figure 2.10, but with a more equal distribution between the two peaks. This could be to the difference in grinding intensity compared to process 2. Process 4 did not have to remove any bran and therefore was milled differently and could attribute to more flour being produced in the break system. The Desi meal was peaked around 600 microns. The extras sieves used and shown in Figure 2.5 allowed greater control and observation of the particle range and the roll gaps were adjusted to target 600 microns.

2.3.6 Extrusion Pre-cooking of Chickpea Meal and Flour

All samples ran consistently and were stable with no surging observed. Each extruded sample was allowed 15 minutes of transition to reach a steady state. Oil was expelled around the die on sample C, Desi meal at 10.7% MC (w.b.). The results of the extrusion experiment were recorded in Table 2.7.

Extruded Desi chickpea samples lost an average of 3.37 to 3.71% moisture due to steam flash off at the die and moisture loss during ambient cooling with the largest loss in moisture from sample C, Desi meal sample hydrated to 10.7% moisture (w.b). The lowest loss for chickpea samples was sample B, Desi meal hydrated to 16% moisture (w.b.). Sample A, the cornmeal control, lost the least amount of moisture at 3.05% (w.b.) despite having the second highest die temperature of all samples. These results were expected as lowering water level typically leads to higher levels of mechanical energy due to less lubrication from the water (Bouvier and Campanella, 2014).

Increased torque was observed with sample D, chickpea flour, compared to samples B and C, meal. This was most likely due to the increased energy to flow finer particle materials through an extruder. Decreases in the net torque were observed as water was lowered from samples B to C. The oil that was expelled on sample C could have lubricated the screws and therefore reduced the mechanical energy shown in the torque.

The die temperature of sample C was larger than sample B even though the normalized torque was lower. The normalized torque as mentioned before could have been affected by the oil expressed. The increase could be due to the lower water level in sample C than B. The lower water level would result in a lower specific heat and therefore absorb heat more efficiently and quickly.

The piece density is highly related to the expansion ratio and specific length. As radial expansion increases the piece density increases. The specific length shows the trends of the longitudinal expansion. As radial expansion, expansion ratio, increased the specific length, longitudinal expansion decreases. All chickpea samples had an increased radial expansion compared to the cornmeal. This could be due to the increased protein and reduced radial expansion. Protein affects expansion by puncturing films created by the molten starch (Normell Jhoe E. de Mesa et. al. 2009)

Expansion was not the main goal of the extrusion process. However, it is related to the amount of mechanical energy inputted as well as the product composition (Bouvier and Campanella, 2014) and can lead to less energy needed to regrind the product into flour. The expansion ratios followed similar trends as the die temperature with higher die temperature leading correlated to higher expansion. This could be caused by the increased heat leading to more steam flash off at the die that created more expansion than lower die temperature samples. Comparing expansion ratios sample A, corn meal, had the highest expansion and lowest piece density. This was expected as cornmeal is known to expand well, due to its higher starch and lower protein level than the chickpea samples. No expansion differences were observed in the Desi meal samples, B and C. However, the die temperature increased as water was lowered, showing signs of increased mechanical energy. The Desi flour had an increased expansion most likely attributed to the lower particle size. A lower particle size can result in more gelatinization and increased cooking of the starch due to the increased surface area to volume ratio of the particles.

2.3.7 RVA of Raw and Extrusion Pre-Cooked Chickpea Flours

The results of the RVA testing were recorded in Table 2.8. The table showed the temperature that the paste began thickening at (pasting temp), the highest viscosity obtained during heating but before cooling (peak viscosity), the amount of viscosity lost as the temperature was held at 95°C (breakdown), the final viscosity at the end of the test (final viscosity), and the amount of viscosity gained as the slurry was cooled (setback).

2.3.7.1 RVA Wheat Flour vs. Raw Chickpea Flour

Hard red winter (HRW) wheat flour had significantly lower pasting temperatures than raw chickpea flours. This could be related to differences in starch structure. HRW flour had a significantly larger peak and final viscosity than the raw chickpea flours. The significant difference between wheat and chickpea can be mainly attributed to starch content. Wheat has a substantially higher starch level than chickpeas. HRW flour also had a larger breakdown than chickpea flour that also could be explained by the lower starch content as there was less starch to break down. Another effect, but not as significant, could be the fat content of the chickpeas versus the wheat flour. Wheat is known to contain approximately 2-2.5% lipids (d.b.) and the chickpea flour tested had between 5.9-6.7% lipids (d.b.). Lipids are known to interfere with starch swelling and could have resulted in the lower viscosities.

2.3.7.2 RVA Raw Chickpea Flour vs. Precooked Chickpea Flour

All precooked chickpea flours had lower peak viscosities compared to the raw chickpea flours. This result was expected as the precooking process gelatinizes and degrades the starch granules. The lower pasting temperatures of the extruded samples showed evidence of pregelatinizing. The breakdown of the raw chickpea flour was reduced by almost 70% compared to the precooked chickpea flours. This value was expected to increase due to the starch already being subjected to thermal and mechanical energy making it more likely to breakdown. However, there was less intact starch in the precooked flour to contribute to the breakdown.

2.3.7.3 RVA Commercial vs. Extrusion Precooking

Results from the commercial precooked chickpea flour showed a horizontal trend that differed considerably compared to all other samples. The viscosity ranged from 30 to 80 cP with no apparent change from temperature. This lower viscosity could be due to the processing methods that led to annealing of the starch thus lowering the ability of the starch to interact with water (Tester and Debon, 2000). The outer layer of the starch granule could be annealed and reduced the ability for water and starch to interact. The extrusion precooked samples still showed trends and responses to the temperature changes in the RVA profile showing that these samples were not annealed. The difference in RVA trends of the extrusion precooked samples showed an increased functionality than the commercial flour.

2.3.7.4 RVA Extrusion Precooked Samples

The extrusion precooked samples only showed significant differences in peak and final viscosities between samples B compared to C or D. These differences showed different processing conditions and levels. The final viscosity trends did not appear be related to the normalized torque, or die temperatures reported in Table 2.7. The differences appeared to be more related to the in-barrel moisture content and the particle size. Extruded flour B had a higher torque than flour C, however it appeared that lowering the water to 10.7% increased gelatinization and starch degradation as shown in the lower peak and final viscosity. This further showed that torque was not directly related to how much the starch was being cooked because of the oil being expressed with sample C. Particle size was shown to have the same effect as moisture level on starch during extrusion. The flour had the lowest, but not significant, final viscosity and highest normalized torque out of all of the extruded samples.

2.3.8 Instrumental Crackers Texture: 3-Point Bend Test

The results of the cracker hardness analyzed with the texture analyzer can be found in Figure.1.11.

2.3.8.1 Wheat vs. Chickpea

The wheat control cracker had a hardness similar to the extrusion precooked crackers and was softer than the crackers made with raw Desi flour. This could have been caused by many effects including differences in formulation, hydration levels or differences in protein.

2.3.8.2 Raw vs. Precooked

The raw Desi flour sample with native starch was more difficult and required more energy to sheet to than the precooked samples. The increased energy showed a stronger starch matrix in the native starch that led to a harder cracker. The precooked flour samples sheeted easily with little resistance, showing a reduced strength in the starch matrix. This reduced matrix strength reduced hardness of the crackers. These sheeting and hardness trends were consistent with viscosity trends seen in the RVA data. The lower viscosities correlated with a softer cracker.

2.3.8.3 Commercial vs. Extrusion Precooked

The commercial flour had the lowest hardness out of all of the samples. This matched the RVA data and the theory that the starch was annealed. The annealed starch would not be able to create a strong starch matrix that would lead to increased hardness. The extruded samples were significantly higher than the commercial flour and significantly lower than the crackers made with raw Desi flour. Differences amongst the extruded samples were not significant; however, they followed the same trends found in RVA final viscosity. The lower viscosity should more starch damage that led to a softer cracker. They may not be significant, but the trends were not contrary to previous results.

2.3.9 Crackers Sensory: Texture and Flavor

The trained sensory panelists were able to detect similar trends as observed through the texture analyzer. The results of the cracker texture and flavor sensory were recorded in Tables 1.9 and 1.10 respectively. The commercial chickpea crackers gave the lowest hardness similar to Saltines^{TM} and Wheat Thins^{TM}. The wheat control cracker differed than the texture analyzer with a lower hardness than the extruded samples but were still harder than the commercial chickpea crackers. Due to the variability in the data there were no statistical differences between the raw and extruded sample hardness. However, numerically they followed the same patterns with starch gelatinization and damage reported in both the RVA and texture analyzer data. The extruded crackers showed an increased crispness and sustained crispness compared to other samples.

Comparing these chickpea crackers to what is currently available on the market, the chickpea crackers were more dense and harder than Wheat Thins^{TM}. The wheat control crackers had a similar to the extrusion precooked crackers. The wheat control crackers also had similar tooth packing scores with the crackers made with raw flours. The precooked chickpea crackers had some improved sensory characteristics compared to raw and commercial crackers, including a lower tooth packing score and a lower desire to clear your throat.

The chickpea cracker formula used in this research was not intended to be ideal for all sensory attributes. The cracker formula did not contain any coatings that would enhance texture or flavor. Without the coatings or flavors, changes can be isolated to the different chickpea flours being used. The commercial cracker samples did contain external coating of oils, flavors, and salt. These can be seen in the increased salt and sweet scores of the Wheat Thins™. The wheat control also had a higher salt score as expected due to the increased salt in the formula.

One concern about the flavor of the precooked flours was oil rancidity due to the high heat and pressure during extrusion. Originally the panelists were focused on measuring the rancidity, but the level was low enough that the oil heated value was recorded instead. The oil heated trends followed the same trends observed in RVA, and both hardness.

Another focus of this research was reducing the beany flavor of the chickpea crackers that can be negative to some consumers. Previous research stated that chickpea flour had too strong of a beany flavor that consumers disliked (Yamsaengsung et al., 2012). The overall beany flavor was significantly reduced for the extruded 16% MC Desi flour sample compared to the raw flour, most likely because the high heat and pressure volatized some of the flavor compounds associated with chickpeas. This change was only found with the flour sample and could be attributed to the lower particle size leading to more cooking of the flour that was also shown in the normalized torque, lower final viscosities, and lower hardness. The other extrusion precooked flours did not have significant differences however, they followed similar trends as the previous data. Another benefit of the precooked flours was reducing of several negative flavors such as doughy, starchy, and stale. The extrusion process most likely removed these flavors and enhanced the cooked flavors, such as toasted. The removal of negative flavors can lead to more consumer acceptance.

2.4 Conclusion

Roller milling provided a controlled particle size distribution that was optimized for meal and flour. The use of roller mills for processing chickpeas was more efficient for flour than meal and split and de-hulled Desi chickpeas milled more efficiently than whole Kabuli chickpeas. Use of a purifier in commercial milling system could increase meal yields. The milling processes in this research used less water than previous research making the process more environmentally sustainable. Extrusion precooked flours had higher functionality than commercial precooked flour. Extrusion precooking of chickpeas can be used to create crackers with varying flavors and textures. Extrusion processed flour had lower beany flavor than raw flour that could increase consumer acceptance. This benchtop work can be used to scale this process to pilot and later commercial scale.

Chapter 2 Figures

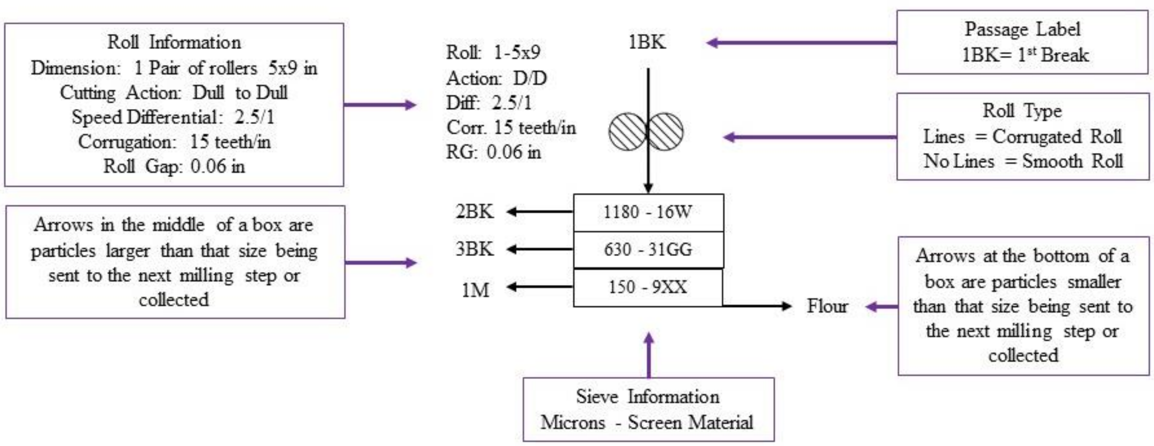


Figure 2.1 Flow Sheet Example

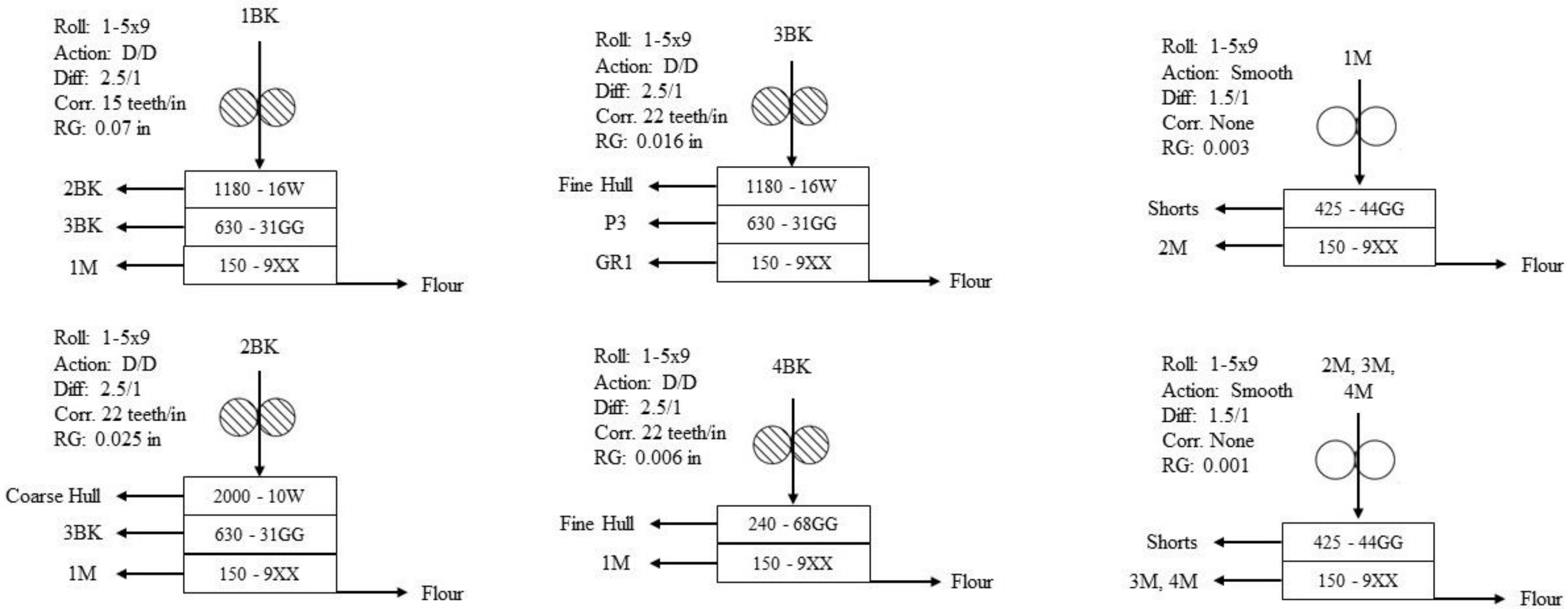


Figure 2.2 Process 1, Kabuli Flour Flow Sheet

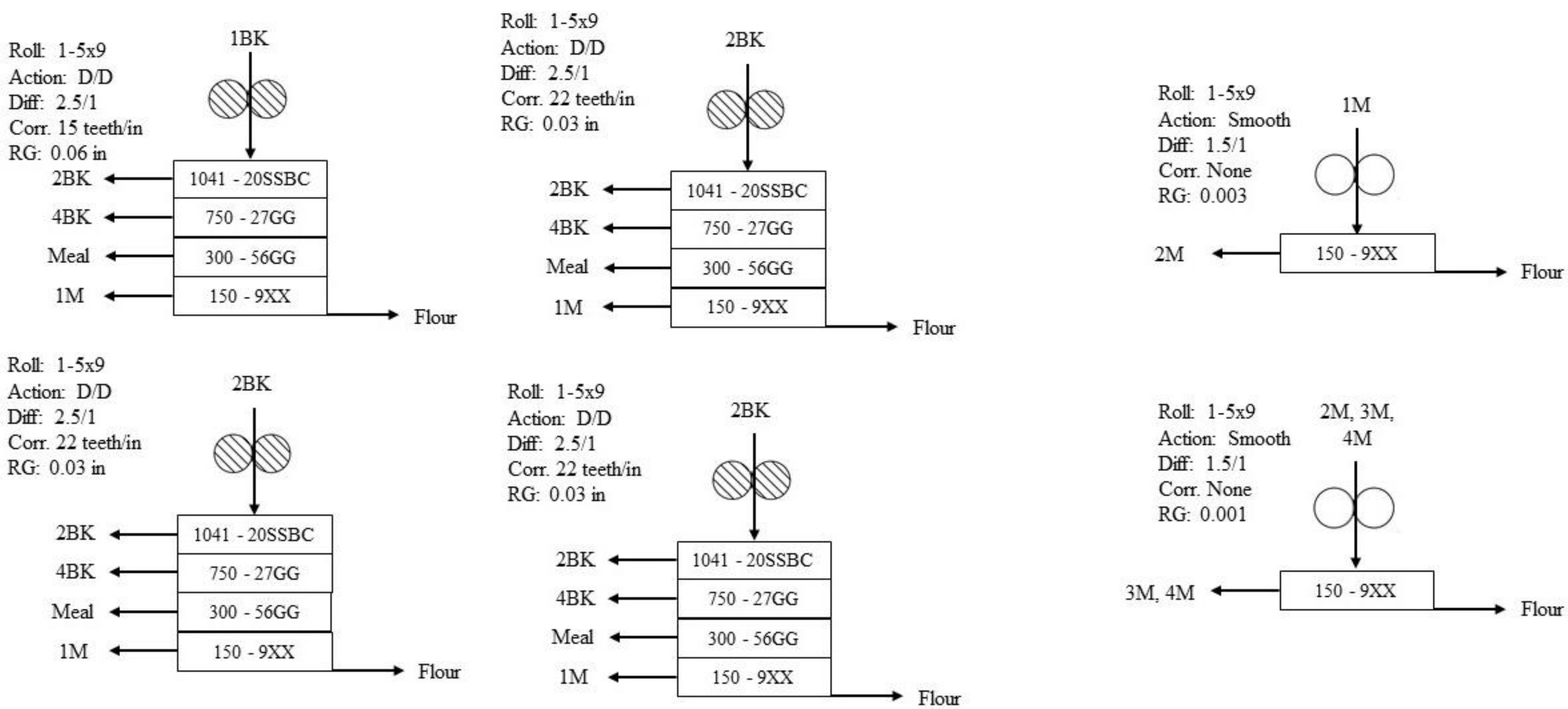
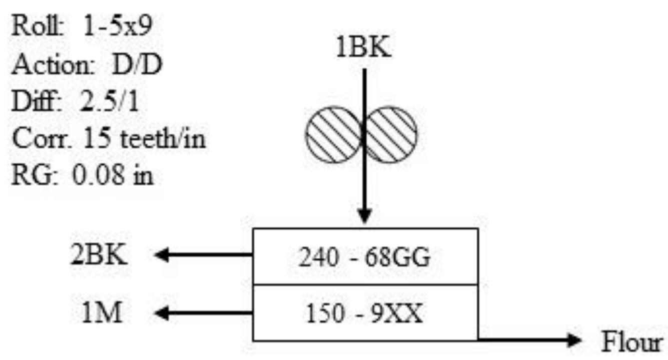
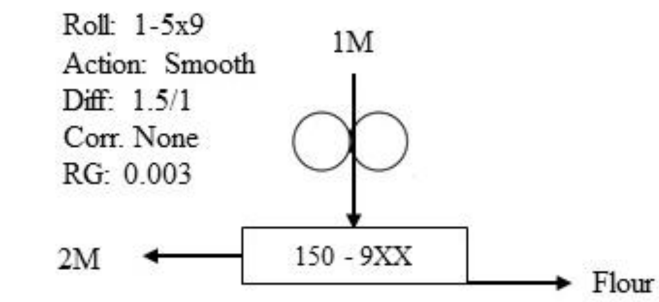
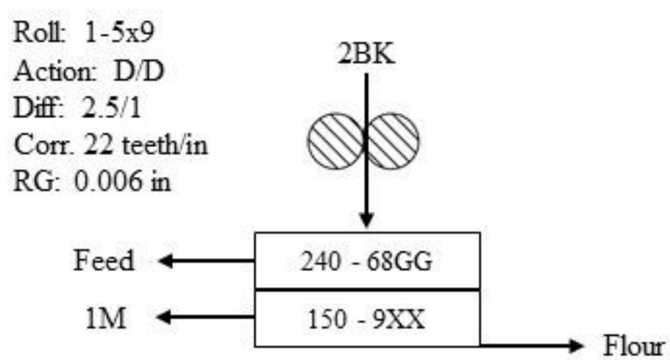


Figure 2.3 Process 2, Kabuli Meal Flow Sheet


Roll: 1-5x9
Action: D/D
Diff: 2.5/1
Corr. 15 teeth/in
RG: 0.08 in
1BK
2BK
1M
240 - 68GG
150 - 9XX
Flour


Roll: 1-5x9
Action: Smooth
Diff: 1.5/1
Corr. None
RG: 0.003
1M
2M
150 - 9XX
Flour


Roll: 1-5x9
Action: D/D
Diff: 2.5/1
Corr. 22 teeth/in
RG: 0.006 in
2BK
Feed
1M
240 - 68GG
150 - 9XX
Flour

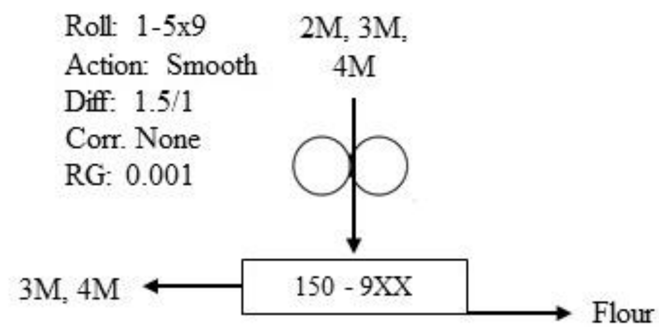

Roll: 1-5x9
Action: Smooth
Diff: 1.5/1
Corr. None
RG: 0.001
2M, 3M, 4M
3M, 4M
150 - 9XX
Flour

Figure 2.4 Process 3, Desi Flour Flow Sheet

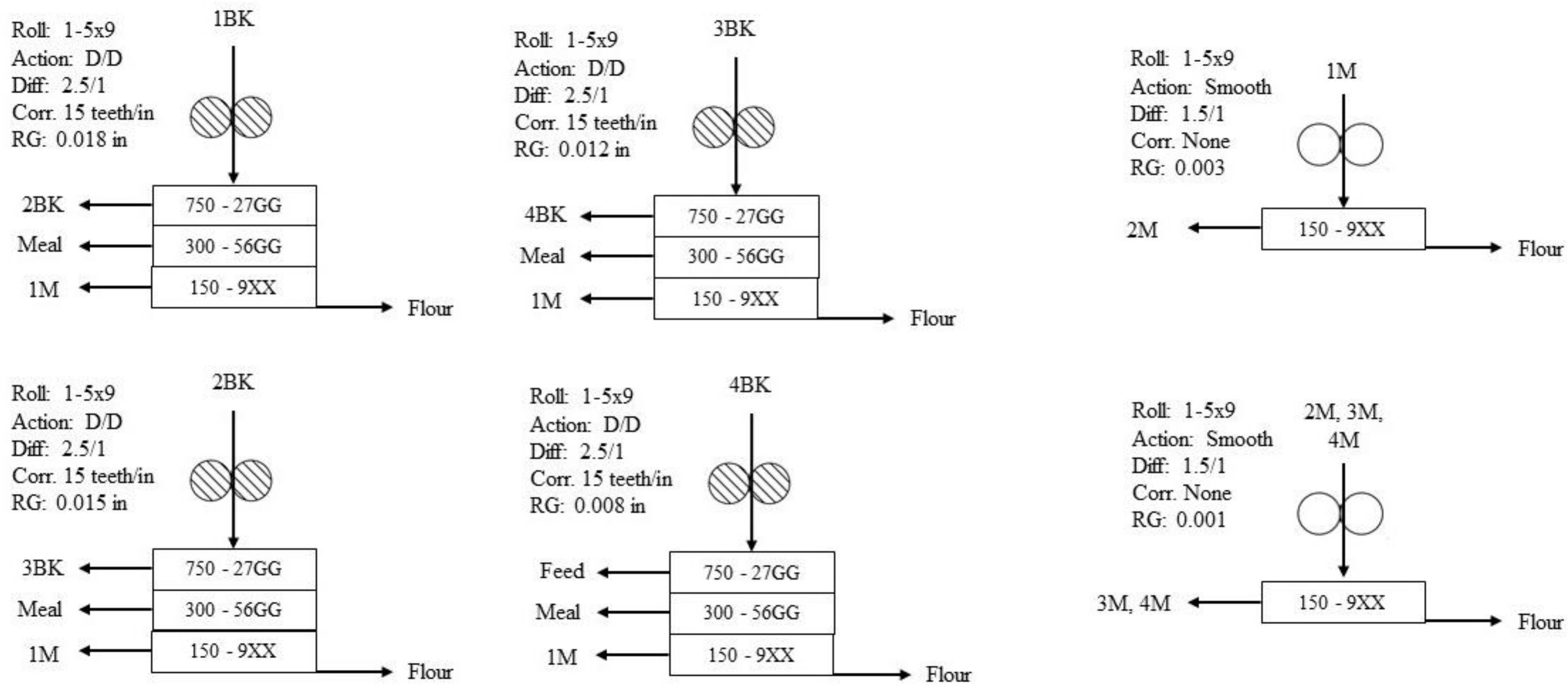
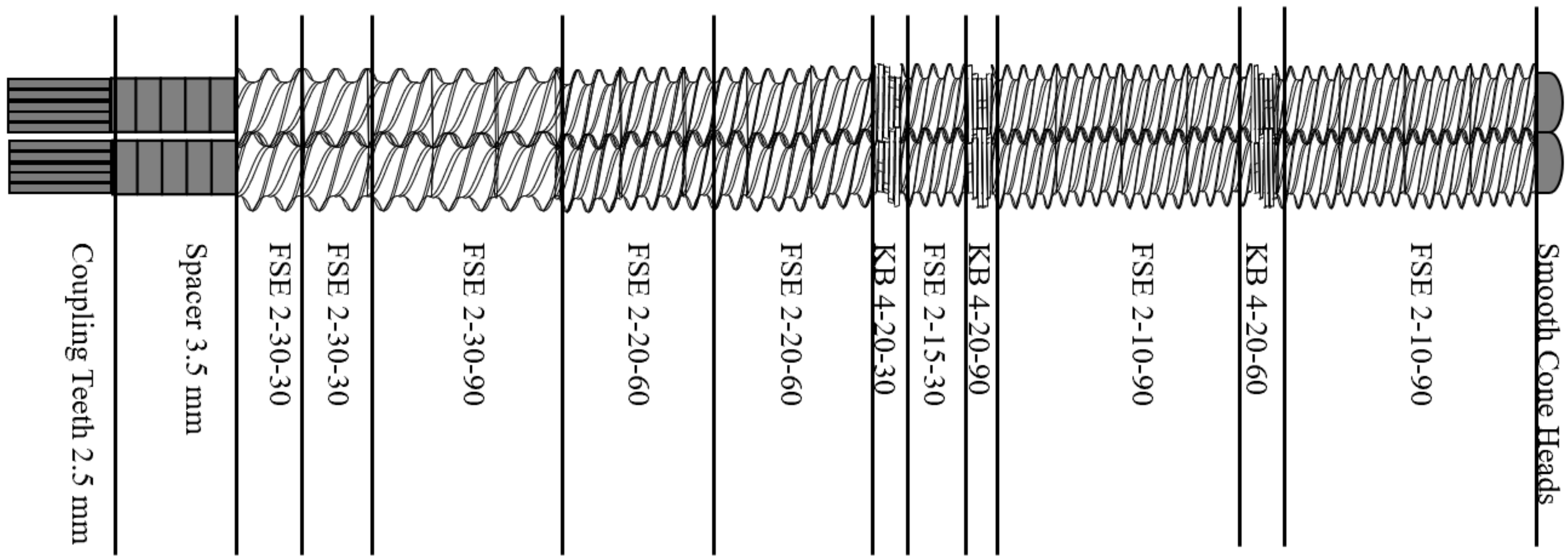


Figure 2.5 Process 4, Desi Meal Flow Sheet

Head No.	1	2	3	4	5	6
Temp.(°C)	30	60	80	90	100	110



FSE: forward conveying screw element (all double flight, intermeshing)
FKB: forward kneading block; RKB: reverse kneading block
Numbers on screw elements: pitch (mm)-element length (mm)
Numbers on kneading blocks: number of disks-total block length (mm)-staggering angle of disks

Figure 2.6 Extruder Screw Profile

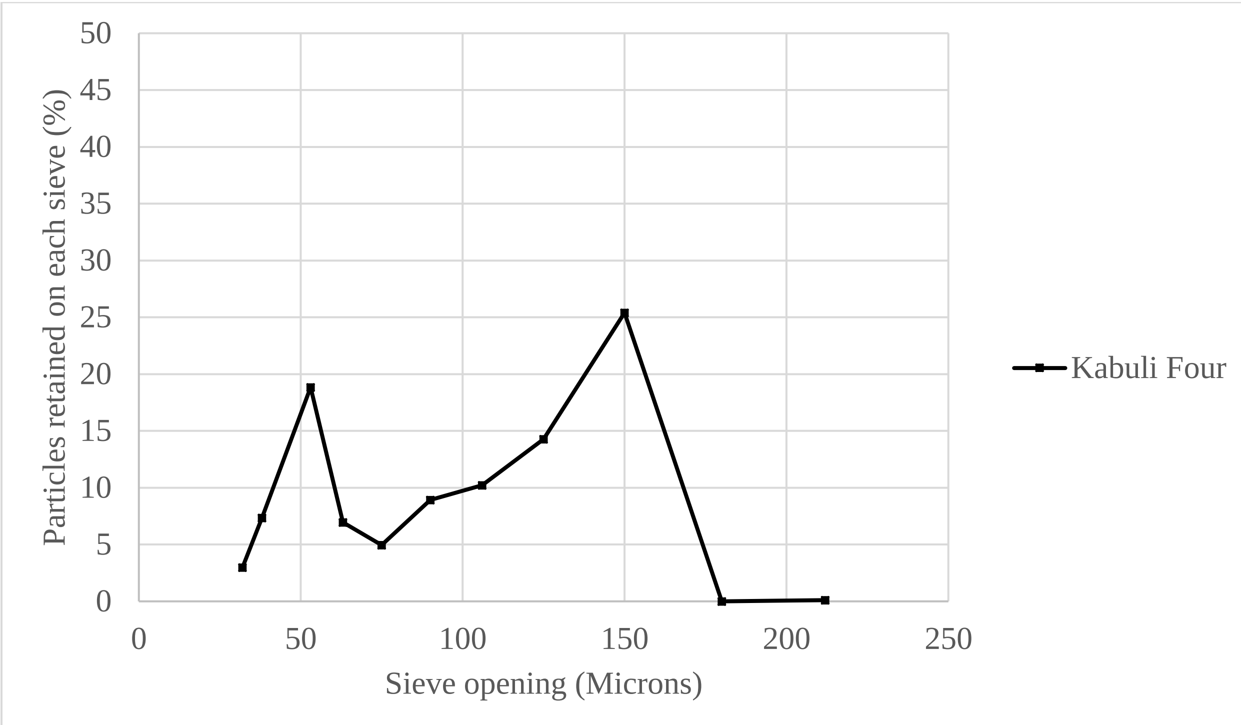


Figure 2.7 Particle size distribution of Process 1, Kabuli flour

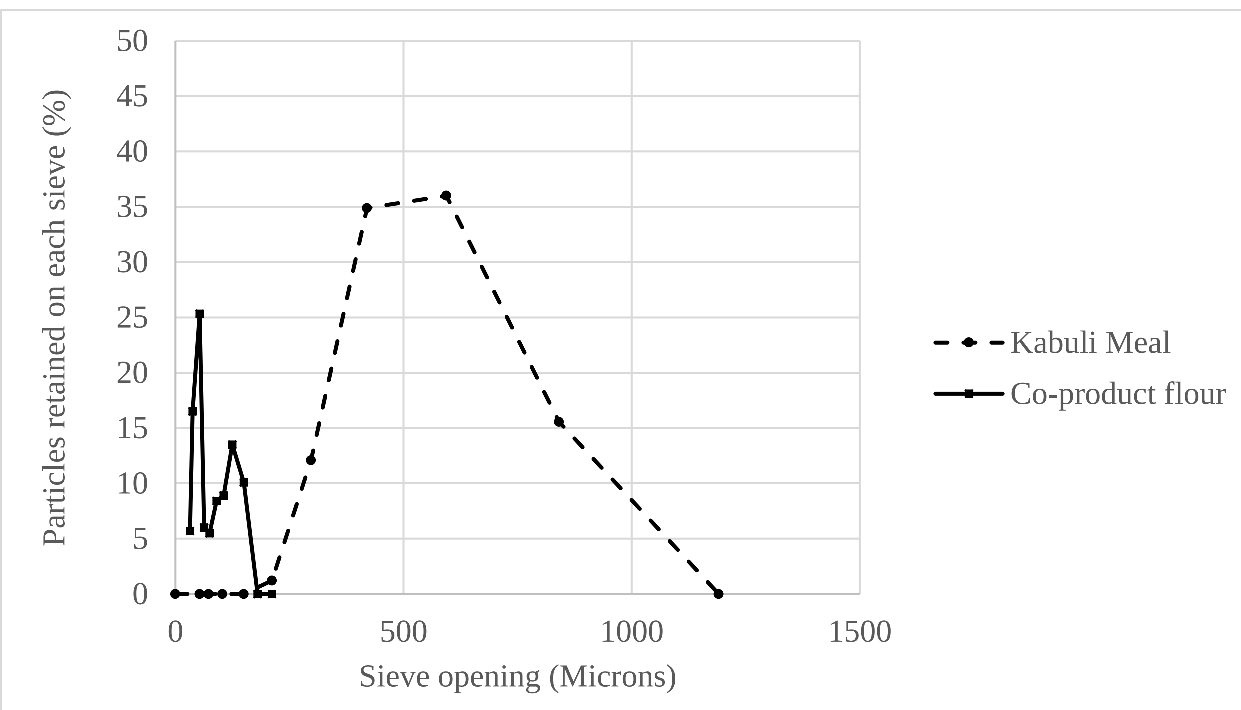


Figure 2.8 Particle size distribution of Process 2, Kabuli Meal and Flour

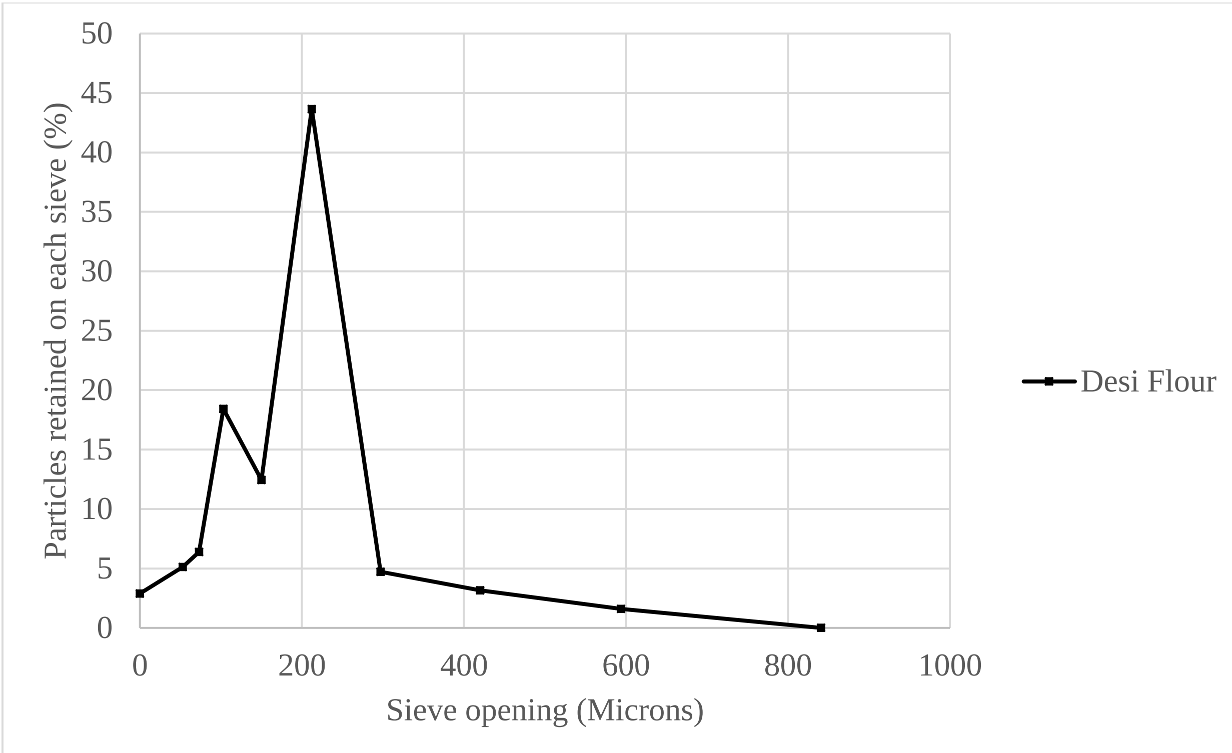


Figure 2.9 Particle size distribution of Process 3, Desi Flour

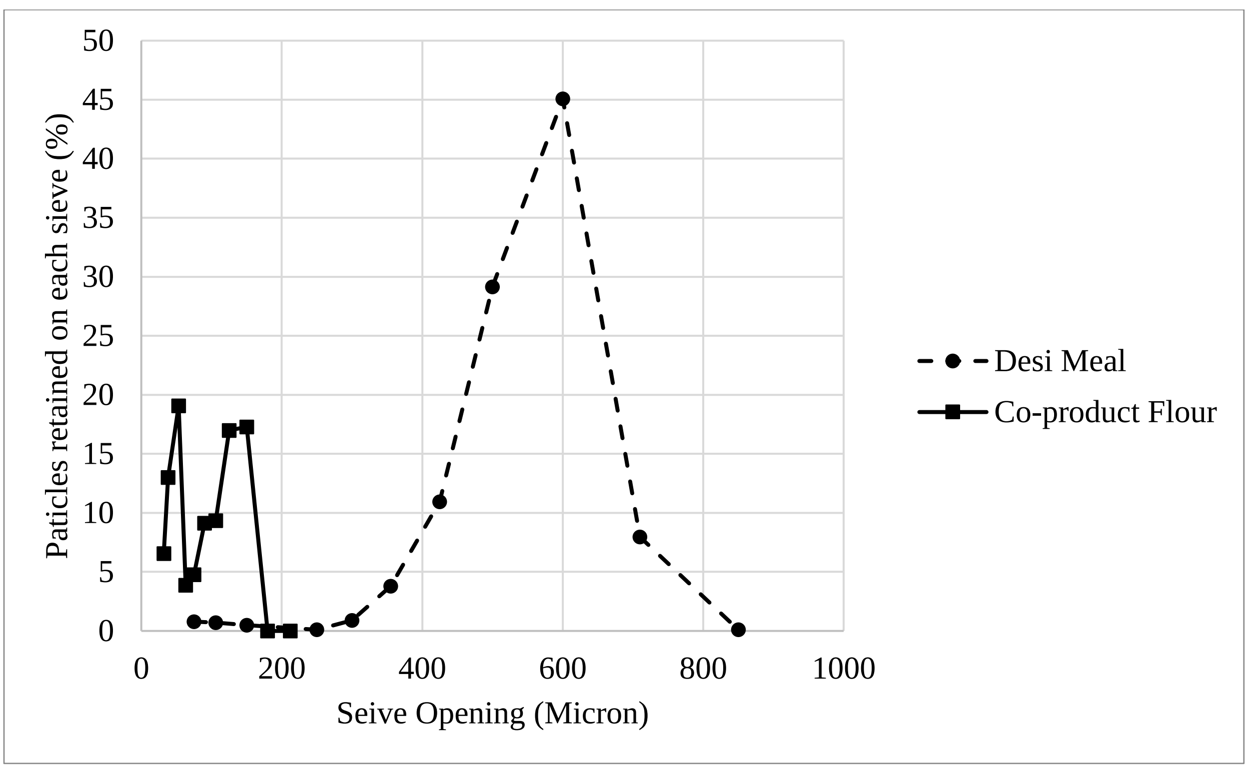


Figure 2.10 Particle size distribution of Process 4, Desi Meal and Flour

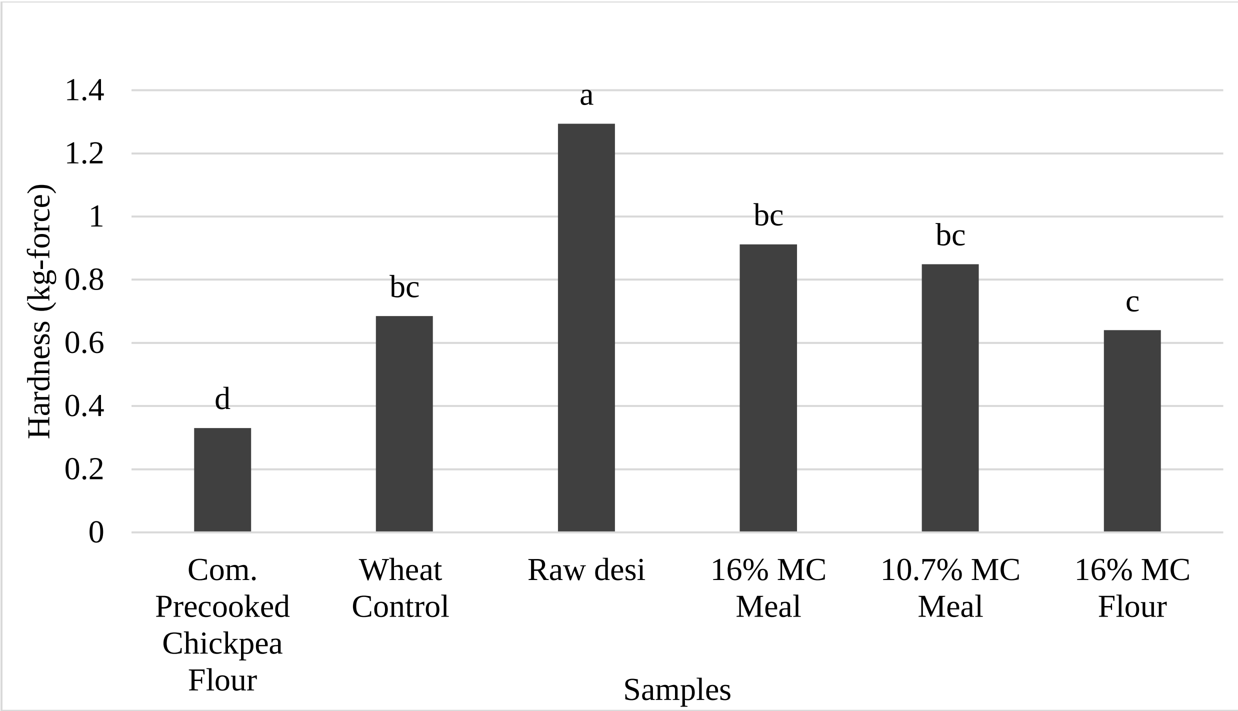


Figure 2.11 Cracker Hardness

Chapter 2 Tables

Table 2.1 Flavor attributes for sensory evaluation

Flavor Attribute	Definition
Oil Heated	The aromatics/flavors associated with heated cooking oils that may include olive oil, vegetable oils such as corn or soybean, and other common cooking oils. Characteristics include a lack of freshness, accompanied by slight brown and musty notes.
Overall Beany	A flavor characteristic of cooked beans and bean products, includes must/earthy, musty/dusty, sour aromatics, starchy, powdery feel, and one or more of the following characteristics: green/pea pod, nutty, sweet or brown.
Doughy	A moist, under baked impression associated with grain products.
Toasted	A moderately brown, baked impression
Leavening	The flat metallic somewhat sour and bitter aromatics associated with baking soda and/or baking powder in baked flour products.
Cardboard	A flat flavor note associated with cardboard or paper packaging that may be associated with a stale characteristic
Musty	Aromatics and flavor associated with wet grain and damp earth.
Overall Grain	A general term used to describe flavor associated with grains. It is an overall grainy impression characterized as sweet, brown sometime generic nutty
Starchy	The flat flavor note associated with raw or processed starch-based grain products such as wheat, rice, oats, and other grains.
Wheat like	Dusty brown, nutty aromatics/flavors that may include light raw or caramelized notes, as well as a slight metallic note.
Bran	Light dusty brown grain-like aromatic/flavor impression that may include characteristics such as slightly raw, sweet, or bitter.
Stale	A perception of lack of freshness, flat
Sweet Aromatics	Aromatics associated with the impression of sweet substances.
Sweet	A fundamental taste factor of which sucrose is typical.
Salt	Fundamental taste factor of which sodium chloride is typical
Metallic	The impression of slightly oxidized metal such as iron, copper, and silver spoons.
Bitter	The fundamental taste factor associated with a caffeine solution.
Astringent	The drying, puckering sensation on the tongue and other mouth surfaces.

Table 2.2 Texture attributes for sensory evaluation

Texture Attribute	**Definition**
Hardness	The force required to bite through the sample with molar teeth (until breaking). Evaluated on first bite down with the molars.
Fracturability	The force with which the sample ruptures. Evaluated on first bite down with the molars.
Initial Crispness	The intensity of audible noise at first chew with molars.
Sustained Crispness	The duration of crispness (audible noise) perceived during mastication that is equal to the first bite.
Flakiness	The perception of individual layers or lamination within the product during first bite down with the molars.
Denseness	Size and ratio of air cells to solid product evaluated during compression of sample with molars on the first bite.
Cohesiveness of Mass	The degree to which the mass holds together during mastication after 5-7 chews.
Moistness of Mass	The perceived amount of wetness of the product in the mouth following 5-7 chews.
Tooth Packing	The amount of sample packed in and between the molar teeth after swallowing.
Particles (residuals)	The amount of small pieces of sample remaining in mouth just after swallowing. This does not incorporate tooth packing and refers only to particulate matter on mouth surfaces other than in and between the molar teeth.
Powdery	Perception of a powdery substance/ coating on the product.
Gritty	The perception of small, hard, sharp particles reminiscent of sand, or granules in pears.
Throat Clear (Yes/No)	The desire to clear throat or cough in order to remove residual from throat

Table 2.3 Physical characteristics of chickpea seeds (Desi and Kabuli)

Sample	Seed Characteristics	Average
Whole Desi (Ravi and Harte, 2009)	Seed Diameter (mm)	6.97 ± 0.10
	100 Seed Weight (g)	20.21 ± 0.67
	Volume of 100 g of seeds (mL)	77.5 ± 0.53
	Bulk Density (g/mL)	0.76 ± 0.01
	True Density (g/mL)	1.29 ± 0.03
Whole Kabuli (Ravi and Harte, 2009)	Seed Diameter (mm)	8.52 ± 0.10
	100 Seed Weight (g)	40.17 ± 0.74
	Volume of 100 g of seeds (mL)	80.2 ± 0.52
	Bulk Density (g/mL)	0.77 ± 0.00
	True Density (g/mL)	1.25 ± 0.00

(Ravi and Harte, 2009) Average ± Standard Deviation.

Table 2.4 Proximate analysis of whole Kabuli and Desi milled fractions

% Dry Basis	Sample	Crude Protein	Crude Fiber	Fat	Ash	Total Starch
Raw Materials	Whole Kabuli Seeds	23.99b	3.84b	5.54d	2.53c	39.9d
	Split Desi Seeds	24.34ab	1.44e	6.47b	2.45d	42.25cd
Process 1 Focus: Kabuli Flour	Flour	24.550ab	0.920g	6.68a	2.41d	46.55bc
	Bran and Shorts	14.22d	22.56a	3.90f	4.31a	12.95f
Process 2 Focus: Kabuli Meal	Meal	23.87b	3.14c	6.43b	2.65b	31.00e
Process 3 Focus: Desi Flour	Flour	22.86c	0.975g	5.93c	2.34e	51.75a
Process 4 Focus: Desi Meal	Meal	25.03a	2.590d	5.15e	2.53c	32.05e
	Flour	24.85a	1.120f	6.83a	2.42d	49.80b

†Letters denote statistical significance for each column P<0.05

Table 2.5 Tempering optimization for Process 1

%	11% for 6 hours	11% for 12 hours	11% for 24 hours
Coarse Bran	3.79a	3.41b	3.12c
Fine Bran	2.89a	3.16a	3.21a
Shorts/Feed	1.67b	0.87b	6.43a
Flour	91.64a	92.55a	87.24b
Process Loss	4.21b	2.07c	7.46a

†Letters denote statistical significance for each column P<0.05

Table 2.6 Milling yields from optimized flour and meal flow sheets

%	Meal	Flour	Bran/Hull	Shorts/Feed	Process Loss
Process 1 Focus: Kabuli Flour	NA	90.64b	6.43a	0.85a	2.07b
Process 2 Focus: Kabuli Meal	66.00b	25.37c	6.11a	0.26b	2.25b
Process 3 Focus: Desi Flour	NA	96.26a	NA	0.014c	3.74a
Process 4 Focus: Desi Meal	76.94a	21.41d	NA	0.04c	2.26b

NA= Not Applicable. †Letters denote statistical significance for each column $P<0.05$

Table 2.7 Extrusion parameters and product characteristics

Sample	Material	In-Barrel Moisture %	Normalized Torque (N-m)	Die Temperature (°C)	Piece Density (g/L)	Specific Length (mm/g)	Expansion Ratio
A	Cornmeal	16	16.1	141.3	278.17c	23.90d	4.22a
B	Process 4: Desi Meal	16	5.9	130	995.03a	89.03a	1.12c
C	Process 4: Desi Meal	10.7	5.0	146.3	913.07b	84.12b	1.21c
D	Process 3: Desi Flour	16	6.6	131.2	1091.64a	43.86c	1.52b

†Letters denote statistical significance for column $P<0.05$

Table 2.8 RVA results of raw and precooked flours

Sample	Pasting Temp (^oC)	Peak Viscosity (cP)	Breakdown (cP)	Final Viscosity (cP)	Setback (cP)
HRW Wheat Flour	68.0c	2983.6a	1196.6a	3393.3a	1606.4a
Process 1: Raw Kabuli Flour	77.5a	888.3c	105.7b	1052.3c	269.7b
Process 3: Raw Desi Flour	76.7a	1159.0b	90.7bc	1366.0b	297.7b
Commercial Precooked Chickpea Flour	-	30-80	-	30-80	-
Extruded Flour B	74.5ab	449.7d	37cd	612.7d	200.0c
Extruded Flour C	70.0bc	249.7e	32cd	378.3e	161.33c
Extruded Flour D	59.1d	208.3e	25.0d	268.7e	85.3d

†Letters denote statistical significance for each column $P<0.05$

Table 2.9 Cracker sensory - Texture

	Original Wheat Thins™	Saltine Crackers™	Wheat Control	Raw Desi Flour Control	Commercial Chickpea Flour	Extrusion Precooked Flour: B	Extrusion Precooked Flour: C	Extrusion Precooked Flour: D
Hardness	5.033 cd	4.367 d	6.033 b	8.600 a	4.467 d	8.167 a	8.233 a	7.833 a
Fracturability	3.900 d	3.600 d	5.100 c	6.467 b	3.800 d	7.867 a	7.733 a	7.200 ab
Initial Crispness	7.200 c	6.100 cd	6.467 cd	8.533 b	6.100 cd	9.933 a	10.367 a	10.400 a
Sustained Crispness	3.633 bc	3.567 c	3.667 bc	3.867 bc	3.267 c	5.100 a	5.633 a	4.667 ab
Flakiness	3.500 ab	4.167 a	2.233 c	0.900 e	1.733 cd	1.000 de	1.000 de	0.900 e
Denseness	5.000 cd	3.533 e	4.867 cde	6.967 ab	4.067 de	7.700 a	7.400 ab	6.100 bc
Cohesiveness of Mass	5.233 a	5.600 a	3.833 b	3.400 bc	2.467 c	3.533 bc	3.300 bc	3.000 bc
Moistness of Mass:	4.267 ab	3.900 abc	3.467 bcd	3.133 cde	2.067 f	2.733 def	2.833 def	2.367 ef
Tooth Packing	3.133 ab	3.167 ab	3.300 a	3.400 a	1.600 c	2.267 bc	2.533 abc	1.867 c
Particles (Residuals)	3.733 ab	2.967 b	3.333 ab	4.167 a	3.600 ab	4.267 a	4.200 a	4.167 a
Powdery	1.533 ab	0.667 cd	1.200 bc	1.733 ab	1.600 ab	1.433 ab	1.933 a	1.867 a
Gritty	2.100 ab	0.700 cd	1.533 bc	2.233 ab	2.667 a	2.933 a	2.833 a	2.533 a
Throat Clear: 1=Yes 2=No	1.733 ab	1.933 a	1.800 ab	1.533 bc	1.533 bc	1.533 bc	1.333 c	1.333 c

†Letters denote statistical significance for each column P<0.05

Table 2.10 Cracker sensory- Flavor

	Original Wheat Thins™	Saltine Crackers™	Wheat Control	Raw Desi Control	Commercial Chickpea Flour	Extrusion Precooked Flour: B	Extrusion Precooked Flour: C	Extrusion Precooked Flour: D
Oil-Heated	4.067 b	1.233 d	3.733 b	4.667 ab	3.967 b	5.033 a	4.100 ab	3.967 b
Overall Beany	1.067 d	0.333 d	2.333 c	3.667 a	2.833 abc	3.267 abc	3.367 ab	2.600 bc
Doughy	0.067 d	0.500 bcd	1.067 a	0.933 ab	0.200 d	0.267 cd	0.000 d	0.000 d
Toasted	5.867 ab	4.033 cd	2.133 f	2.900 ef	4.967 bc	6.667 a	5.900 ab	4.900 c
Leavening	2.200 a	2.033 ab	2.167 a	2.367 a	2.167 a	2.333 a	2.400 a	1.733 ab
Cardboard	2.133 c	3.167 ab	3.500 a	3.133 ab	3.033 ab	3.033 ab	2.667 bc	3.100 ab
Musty:	0.067 bc	0.000 c	0.333 ab	0.533 a	0.067 bc	0.000 c	0.000 c	0.067 bc
Overall Grain	5.000 a	3.667 bcd	3.200 bcd	3.100 cd	3.033 d	3.333 bcd	3.800 bc	3.433 bcd
Starchy	3.933 abc	4.600 ab	4.767 a	4.767 a	3.567 c	3.733 bc	3.867 abc	3.833 abc
Wheat Like	5.633 a	4.500 a	2.667 b	2.300 b	2.300 b	1.933 b	2.367 b	2.033 b
Bran	3.200 a	0.000 c	0.600 bc	0.400 bc	0.700 b	0.333 bc	0.433 bc	0.333 bc
Stale	0.133 d	0.967 abc	1.133 ab	1.433 a	0.600 bcd	0.500 bcd	0.133 d	0.267 d
Sweet Aromatics	2.500 a	0.867 c	1.300 bc	1.300 bc	1.000 bc	1.200 bc	1.100 bc	1.600 b
Sweet	0.967 a	0.100 b	0.300 b	0.367 b	0.267 b	0.200 b	0.367 b	0.133 b
Salt	2.133 a	1.233 bc	1.700 ab	1.133 c	1.100 c	1.267 bc	1.167 bc	1.400 bc
Metallic	0.333 b	0.167 b	0.433 ab	0.833 a	0.467 ab	0.500 ab	0.400 ab	0.333 b
Bitter	2.433 abc	2.000 c	2.500 ab	2.667 ab	2.567 ab	2.800 a	2.633 ab	2.633 ab

Astringent	1.100 bc	0.733 c	1.200 abc	1.433 ab	1.633 a	1.433 ab	1.700 a	1.200 abc
Aftertaste: Overall Beany	0.533 b	0.000 b	1.433 a	2.300 a	1.867 a	1.567 a	1.867 a	1.667 a
Aftertaste: Leavening	1.400 ab	1.400 ab	1.700 a	1.733 a	1.400 ab	1.567 ab	1.100 ab	1.133 ab
Aftertaste: Starchy	2.600 ab	2.867 ab	2.967 ab	3.200 a	2.533 b	2.633 ab	2.833 ab	2.700 ab
Aftertaste: Overall Grain	3.433 a	2.233 b	1.900 b	2.200 b	1.933 b	1.967 b	2.400 b	1.967 b
Aftertaste: Salt	1.533 a	0.700 b	1.667 a	0.833 b	0.600 b	0.933 b	0.733 b	0.833 b
Aftertaste: Metallic	0.400 ab	0.200 b	0.667 ab	0.667 ab	0.767 a	0.600 ab	0.733 a	0.500 ab
Aftertaste: Sweet	0.800 a	0.133 b	0.333 b	0.100 b	0.233 b	0.000 b	0.000 b	0.000 b
Aftertaste: Bitter	1.700 bc	1.067 c	2.233 ab	2.267 ab	2.167 ab	2.500 a	2.267 ab	2.200 ab

†Letters denote statistical significance for each column $P<0.05$

Chapter 3 - Pilot Scale Roller Milling of Chickpeas into a De-hulled Coarse Meal and Fine Flour

Abstract

Chickpeas and other high protein plants are becoming increasingly popular. Chickpea milling has traditionally been done using attrition or hammer mills. Roller mills have been widely used with grains such as wheat or corn and can provide a controlled particle size range. However, the use of roller mills on chickpeas has not been extensively researched. Pilot scale milling trials compared whole Kabuli against split and de-hulled Desi chickpeas. A flow sheet was designed and optimized for meal production with minimal co-product flour produced. Milling yields, particle size, and proximate analysis data were recorded. The optimum flow sheet consisted of 4 break passages, 2 smooth roll passages, and 4 purifiers. Results showed whole Kabuli chickpeas had a higher meal yield, 63.8%, than split Desi seeds, 54.1%, both percentages proportional to initial seed weight. The remaining 36.2% or 45.9% consisted of co-product flour, feed streams and process losses. Both meals had an average particle size between 600-850 microns and both flours had a bimodal particle size distribution with peaks at 53 and 90-150 microns. The use of purifiers allowed greater separation of hull and resulted in lower crude fiber levels in the Kabuli meal. Proximate analysis trends were similar for both chickpea meals with higher protein (~2% more), crude fiber (~1% more) and ash (.1-.3% more) in the meal compared to the co-product flour. The co-product flour had substantially higher total starch (~15% more) than the meal. The results of this research can be used to modify wheat mills to process chickpeas.

Practical Application

This research can be used to mill chickpeas using equipment and facilities traditionally designed for wheat and corn products. The controlled particle range of roller mills allows for more end products besides split seeds and flour. The chickpea meal can be used in processes where raw material flow is a concern, such as in extrusion.

3.1 Introduction

High protein pulses, including chickpeas are gaining consumer focus. Many varieties are commercially available and can thrive in a variety of growing regions and climates. The wide growing region has lead chickpeas to become an important food crop worldwide (Gil et al., 1996). Pulses are gaining more attention recently by being a good source of plant-based protein without being an allergen, like soybeans. Chickpeas contain high levels of proteins, 23-26%, while also containing substantial levels of carbohydrates, 37-39%, (Gil et al., 1996).

Chickpeas can be also be beneficial by containing antioxidant properties (Heiras-Palazuelos et al., 2013). Unfortunately, chickpeas also contain anti-nutritional properties that can reduce digestability. Some of these anti-nutritional properties can be reduced by cooking (Adamidou et al., 2011). Previous research found that 75% of these polyphenolic compounds are found in the hull (Singh, 1988). By milling and removing the hull this can greatly reduce these anti-nutritional factors reducing the need for intense cooking to removed them.

Sustainability is another reason for the growing popularity of pulses. Chickpeas provide plant-based protein that requires less resources, such as land and water, to grow than animal protein (Mekonnen and Hoekstra, 2010). As global demand for protein increases the need for more sustainable plant-based ingredients will need to increase. Due to the increased use, new processing methods are needed to fulfill the demands of consumers. Recent products, such as plant-based meat alternatives, use proteins that are isolated from chickpeas, peas, and other pulses (van der Weele et al., 2019).

Chickpeas are typically sold as whole seeds, split seeds, and flour. Breaking down chickpeas into smaller particles such as in split chickpeas or flour can reduce cooking times compared to whole seeds. This allows for a wide variety of food applications. Some traditional processing methods include roasting, boiling, or slurry cooking. Chickpea milling has been primarily done using dahl mills, which use attrition forces to de-hull the seeds and split the cotyledons apart (Ravi and Harte, 2009). Other milling methods use hammer mills to grind the chickpeas into flour (Ravi and Harte, 2009). These milling and dehulling methods typically require soaking, dehulling, drying, and then milling. This process can be very energy and water intensive and limits capacity by using batch hydration methods.

Roller mills have been used to process grains for hundreds of years. Improvements have been made but the same principle remains of passing material, such as wheat, between two rotating rollers to break open the grain and reduce the particle size. Roller mills have been used extensively on grains such as wheat and corn to produce many products such as de-hulled or whole flours, coarser meals, etc. Previous milling research with chickpeas focused on attrition mills to de-hull and split chickpeas (Wood et al., 2008). Research has not focused on the use of roller mills on chickpeas. Roller mills have been used to remove bran from wheat with minimal water needed for tempering and could be used to de-hull chickpeas. Roller mills also provide a more controlled particle size range than hammer mills allowing for the creation of coarse chickpea meal and fine flour from the same equipment.

This research focused on evaluating the efficiency of milling chickpeas using roller mills in a facility designed to mill wheat. Two varieties of chickpeas at different pre-processing levels were evaluated, whole Kabuli and split and de-hulled Desi. The chickpea samples were evaluated on milling yields, proximate analysis, particle size, and flowability. These varieties are common and commercially available. Whole Kabuli seeds are typically larger and with twice the 100 seed weight of whole Desi seeds (Ravi and Harte, 2009). The split and de-hulled chickpeas will provide insight into whether starting with whole or pre-processing seeds is more efficient. The results of this research can be used and adapted to process chickpeas on equipment typically used in commercial wheat mills. This research provides wheat mills a possibility to diversify their milling portfolio.

3.2 Materials and methods

3.2.1 Materials

Two varieties of chickpeas were studied, Kabuli and Desi. Kabuli chickpeas were received as whole seeds and Desi chickpeas were received spilt and de-hulled seeds. These were chosen to compare differences in chickpea varieties and preprocessing levels.

3.2.2 Pilot Scale Milling

Chickpeas were milled on a pilot scale research wheat flour mill (Hal Ross Flour Mill, Kansas State University, Manhattan, KS, USA). The mill was modified to produce the maximum amount of chickpea meal and minimal co-product flour. This decision was made to create a novel ingredient, chickpea meal, and because designing the flow for meal would be a more difficult task than for flour. The milling flow shown in Figure 3.1 could easily be modified to produce only flour by regrinding the meal to flour, if desired.

3.2.2.1 Cleaning House

Chickpeas were processed through the "cleaning house" system of the flour mill that consisted of a combi-cleaner, scourer and infestation destroyer. The combi-cleaner used aspiration and gyratory vibration to separate based on density. The combi-cleaner removed light materials, such as loose hull or discolored seeds, and denser materials, such as stones. The scourer used abrasion to remove dust and debris from the outside of the seeds. The scourer was originally tested to remove the hull of the chickpea, by increasing intensity, but was found to not be effective. The infestation destroyer used impact force to remove hollowed out grain from insect pests. The chickpea seeds did not have any evidence of insects, but this equipment was used to split some seeds and break off loose hull. All cleaning equipment had a capacity of 6,000 lbs./hr. (2751.6 kg/hr.).

3.2.2.2 Storage and Tempering

After cleaning the chickpeas were stored in tempering bins. Benchtop milling trials, from chapter 2, concluded that tempering to 11% moisture content (MC) wet basis (w.b.) for 12 hours was ideal for hull separation. The chickpeas arrived at the flour mill at 10.9% MC, so tempering was not needed.

3.2.2.3 Roller Milling

Chickpeas were milled using roller mills to create a coarse meal between 300 and 600 microns. Particles that were produced finer than 300 microns were milled to flour less than 150 microns. The roller mills and sifters had a capacity of 2.5 MT/hr. but were operated at 1MT/hr. Milling equipment included a double high break roll stand (MDDO, Bühler Group, Uzwil, Switzerland) and a single high break roll (MDDM, Bühler Group, Uzwil, Switzerland). Samples were sifted with sifter boxes (MPAJ, Bühler Group, Uzwil, Switzerland) to remove larger particles of hull (>1041 microns), finer particles too small for meal (<315 microns) and flour

(<150 microns). Air separation was used to separate light hull from the meal through the use of four purifiers (MQRF, Bühler Group, Uzwil, Switzerland). The final flow sheet used for both Kabuli and Desi chickpeas is shown in Figure 3.1.

The roll gaps were adjusted, but not recorded between samples to ensure similar milling intensity between chickpea samples. The break system was similar to the benchtop trial flow sheet for process 2. The major difference between benchtop and pilot scale was there was no sieve separation between the 1st and 2nd break because a double high roll stand was used. Another difference between the benchtop and pilot scale was only 2 reduction rolls used in the pilot scale versus 4 rolls in the benchtop trials. The pilot scale reduction rolls (2M and 3M) were gear driven and could grind with more force than the belt driven benchtop mills so less roll stands were needed.

Chickpeas were first pneumatically transported from the tempering tanks to the 1st and 2nd Break (BK) double high roll stand. At this double high roll stand the chickpeas were ground twice without sifting in-between to break open the seeds and remove the hull in large pieces. After grinding particles were pneumatically transferred sifters where particles were separated on size. Particles larger than 1041 microns were sent to the third break (3BK), particles larger than 560 microns were sent to the 1st Purifier (P1), particles larger than 315 microns were sent to the 2nd Purifier (P2), particles larger than 118 microns were sent to the grader sifter (GR-1) and particles smaller than 118 microns was collected as flour (F1-2).

The next break roll stand, 3BK, processed the material from the 1/2 BK roll stands and P1. After grinding on 3BK particles were sent to be sifted. Particles were sifted with the same separation as before; the only difference was that particles larger than 1041 were sent to the fourth break roll (4BK) stand.

The 4BK roll stand processed material from 3BK and P1. After grinding on 4BK separation differed from the other break roll stands. Particles larger than 710 microns were separated as hull or feed. Particles larger than 315 microns were sent to the third purifier (P3). Particles larger than 118 microns were sent to GR-1 and smaller than 118 microns were separated as flour.

The grader sifter separated material from 1/2BK, 3BK, 4BK and the 4th Purifier (P4). Particles less than 150 and 118 microns were separated as flour. Particles larger than 150 microns were sent to the 4th Purifier (P4).

Smooth roll stands were used to grind particles too small for meal (<315 microns) but larger than flour (>150 microns). These stands are labeled as they would be in a commercial flour mill as 1M and 2M for processing "middlings". After grinding on the first smooth roll, 1M, particles less than 150 microns were separated as flour and particles larger than flour were sent to 2M. The same separation was used after 2M but with larger particles removed as feed and labeled as overs of 2M or shorts.

The purifiers had 3 decks and used screens with the openings recorded in grit gauze (GG). The particles pass along each screen, aided with air agitation, from left to right with larger GG numbers corresponding to smaller openings. As particles fall through one deck they pass onto the lower deck. Empty squares in the purifier figure show where screens were removed. These screens were removed to reduce the amount of purified chickpea meal being sent to be reground. Screen size could be manipulated in future research or milling facilities to achieve desired particle ranges.

For P1, particles that did not fall though the first deck were sent to 3BK to be reground. For P2 and P3, particles that did not fall through to the second deck were collected as hull.

Particles that fell through the first deck but remained on the second deck and fell through the open screen at the end were collected as meal. Particles that fell through the first two decks and remained on the 3rd deck until falling through the open screen were also collected as meal. P4 differed from the other purifiers by having all right end sieves removed as no hull contamination was found in any of the outlets. The last purifier, P4, was not needed for sifting but was necessary to ensure the product flowed through the correct pneumatic lines for separation.

3.2.2.4 Packaging and Sealing

Final products, meal and flour, were bagged in plastic lined kraft paper bags and sealed with thread. Each bag weighed approximately 50 lbs. (22.7 kg) and was palleted with 5 bags per row and no more than 10 rows high.

3.2.3 Proximate Analysis

Proximate analysis of samples was done by SDK laboratories (Hutchinson, KS, USA) in duplicate. The crude protein (AOAC 976.06) was measured by combusting samples and analyzing the amount of nitrogen in the sample. Crude protein for chickpeas was calculated using N x 6.25 (Tavano et al. 2016). Crude fiber (AOAC 962.09) was determined after digestion of sample with sulfuric acid and sodium hydroxide and then combusted. Crude fat by acid hydrolysis (AOCS Ba 3-38) was measured by extracting oil with petroleum ether and given as a percentage of original sample weight. Total starch (AOAC 979.10) was measured by digesting starch with enzymes and the glucose level was measured through spectrophotometry. Whole chickpea moisture contents were determined using a laboratory oven at 105oC for 72 hours (ASAE S352.2). Moisture contents of ground samples were determined using a laboratory oven at 135oC for 2 hours (AACC44-19.01).

3.2.4 Particle Size

Particle size analysis on final flour and meal streams was done using an Alpine jet sieve analyzer (e200LS, Hosokawa Alpine, Germany) or a Ro-Tap sieve (RX-29, W.S. Tyler, Mentor, Ohio, U.S.A.). Samples were measured in triplicate.

3.2.5 Flow Properties

Bulk density of the meal and flour was done using a Winchester cup arrangement that ensured consistent filling into a cup of known volume and the mass was recoded. Bulk density was calculated using the equation below.

$$\frac{Sm}{Sv} \qquad \text{Equation (2.3)}$$

Where Sm is sample mass (g) and Sv is sample volume (4.732x10-4 m3).

Tapped density was calculated using an Autotap density analyzer (Quanta Chrome Instruments, Boynton Beach, FL, USA). A graduated cylinder was filled with a known mass of sample and then the cylinder was then tapped 720 times (260 taps/min) and the volume was recorded after tapping. The tap density was calculated using the sample mass and tapped volume and recoded in g/mL.

Angle of repose was measured using a Winchester cup arrangement. The funnel was filled with 100g of sample and allowed to pour from a height of 10 cm to a flat aluminum tray. The diameter of the pile was recorded three times from varying angles and averaged. The height was measured once. Angle of repose was calculated using the following equation.

$$\theta = tan^{-1}(\frac{2H}{D}) \qquad \text{Equation (2.4)}$$

Where Θ is the angle of repose, H is the height of the pile formed, and D is the average diameter of the pile.

The flowability of the flour and meal was measured by comparing the Hausner ratio (HR) shown in Equation 5 and the Compressibility Index (CI) shown in Equation 6. These values, along with the angle of repose, will be able to categorize the flow properties of the product as excellent to very, very poor, as shown in Table 2.

$$\text{Hausner ratio}=\frac{TD}{BD} \qquad \text{Equation (2.5)}$$

Where TD is the tapped density and BD is the bulk density.

$$\text{Compressibility Index}=100*\left(\frac{TD\text{-}BD}{TD}\right) \qquad \text{Equation (2.6)}$$

Where TD is the tapped density and BD is the bulk density.

3.3 Results and discussion

3.3.1 Milling Yields

The overview of the milling yields can be found in Table 3.2 Almost twice the amount of Kabuli chickpeas were milled compared to Desi chickpeas. This was important to note because process loss was higher for the Desi chickpeas and this loss was most likely attributed to the shorter run time. The process loss for both chickpeas would be expected to be lower if the mill was ran for a longer production time.

Kabuli chickpeas milled more efficiently into meal than Desi chickpeas with almost 10% more meal. Desi chickpeas produced less meal and less flour but produced more “overs of 4th BK” this was coarser material that would be hull if it were Kabuli chickpeas. Upon visual inspection, this stream was coarse endosperm. This larger section showed that the break system should have had smaller roll gaps to increase grinding action to produce smaller particles. Another solution could have been to send this section back into the break system. However, due to the capabilities of the Hal Ross Flour mill it was not possible to re-route this stream back in the process.

Comparing only the products of each process, (meal/(meal+flour) or flour/meal+flour), Desi chickpeas actually produced more meal than flour. Kabuli chickpeas, using the previous formulas produced 72.7% meal and 27.3% flour compared to Desi Chickpeas yields of 77.1% meal and 22.9% flour. If the “Overs of 4th BK” from process 2 (Desi) could have been re-entered into the break system this could have increased the meal and flour production. This could have made split Desi chickpeas more efficient to mill. Both meal yields were still fairly low (<80%) and could not be considered highly efficient process when designed for meal. Selling the co-product flour would increase the cost effectiveness of the process.

The hull stream, “Overs of 4th BK”, yielded 6% hull removal from the Kabuli chickpeas. This is similar to levels reported previously that chickpeas contained 5% hull (Ravi & Harte, 2009). The 1% difference could have been from endosperm still in the hull stream or due to varietal differences. The remaining 1% could be separated by density or air separation but since the amount is so small it would not likely be cost effective. The “overs of 2M” represent any material that was not ground to flour through the reduction system. This material was harder than the rest of the flour and therefore stayed intact longer. This increased strength most likely was caused by the increased protein level. It has been reported previously that the outer layer of the chickpea endosperm had higher protein levels while the center of the endosperm consisted of more starch (Wood et al., 2011).

3.3.2 Proximate Analysis

The proximate analysis data for both processes was recorded in Table 3. The raw material section showed the similarities and differences between the two chickpea types. They both had similar protein levels around 24%. Crude fiber was lower in the Desi seeds because they had been dehulled previously. The dehulling partially explained the increased fat and starch in the

Desi seeds as chickpea hull is known to contain low levels of fat and protein while having high levels of fiber (Soni and Sarita, 2014). Direct correlations cannot be made solely between the raw materials as they can have varietal differences. When all proximate contents were combined it was clear that a portion of the composition was missing. The large difference (~25%) was believed to be oligosaccharides that would have not shown up in any of the other analysis (Xu et al., 2014).

The proximate analysis of process 1 showed the effect of de-hulling process as well as differences in meal and flour. The hull stream contained the largest amount of crude fiber and ash of all of the process 1 streams. The meal stream had higher crude fiber and ash than the flour stream showing signs of higher hull contamination in the meal. The ash content of the hull contradicted the benchtop work with Kabuli chickpeas that found that ash content was not significantly lowered by hull removal. One possibility was that the use of the purifiers increased hull separation and reduced endosperm in the hull stream that allowed for proximate analysis differences to be observed. Further studies would need to be done to correlate the ash content and hull contamination in chickpeas before ash could be used as an indicator, similar to wheat milling.

The significantly higher protein and lower starch in the meal stream from both processes further enforced the theory that protein content increases strength. The outside of the endosperm that contained higher protein remained in larger granules than the inner endosperm that contained more starch (Wood et al., 2011). Similar trends are seen with corn, horny vs floury endosperm, and wheat, hard vs soft wheat (Hoseney, 1986). The “Overs of 2M”/shorts had significantly higher protein than the flour stream again reinforcing the strength theory.

Process 2 results followed similar patterns as process 1. The meal stream again contained significantly more protein and lower levels of starch. The flour stream from process 2 had the highest starch content of any sample tested. The "Overs of 4th BK" proximate results were practically similar to the meal stream. This similarity further emphasizes that the "Overs of 4th BK" stream should be re-milled to create meal and not discarded as feed.

The differences in starch and protein showed additional benefits to focusing on meal. The separation based on particle size allowed for different proximate results. These differences, such as in the flour, could lead to different functionality in the raw flour making it more beneficial in products or processes where the increased protein is not desired. The decreased protein was also done without the use of water or chemicals further increasing the sustainability of the ingredient.

3.3.3 Particle Size

Particle size data were recorded in Figures 3.2-3.4. The particles retained on each sieve were represented as a percent of each sample and the magnitude of the distributions was not related to yield.

The particles sizes of the final products from both processes was recorded in Figure 3.2. The flour for both chickpeas follows similar particles size ranges with a bimodal distribution around 53 and 90-150 microns. These bimodal peaks were also seen in benchtop milling trials as well (Martin et al., 2020). The previously mentioned strength theory that compared meal and flour could explain the bimodal peaks. The larger micron peak could contain more protein than the smaller micron peak. Further testing could be done to confirm this.

The wider range of Kabuli meal was previously observed in benchtop trials and was due to the grinding intensity of the break system. However, at pilot scale, the larger range was more likely attributed to the removed purifier screens. The range of meal could be adjusted further by a change of purifier screens. The majority (~92%) of Kabuli meal was less than 850 microns which ensured it was still an acceptable range of meal.

All products from process 1 are shown in Figure 3.3. The extremely large range of the hull showed that the break system was efficient at removing the hull in as large of pieces as possible. The parts of the meal and hull distribution that overlap showed the importance of the purifiers in the milling flow. The purifier separated the bran with air separation that couldn't be separated by only particle size differences. The smaller particle range of the shorts stream showed that this could have been collected as flour. It was not clear if blinding of the screens led to these smaller particles not being included in the flour stream. Yet, because this stream was so small, 1.9%, it was not a major concern that warranted further research.

Shown in Figure 3.4, the "Overs of 4th BK" for Desi chickpeas is would only need minimal grinding to convert it into meal. As mentioned previously, there was not a way to transport this stream back into the break system. In a commercial mill this would not be wasted and would increase meal and flour yields. Again, the shorts stream should have been collected as flour, but this stream only contributed to 0.7% of the total products and was not considered practically significant.

3.3.4 Flow Properties

The flow properties of the chickpea products were recorded in Table 3.4. As expected, both flour streams flowed less easily compared to the meal streams. Kabuli flour from process 1 had better flow properties than Desi Flour. Kabuli flour was labeled as "excellent" by the Hausner Ratio and Compressibility Index, but only "passable" by the Angle of Repose test. Desi Flour was labeled "good" by the Hausner Ratio and Compressibility Index, but on the upper end of "passable" by the Angle of Repose" test. These tests show the importance of using more than

1 flowability measurement when testing a sample, as they can often times result in different classifications. Fortunately, by this scale neither of the flour streams showed any major flowability or transportation issues.

The meal streams flowed better than the flour samples. This was expected due the larger particle size. Kabuli and Desi meal were labeled as “excellent” or better. The Hausner ratio and Compressibility Index values were better than shown in the table due to the tapped density levels. Both meals flowed so well it caused negative values for the Compressibility index.

3.4 Conclusion

The results of this research showed that chickpeas can be de-hulled and ground into meal and flour using roller mills. Whole Kabuli chickpeas milled more efficiently than split and de-hulled Desi chickpeas. Differences in the protein and starch levels reinforced that protein is not distributed evenly across then endosperm and led to higher protein and lower starch levels in the meal streams. Flowability tests confirmed that the chickpea products produced would not lead to any major flow concerns. More research will be needed to increase the meal yields of both processes; however, selling the flour as a desirable product would increase profitability.

Chapter 3 Figures

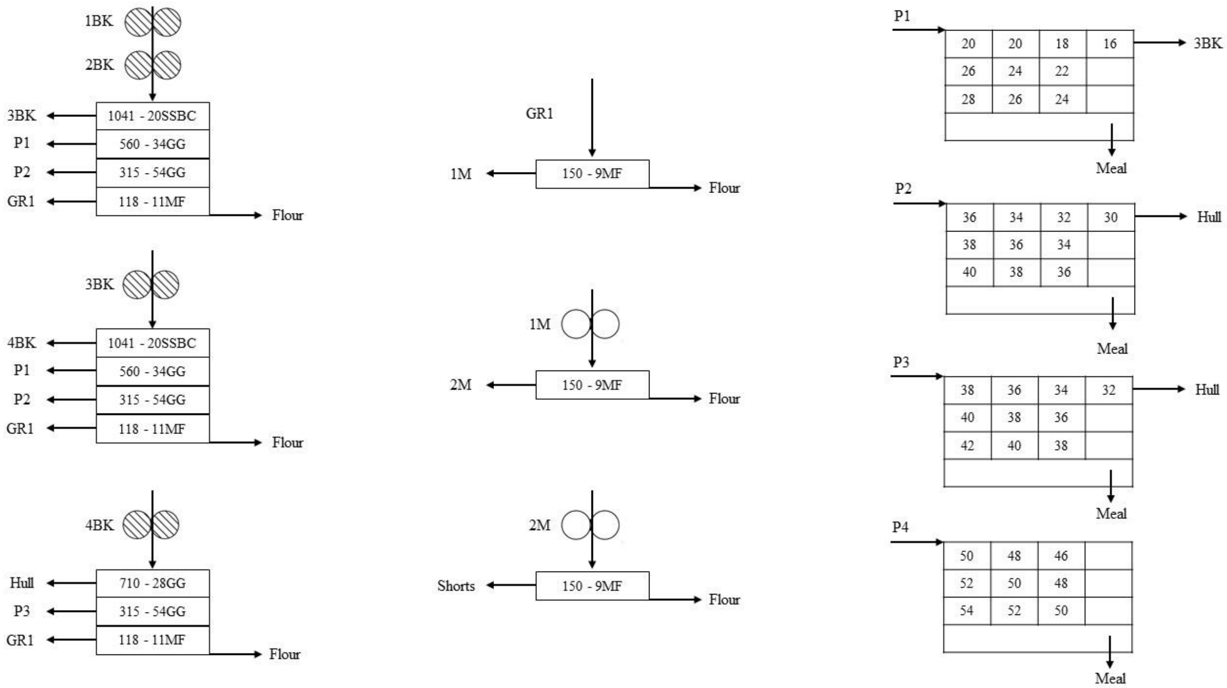


Figure 3.1 Chickpea Meal Flow Sheet

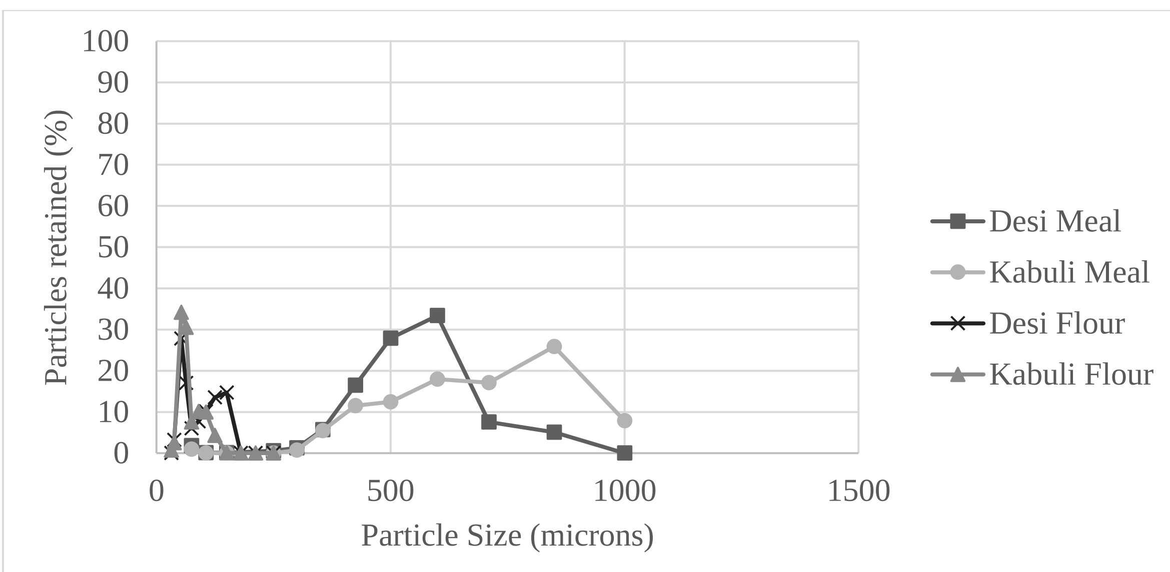


Figure 3.2 Particle Size of Chickpea Meal and Co-Product Flour Streams

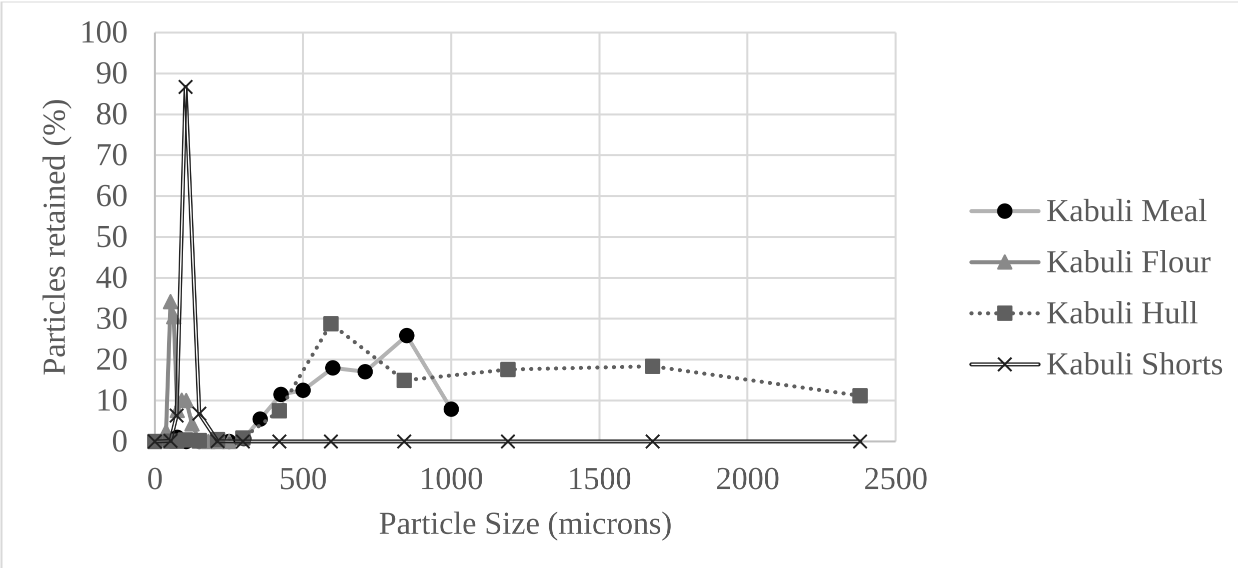


Figure 3.3 Particle Size of Process 1, (Kabuli) Milling Streams

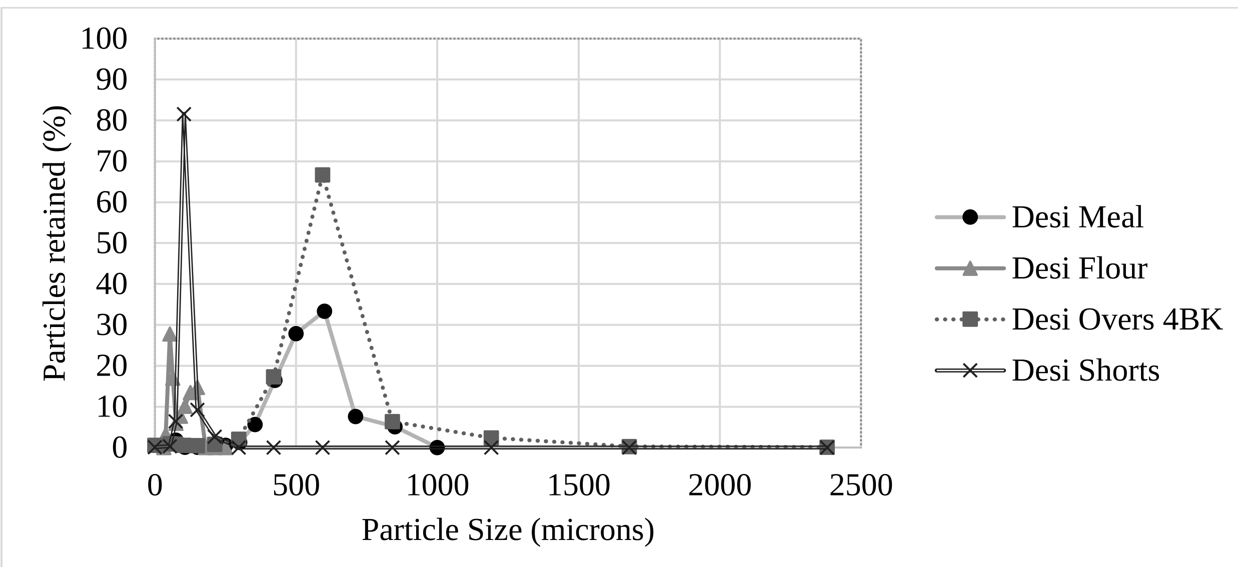


Figure 3.4 Particle Size of Process 2, (Desi) Milling Streams

Chapter 3 Tables

Table 3.1 Flow Characteristics and Values

Flow Characteristic	**HR**	**CI (%)**	**Angle of Repose**
Excellent	1.00-1.11	<10	25-30
Good	1.12-1.18	11-15	31-35
Fair	1.19-1.25	16-20	36-40
Passable	1.26-1.34	21-25	41-45
Poor	1.35-1.45	26-31	46-55
Very Poor	1.46-1.59	32-37	56-65
Very, Very Poor	>1.6	>38	>66

(Riley and Hausner, 1970)

Table 3.2 Overview of Milling Yields

	Starting Material (kg)	**Meal (%)**	**Flour (%)**	**Overs of 4th BK Hull* (%)**	**Overs of 2M Shorts (%)**	**Process Loss (%)**
Kabuli	3641.44	63.8	23.9	6.0	1.9	4.37
Desi	2147.31	54.07	16.03	17.37	0.7	11.8

Table 3.3 Proximate Analysis Results

% Dry Basis	**Sample**	**Crude Protein**	**Crude Fiber**	**Fat**	**Ash**	**Total Starch**
Raw Materials	Whole Kabuli Seeds	23.99cd	3.84b	5.54c	2.53f	39.90d
	Split Desi Seeds	24.36cd	1.44f	6.47b	2.45fg	42.25c
Process 1: Whole Kabuli Seeds	Meal	24.63b	2.72c	4.71d	2.74d	33.25g
	Flour	22.41e	1.44g	6.45b	2.41gh	49.70b
	Hull	14.65f	20.90a	3.42f	4.52a	14.9i
	Shorts	29.09a	2.66c	6.77b	3.29b	31.75h
Process 2: Split Desi Seeds	Meal	24.64c	2.09e	4.53de	2.59fg	37.15f
	Flour	22.86e	0.94g	5.91c	2.34h	51.95a
	Overs of 4th Break	23.87c	2.43d	4.27e	2.64e	38.95e
	Shorts	27.50b	2.01e	7.40a	2.89c	37.55f

Letters denote significant difference for every column $P<0.05$

Table 3.4 Flow Properties

	Sample	Bulk Density (g/ml)	Tap Density (g/ml)	Hausner Ratio	Compressibility Index (%)	Angle of Repose (Degrees)
Process 1	Kabuli Meal	0.719b	0.689b	0.958c	-4.337c	28.9b
	Kabuli Flour	0.508c	0.556c	1.095b	8.703b	42.1a
Process 2	Desi Meal	0.775a	0.719a	0.927c	-7.826d	29.0b
	Desi Flour	0.448d	0.520d	1.161a	13.896a	45.2a

Letters denote significant difference for every column $P<0.05$

Chapter 4 - Physio-chemical properties of extrusion precooked chickpea flour

Abstract

Chickpeas and other pulses are rapidly becoming a popular ingredient in today's food industry. Chickpeas provide many benefits including being nutritious and sustainable. Some drawbacks to chickpeas include anti-nutritional properties and a poor functionality in baked products. Extrusion processing was proposed to pre-cook the starch and remove volatile and anti-nutritional compounds. Two varieties of chickpeas, Kabuli and Desi, were milled to a de-hulled chickpea meal that was then extruded using a pilot scale twin screw extruder, dried, and then milled back into an extruded chickpea flour (ECPF) with an average particle size between 90-150 microns. Flours were evaluated on degree of starch cook, pasting properties, and baking quality in crackers. A commercial pre-cooked chickpea flour, not extrusion processed, was used for comparison. ECPF had a higher cold and hot paste viscosity than commercial precooked chickpea flour (600-900 cP more). Desi samples gelatinized ~20% more than Kabuli samples. Crackers baked with ECPF were less gritty (2 pts) and did not have increased rancid flavors. Cracker hardness was loosely correlated with mechanical energy levels. Extrusion precooking provided a sustainable low water method to enhance the properties and characteristics of chickpea flour.

Key Words: Chickpea, extrusion, baking, precooked flour

Practical Application

This research provides a precooking method for chickpeas that is efficient and controllable. This research shows the flexibility of extrusion precooking. Varying processing parameters led to precooked flours with varying properties and crackers with varying textures.

4.1 Introduction

Plant-based proteins are increasing in demand due to their increased sustainability in comparison to animal proteins. Plants require less water to grow an equivalent amount of protein when compared to common animal proteins such as beef (Mekonnen and Hoekstra, 2010). Some pulses also do not require additional fertilizers as they are nitrogen fixers, which can improve soil quality (Sinclair and Serraj, 1995). This increased sustainability has pushed the industry to utilize plant proteins in recipe formulations and raises light to advantages and challenges with plant-based proteins.

In the past the main plant-based protein used in the food industry was soybeans. This is due to the high protein levels and complete amino acid profile. Recently, pulses such as chickpeas have become more popular because they are not a major allergen in the U.S.. Chickpeas are a good source of protein with levels ranging between 23-36% dry basis, while also being a good source of carbohydrates, 37-39% dry basis (Gil et al., 1996). However, they are not a complete protein and need to be complemented with other complementary proteins such as wheat or corn (Candela et al., 1997).

Raw chickpeas and raw chickpea ingredients have some undesirable compounds including antinutritional factors. These antinutritional factors can include trypsin inhibitors which reduce the digestability (Sreerama et al., 2010). Typically, chickpeas are cooked to remove these anti nutritional factors. Common chickpea cooking methods include dry roasting and pressure cooking. These methods are often batch processes that can require large amounts of time, energy, and in the case of pressure cooking, water. Precooking chickpeas into precooked flour has been to shown to alter the functional properties by gelatinizing the starch and denaturing proteins (Xu et al., 2014).

Extrusion processing is a well-established cooking process that can use minimal water while fully cooking foods in a quick and continuous process (Bouvier and Campanella, 2014). Research has been done in the past evaluating the effect of extrusion precooking on different pulse ingredient blends (Adamidou et al., 2011). Extrusion precooking improved the nutritional quality and led to an 85-92% reduction in trypsin inhibitors when compared to raw flours. That research primarily focused on nutritional composition and did not evaluate the functional properties.

Precooking may also be used to improve the flavor as some consumers do not like the “beany” flavor of chickpeas (Mohammed et al., 2014). Sensory studies have evaluated in chickpea flour addition in baked breads (Mohammed et al., 2012) and found that adding any amount of chickpea flour addition reduced sensory and texture scores. Evaluating differences in gluten free chickpea based baked goods has not been heavily researched.

This research evaluated extrusion precooking on two varieties of chickpeas, Kabuli and Desi. These varieties were ground into a coarse meal in a prior milling study to a particle size between 300-600 microns. Both chickpea meals were extruded using a twin-screw pilot scale extruder at 3 different in-barrel moisture levels (low, medium, and high). The extruded product was then re-milled to less than 150 microns to create a precooked chickpea flour. The raw and precooked flour was evaluated on pasting properties, starch damage, degree of gelatinization, water absorption, and water solubility. Crackers were baked with the raw and precooked flours and evaluated on texture and sensory properties.

4.2 Materials and Methods

4.2.1 Materials

The two varieties of chickpeas used for this study were whole Kabuli seeds and split and de-hulled Desi seeds. The chickpea samples were milled at Hal Ross flour mill to produce coarse meal (300-800 microns). A commercial precooked chickpea flour (not extrusion precooked) was used as a control. A hard-red winter wheat flour (Hal Ross Flour Mill, Manhattan, Kansas, U.S.A) was used to evaluate and compare cracker texture.

4.2.2 Proximate analysis

Proximate analysis of ground samples was done by SDK laboratories (Hutchinson, KS, USA) in duplicate. The crude protein (AOAC 976.06) was measured by combusting samples and analyzing the amount of nitrogen in the sample. Crude protein for chickpeas was calculated using N x 6.25 (Tavano et al. 2016). Crude fiber (AOAC 962.09) was determined after digestion of sample with sulfuric acid and sodium hydroxide and then combusted. Crude fat by acid hydrolysis (AOCS Ba 3-38) was measured by extracting oil with petroleum ether and given as a percentage of original sample weight. Total starch (AOAC 979.10) was measured by digesting starch with enzymes and the glucose level was measured through spectrophotometry. Moisture contents were determined using a laboratory oven at 135^{o}C for 2 hours (AACC44-19.01). Moisture tests were performed in triplicate.

4.2.3 Extrusion Process

The extrusion process was done using a pilot scale co-rotating twin screw extruder (TX-52, Wenger Manufacturing, Sabetha, KS, USA). The screw profile is shown in Figure 4.1 with a

L/D ratio of 25. Temperature zones were increased from inlet to die in 4 zones set at 40, 60, 90, and 120^oC. A throttle valve was used that created another restriction and compression zone before the die. This was used to increase the mechanical energy into the product. The throttle valve had a maximum of 4.5 turns before it would completely close the die assembly and all samples were run with the valve at 4.3 turns leaving an approximately 1mm opening. Die temperature and pressure were recorded for each sample. The extruded product was cut by three hard blades spinning at 1311 RPM. Extruded product was then pneumatically conveyed to a dual pass dryer with a single pass cooler (4800, Wenger Manufacturing, Sabetha, KS, USA). The product was dried for 10 minutes at 104^oC and cooled for 5 minutes using ambient temperature air. Each variety was extruded at 3 in-barrel moisture levels low (8.6-9.8%), medium (12.7-14.1%), and high (17.3-18.0%). The variation was due to the starting raw material moisture level and variation in the water controls on the control panel. Sufficient time was allowed (>20 minutes) in between samples for the extruder to reach a steady state. Then each treatment was processed for 30 minutes with samples for bulk density and moisture being collected at the beginning, middle, and end of each treatment. Specific mechanical energy (SME) for each treatment was calculated using the equation below.

$$SME = \frac{\frac{(T-To)}{100} * \frac{N}{Nr} * Pr}{mf} \qquad \text{Eq. (3.1)}$$

Where T is percent torque, To is no load torque (22%), N is screw speed, Nr is rated screw speed (500 RPM), Pr is rated motor power (22.4 kW), and mf is feed rate in kg/sec. SME was recorded in kJ/kg units. Bulk density was also recorded off the extruder (OE) and off the dryer (OD) by collecting material in a scoop and gently pouring, without compaction, into a container of known volume (1L) and recording the mass.

4.2.4 Post Extrusion Grinding

After extrusion, the extrudates were ground using a hammer mill with a 0.87 mm screen size. The ground samples were then sifted to separate flour using a 150-micron screen. Particles larger than 150 microns were reground in two passes of a lab scale roller mill (Ross Machine & Mill Supply Inc. Oklahoma City, Oklahoma, USA) with a roll gap of 0.003 and 0.001 inches respectively. The final product was a precooked flour with 100% of the particles below 150 microns.

4.2.5 Particle Size Analysis

Particle size analysis on final flour streams was done using an Alpine jet sieve analyzer (e200LS, Hosokawa Alpine, Germany). Samples were measured in triplicate.

4.2.6 Rapid Visco Analysis (RVA)

The standard RVA method (AACC Method 76-21.02) was modified to analyze pasting properties of raw, precooked chickpea flours, and a commercial control. The modified method included hydrating 3.5 g samples with water added to obtain a solids level of 20% (w.b.) and can be viewed in Figure 4.2. The samples were initial mixed at 960 RPM at 30oC for 15 seconds. The sample was then constantly mixed at 30^{o}C at 160 RPM for the next 3 minutes. The temperature was then increased to 95^{o}C over the next 7 minutes. The temperature was held at 95^{o}C for 4 minutes, then the temperature was reduced to 50^{o}C over the next 4 minutes. Finally, the sample was mixed for 1 minute at 50^{o}C. This modified method resulted in more consistent testing due to the increased absorption time and reduced temperature at the beginning.

4.2.7 Differential Scanning Calorimetry

Gelatinization was analyzed by differential scanning calorimetry (DSC). For each analysis 8-10 mg of sample was weighed into high volume steel pans. Moisture was added at twice the dry weight of the sample and the pans were sealed and allowed to hydrate overnight at room temperature. The samples were scanned against an empty pan at a heating rate of 10 C/min, from 10 to 140^{o}C (Q100, TA Instruments, New Castle, DE). Endothermic peaks greater than 0.2 mW in the temperature range between 60-90^{o}C were classified as gelatinization. The degree or % gelatinization was based on the peaks of the raw material samples. All samples were measured in triplicate.

4.2.8 Water absorption index (WAI) and water solubility index (WSI)

Flour samples of 2.5 ± 0.05 g were immersed in 30 mL of distilled water at room temperature. The sample was mixed with a metal spatula to ensure no clumps remained and vortexed with a test tube mixer (Type 37600 mixer, Thermolyne, Dubuque, Iowa, USA) for 15 seconds. The samples were then continuously agitated using an Innova 44 shaker table (New Brunswick Scientific. Edison, New Jersey, USA) at 100 rpm for 30 minutes. After agitation the samples were centrifuged at 3000G for 15 minutes in a centrifuge (Eppendorf 5810R 15 Amp). The supernatant was poured into a tared evaporating dish. The remaining gel was weighed, and WAI was calculated using the equation below. Where Wgel is the weight of the gel and Wdsample is the weight of the dry sample. All tests were done in triplicate.

$$WAI = \frac{Wgel}{Wdsample} \qquad \text{Eq. (3.2)}$$

The WSI was determined from the amount of dry solids recovered by evaporating the supernatant at 100oC for 5 hours and calculated using the equation below. Where Wdsuper is the weight of dry solids from the supernatant and Wdsample is the weight of the dry sample.

$$WSI = \frac{Wdsuper}{Wdsample} * 100 \qquad \text{Eq. (3.3)}$$

4.2.9 Damaged Starch

The amount of damaged starch was measured using an SDmatic (Chopin Technologies, Cedex, France). This amperometry method measured the amount of iodine absorbed by starch at 35^{o}C. This method (AACC 76-31) was designed for wheat flour and therefore cannot give accurate results. However, this method can be used to evaluate the damage of the starch from the extrusion process and compare iodine absorption rates.

4.2.10 Cracker Baking

The cracker formula consisted of equal parts dry mix and water for pre-cooked flours and 2 parts dry mix to 1 part water for raw flours. The difference in water ensured a consistent dough viscosity amongst samples to allow sheeting. The dry mix included 61.4% chickpea flour, 20.46% potato flakes, 10.91% waxy pre-gelled corn starch, 3.94% corn oil, 2.05% oat fiber, 0.49% monocalcium phosphate, 0.41% sodium bicarbonate and 0.34% salt. A commercial chickpea flour, that was not precooked with extrusion, was used as comparison. The only independent variable of the formula was the type of chickpea flour used.

A wheat cracker control was also baked using the same HRW wheat flour used in the RVA analysis. The formula for the wheat cracker included 65.57% wheat flour, 22.95% water, 6.56% vegetable oil, 3.28% sugar and 1.64% salt. This formula was based off a typical wheat cracker and does not contain many of the ingredients that the chickpea cracker formula includes. This change in formulas was due to differences associated with gluten development in the wheat samples.

Dough was mixed using a stand mixer with a paddle attachment and combined for 4 minutes on low to medium speed until the dough was evenly mixed and had a smooth exterior surface. The dough was sheeted without lamination and cut using a rotary cutter into 0.5-inch-wide by 2-inch-long crackers (12.7 by 50.8 mm). Raw cracker dough was consistently checked to ensure 10 pieces had an even thickness and weighed 10.6 ± 0.5 grams. A two-stage baking process was used in a convection oven (Oshikiri, Fujisawa-City, Japan) with two separate heating decks and no steam addition. The crackers were first baked for 2.5 minutes at 232^{o}C and then they were moved to another oven at 135^{o}C for 17 minutes. This two-stage system mimicked a tunnel oven system with different heating zones, typically used in industry.

4.2.11 Cracker Instrumental Texture

Prior to testing, crackers were placed in a controlled humidity chamber at 30^{o}C and 35% relative humidity. This ensured all crackers had a similar moisture content and differences would be limited to the type of flour used. The texture analysis was measured on a TAXT2i texture analyzer (Texture Technologies, Hamilton, MA, USA) with a three-point bend test designed to evaluate the cracker's snap force or hardness. An aluminum rounded blade with a diameter of 2mm was used. The crackers were supported on a rig at each end with a gap of 20 mm in between. The pretest speed was set at 1mm/s, the test speed was set at 1mm/s, and the post-test speed was set at 10mm/s. Crackers made with raw chickpea flour, precooked chickpea flour and HRW wheat flour were tested. Hardness was recorded as the peak force during breaking and fracturability as the distance to the first peak. Crackers were sampled with 20 replicates each.

4.2.12 Cracker Sensory

A descriptive analysis was done on crackers made with raw chickpea flour, precooked chickpea flour, and commercial control crackers. Controls used included Original Wheat Thins™ (Nabisco, East Hanover, NJ, USA), Good Thins™ (Nabisco, East Hanover, NJ, USA), a rice-based cracker, and the commercial precooked chickpea flour. Individual analysis of the crackers was done in duplicate using 5 highly trained panelists. Seven pieces of crackers were served in 3.25 oz containers. The crackers were ranked on attribute intensity scores ranging from 0-15 with 0.5 increments. Panelists were provided cucumber slices and deionized water for palate cleansing between samples. Textural attributes recorded were hardness, fracturability, initial crispness, cohesiveness of mass, and gritty. The flavor attributes recorded were oil heated, overall beany, overall grain, bitter, and sweet. Definitions of each attribute can be found in Tables 4.2 and 4.3.

4.2.13 Statistical Analysis

Statistical analysis was performed using a two-way ANOVA test conducted with a 95% confidence level using SAS software 9.4. Variety, raw vs. cooked, and water level were the independent factors where applicable. Table 4.1 visually represents the experimental model. Pair-wise differences were analyzed with a general linear model (GLM) and least square mean comparison. Significantly different values were denoted with different lower-cased letters.

4.3 Results and Discussion

4.3.1 Proximate Analysis

Proximate analysis results can be found in Table 4.4. The Kabuli meal contained statistically higher protein however the difference of 0.01% was not practically significant. The Kabuli meal also had significantly higher levels of crude fiber, fat, and ash. This could have been from hull contamination that was not observed in the Desi sample. The major difference in proximate analysis was the total starch. The Desi meal contained 3.9% more starch, the higher starch impacted further tests that measure starch properties including DSC and RVA. These results were similar to other chickpea research reported (Sreerama et al., 2010) and any minor differences could be explained by growing region differences or by the experimental milling process.

4.3.2 Extrusion Processing

Extrusion trial data was reported in Table 4.5 and shown in Figures 4.3-4.9. The goal of the water addition was to lower the process intensity as more water was added. This was due to the plasticizing and lubricating effect of water that would reduce the viscosity in the extruder barrel. The in-barrel moistures shown in Figure 4.4 show that the Desi samples had a slightly higher IBM. This was due to the higher raw material moisture content. The distinct processing trends were observed in the lowered the die temperatures (Figure 4.8) and the increased bulk density (Figure 4.9) with increased water. However, SME values did not follow this pattern for both varieties. For the Desi variety, as water was added from the low (L) to the medium (M) level the SME was reduced, however when further water was added at the high level (H) the SME was returned to the 330 kJ/kg. This could be possibly due to the difference in starch level; the extra starch in the Desi sample could have increased viscosity enough to overcome the water's effects. This theory was supported by the extruded product shape. Both varieties at the low IBM level had irregular shapes and a lightly burned appearance. The medium IBM level yielded pieces that were rough but still irregular disks. At the high IBM level the Kabuli sample was flat and elongated retaining the shape of the throttle valve restriction, while the Desi sample was formed in uniform disks. These increased starch in the Desi sample could have held the product together and increased viscosity while the Kabuli sample with less starch and more oil could not for a coherent matrix.

The die pressure also varied between variety. With the Kabuli samples, pressure was slightly lowered with IBM increases, showing a reduction in process intensity. This was further evident by the shape of the intermediate product. With Kabuli samples the material did not reform correctly after the throttle vale and therefore steam could escape out of the die and not through the material. It was unclear what caused the shape differences as the protein and starch levels were practically similar.

Moisture loss, shown in Figure 4.5, off the extruder die was highly related with IBM. The higher IBM the more water was lost as steam flash off from the die. At the low IBM levels there was an approximately 5% reduction in moisture while the high IBM samples lost approximately 9%. All samples were dried to approximately 4% moisture except for the Kabuli medium IBM sample because of complications with the dryer feed system that were addressed during processing. The moisture was still reduced to less than 10% and deemed shelf stable.

4.3.3 Particle Size Distribution

Milling of extruded product yielded approximately 60% flour during the hammer milling step and the other 40% was recovered during the roller milling steps. Particle size of the ECPF and commercial chickpea flour was shown in Figures 4.10 and 4.11. For clarity, Kabuli and Desi samples are also shown in Figures 4.12 and 4.13 respectively. Particle sizes amongst extruded samples did not vary greatly with averages between 90 and 150 microns. The commercial precooked chickpea flour had a slightly lower average particle size with a peak between 75 and 90 microns, but it contained a right tail of particles that reached 300 microns. This difference is clearly shown in the cumulative particle size data shown in Figure 4.11. Upon inspection of these larger pieces it appeared to be chickpea hull. The evidence of chickpea hull shows that this commercial flour is from whole chickpeas and would contain presumably higher fiber levels than the Kabuli or Desi samples.

4.3.4 Differential Scanning Calorimetry (DSC)

DSC results are reported in Table 4.6 and shown in Figure 4.14. Varity was the only factor that had a significant effect on the degree of gelatinization. Table 4.6 shows more varietal differences with the raw Desi meal having almost double the enthalpy as raw Kabuli meal. This was most likely attributed to the higher starch content and the lower fat content. The lowered fat content in the Desi sample would form less amylose-lipid complexes that would reduce endothermic peaks (Bhatnagar and Hanna, 1994). Interestingly, the commercial precooked chickpea flour had no endothermic peak in the gelatinization temperature range. This showed that the starch had been completely cooked and gelatinized. Although not significant due to variability, there is a slight decrease in gelatinization for Desi samples as IBM is increased. This further enforces that adding water reduces the processing intensity on the final flour but higher levels may be needed to see major effects.

4.3.5 Water absorption Index (WAI) and Water Solubility Index (WSI)

WAI and WSI were reported in Table 4.7. Water absorption was significantly higher for Kabuli samples than Desi while IBM did not have a clear effect. WAI is associated with degree of starch cook or damage because gelatinized or damaged starch can absorb more water than uncooked and intact crystalline starch (Jan et al., 2017). This was shown by both the raw samples having a significantly lower WAI (1.9) than the cooked samples. The commercial precooked chickpea flour was significantly similar to the Desi medium and high IBM samples alluding to similar processing levels. This was reaffirmed by the nearly 100% gelatinization of the Desi samples reported in Figure 4.14.

Water solubility can be an indicator of over processing of starch. If starch is cooked beyond gelatinization it can be broken apart into smaller molecules that are water soluble. The highest WSI reported was the Desi high IBM at 34.4093% showing the highest level of solubility in all the samples. This was contrary to the original intent of the authors as the highest IBM was meant to be the lowest intensity process. One theory was that the highest IBM lead to full hydration of starch that lead to a higher degree of cooking than the lower IBM levels because water was more limited and would not allow the starch to fully gelatinize. The commercial precooked flour had the lowest WSI, even lower than the raw samples. One theory was proposed that the commercial sample had been annealed and thus reduced its ability to interact with water and be gelatinized. However, annealed chickpea starch will still show endothermic peaks during a DSC test (Tester and Debon, 2000)(Chávez-Murillo et al., 2018). The higher WSI of the extruded samples could be due to the high shear effects of extruder screws and of the throttle valve leading to degraded starch (Bouvier and Campanella, 2014).

4.3.6 RVA of Raw and Extrusion Pre-Cooked Chickpea Flours

RVA results are shown in Figures 4.15-4.17. Figure 4.15 showed the unique curves of each of the EPCFs. The differences highlighted the capability and range of properties that can be affected by the extrusion process in real time vs. batch cooking. Kabuli samples on average had higher final viscosities than Desi samples. This was attributed to the lower degree of starch cook observed in the Kabuli samples. During the RVA method the starch goes through further heating and can be subsequently broken down if already highly processed. Figure 4.16 showed the effect of precooking observed in the cold peak which appeared before 60^{o}C. This initial peak was starch that was pregelatinized and could immediately absorb water without heat. All ECPFs had a higher viscosity than the commercial sample, showing increased functionality. Figure 4.17 highlighted the damage done to the starch by the precooking process. The raw samples had the highest hot peak viscosity because all of the starch was still intact and not broken down or gelatinized. The commercial precooked chickpea flour again was lower than the rest of the precooked samples showing a decreased functionality. Again, variety appeared to have a larger effect than IBM with no clear trends in the peak viscosities with changes in IBM.

4.3.7 Damaged Starch

Damaged Starch results were recorded in Table 4.8. These results showed the effect that the extrusion process has on damaging the starch. Although statistically insignificant, the % damage followed similar trends as the SME results with increased damage at higher SME values. This was expected as mechanical energy comes from the friction between the extruder screws and the material. These friction and shear forces can damage the starch as well as cook them.

4.3.8 Crackers Texture: 3-Point Bend Test

The instrumental cracker texture was reported in Table 4.9 with hardness results shown in Figure 4.18. Hardness of the crackers was significantly affected by if the sample was cooked or not, IBM level, and an interaction between variety and if the sample was cooked. Fracturability of the crackers was affected if the sample was cooked, however both variety and IBM level did not have an effect on cracker fracturability.

As before the commercial precooked chickpea flour had the lowest values. The low hardness could be due a reduced ability for the starch to interact with water to create a strong and cohesive matrix. The raw crackers showed an opposite trend with completely intact starch and protein creating the hardest crackers at 1400 and 1000g hardness. The ECPFs followed trends inversely to IBM and SME. As IBM went up and SME went down the crackers increased hardness. The wheat sample was not as hard as the raw chickpea crackers most likely due to protein differences with wheat flour. Chickpeas do not contain gluten and also have typically twice as much protein than wheat.

4.3.9 Crackers Sensory: Texture and Flavor

The sensory results for cracker texture were reported in Table 4.10. This data was more variable and therefore differences weren’t as clear as with the instrumental texture test. However, similar trends can still be seen with the commercial precooked chickpea flour having one of the lowest scores and the raw chickpea cracker having the highest. Although not statistically significant the hardness trends of the sensory panel follow similar trends as the SME values. Further emphasizing the importance of the SME but also the flexibility of the extrusion precooking process. The rest of the sensory data did not appear to be related to variety of processing however precooking did lower the gritty mouthfeel by over 2 points. This reduction in gritty mouthfeel could improve acceptability to consumers. The two varieties had similar texture trends to both wheat thins and good thins showing further acceptability by having a similar texture to popular products in the market.

The sensory results for cracker flavor were reported in Table 4.11. One concern of the researchers was that extrusion precooking may lead to rancid flavors due to the high temperatures and pressures. However, oil heated flavors were not significantly increased by precooking. The overall beany flavor was lowest with the commercial precooked chickpea flour and not significantly affected by the extrusion process. Similar levels for sweet, salt, and bitter were reported for all samples which showed that there was no major flavor changes due to precooking. Also, besides overall beany and overall grain the chickpea crackers had similar flavor scores as commercial products, which showed the potential acceptance by consumers.

4.4 Conclusion

Extrusion precooking of chickpea flour can be a continuous and flexible processing method. Nutritional, varietal, and process differences can lead to precooked flour with unique functionality that should be tailored to the final product. ECPFs had higher viscosities that commercial precooked flours and crackers baked with precooked chickpea flours have less gritty textures and do not increase rancid or oil heated flavors. Extrusion precooking of chickpea flour can create highly functional and customizable ingredients and products.

Chapter 4 Figures

Head No.	1	2	3	4
Temp.(°C)	40	60	90	120

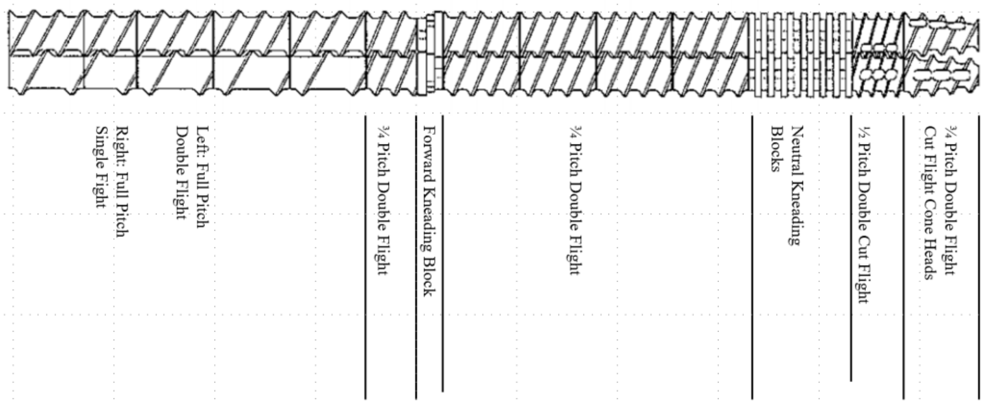


Figure 4.1 Extruder Screw Profile

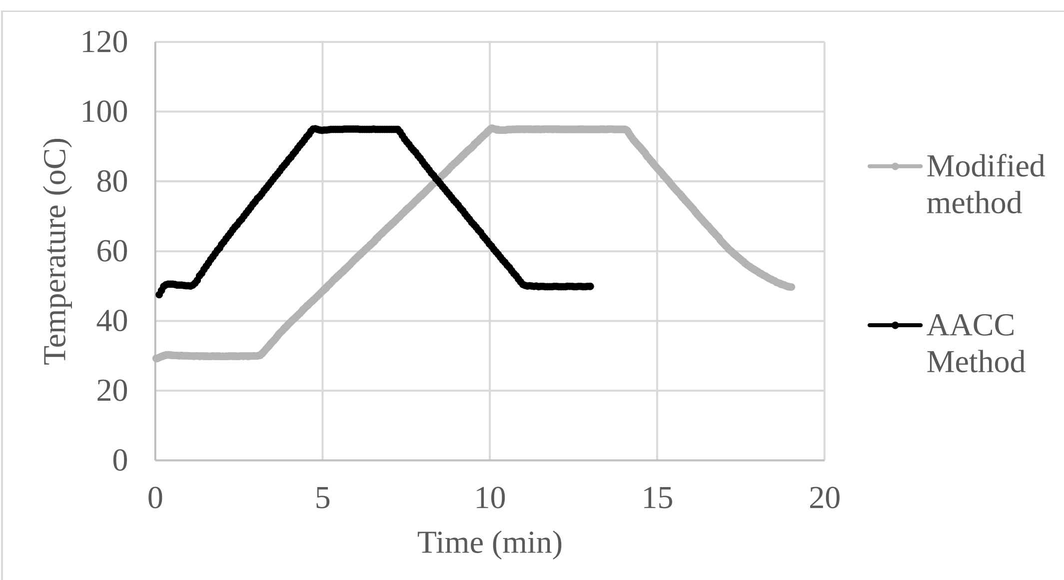


Figure 4.2 Modified RVA Method

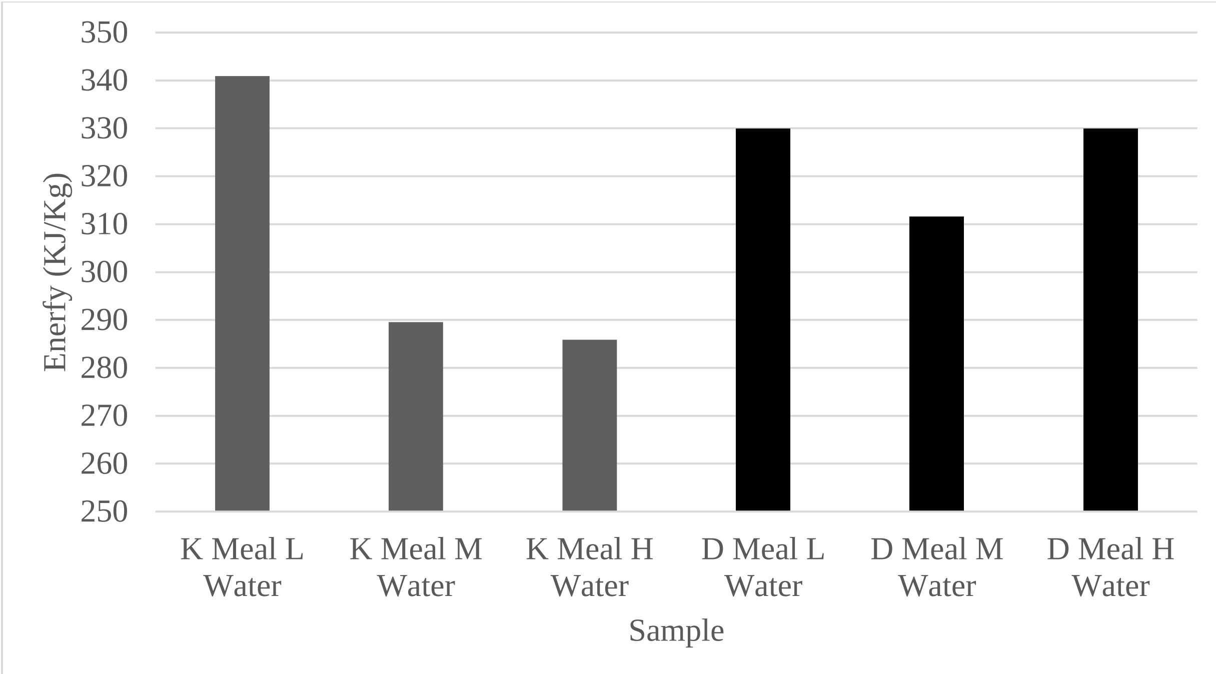


Figure 4.3 Extrusion Data- Specific Mechanical Energy (SME)

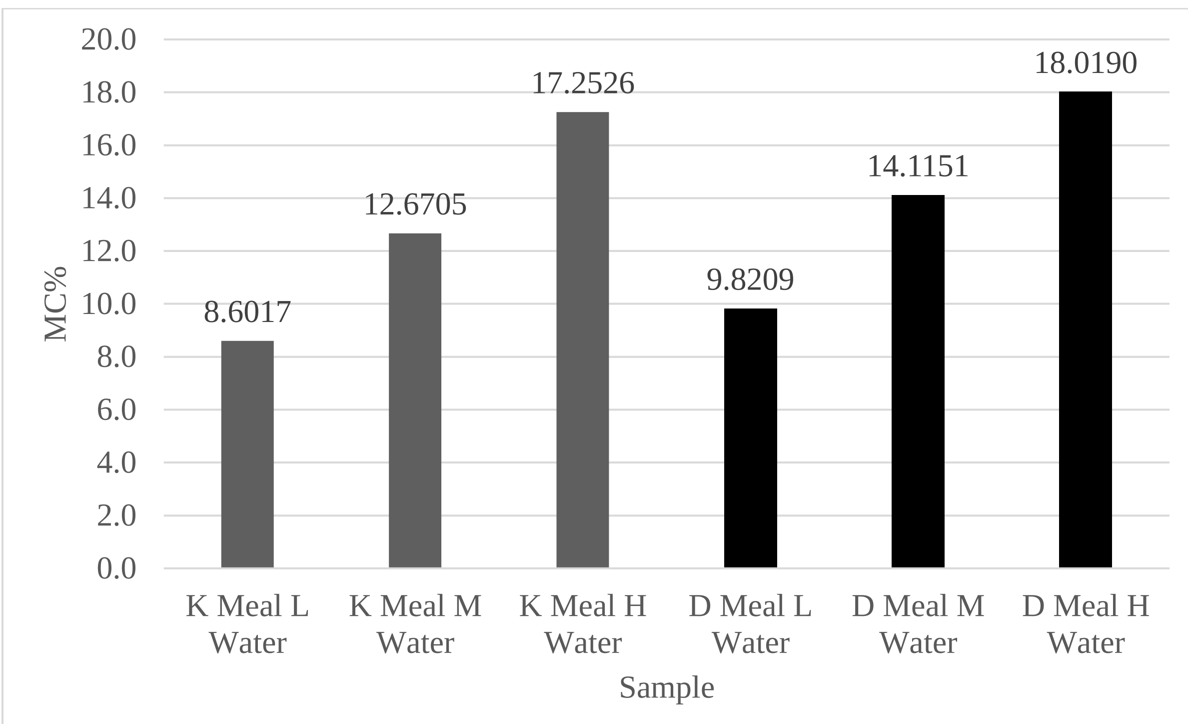


Figure 4.4 Extrusion Data – In-Barrel Moisture Content (IBM)

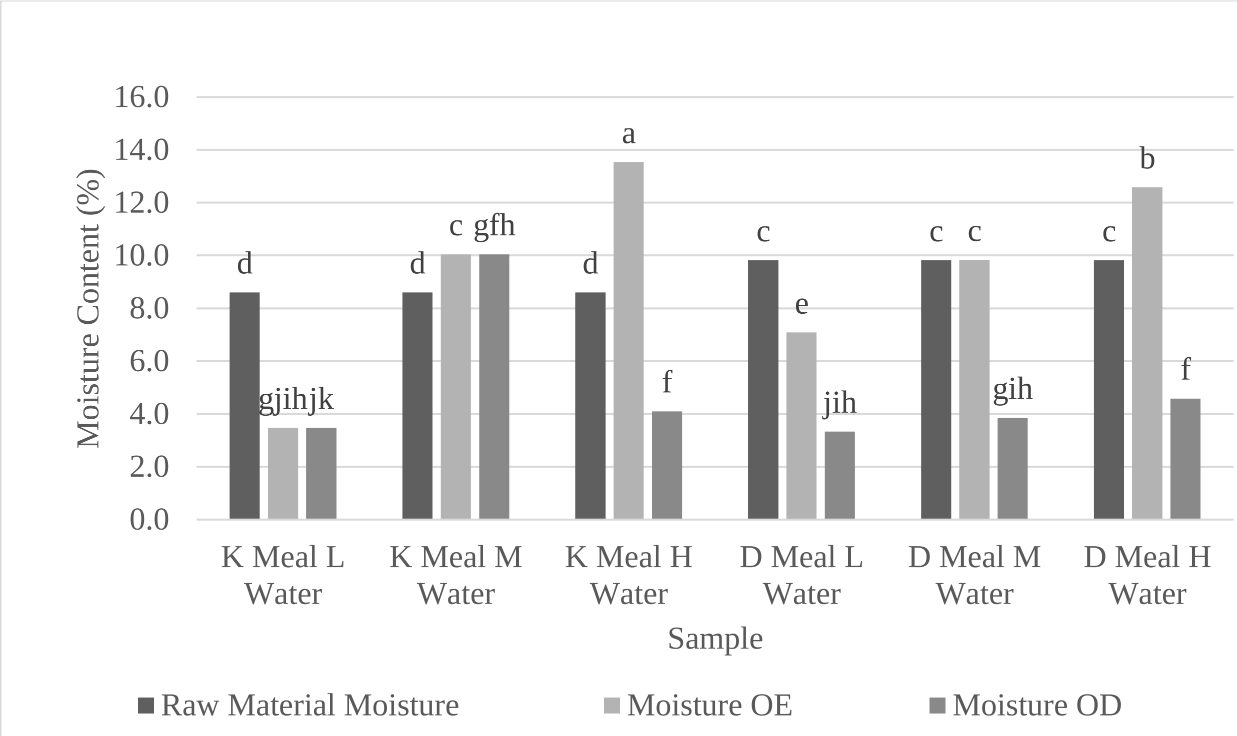


Figure 4.5 Extrusion Data – Moisture Contents

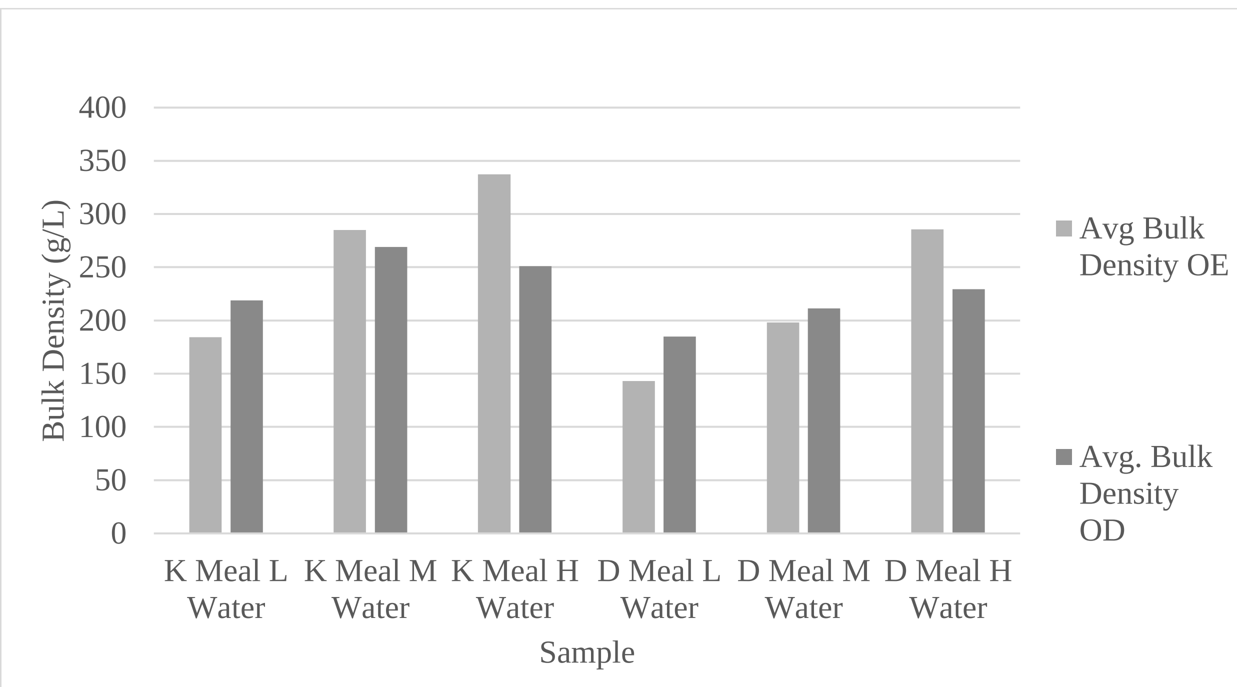


Figure 4.6 Extrusion Data - Bulk Density. OE= Off the Extruder. OD = Off the Dryer

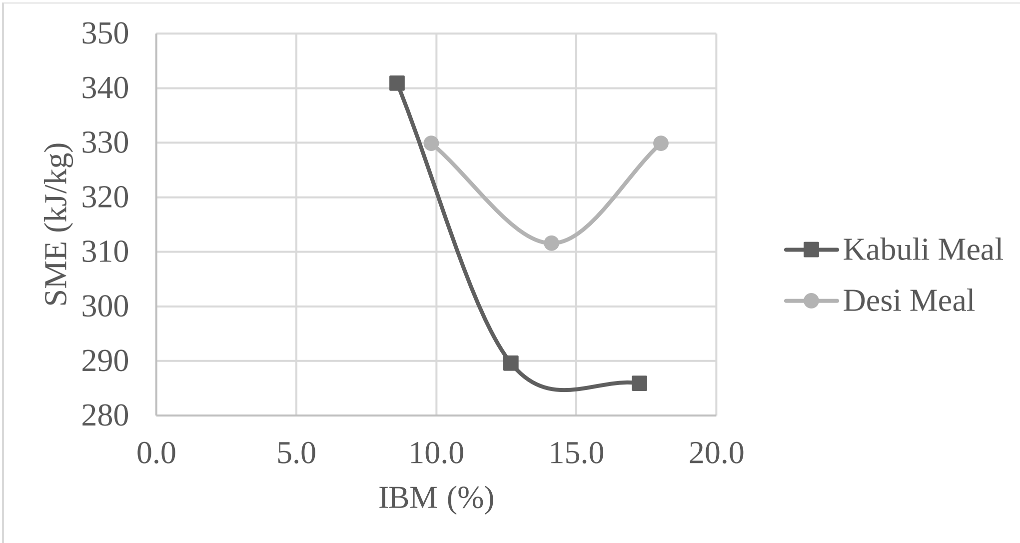


Figure 4.7 Extrusion Data - IBM vs. SME

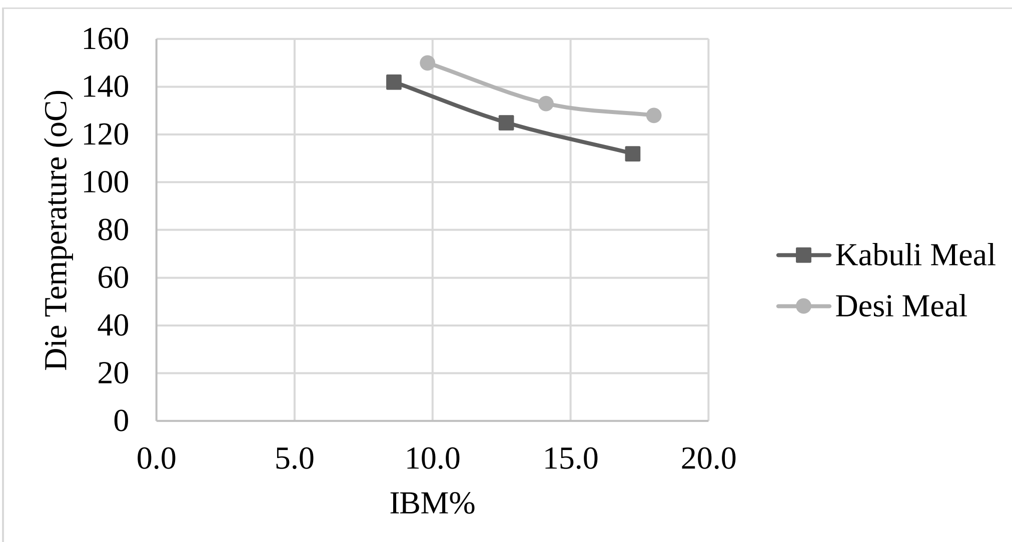


Figure 4.8 Extrusion Data - IBM vs. Die Temperature

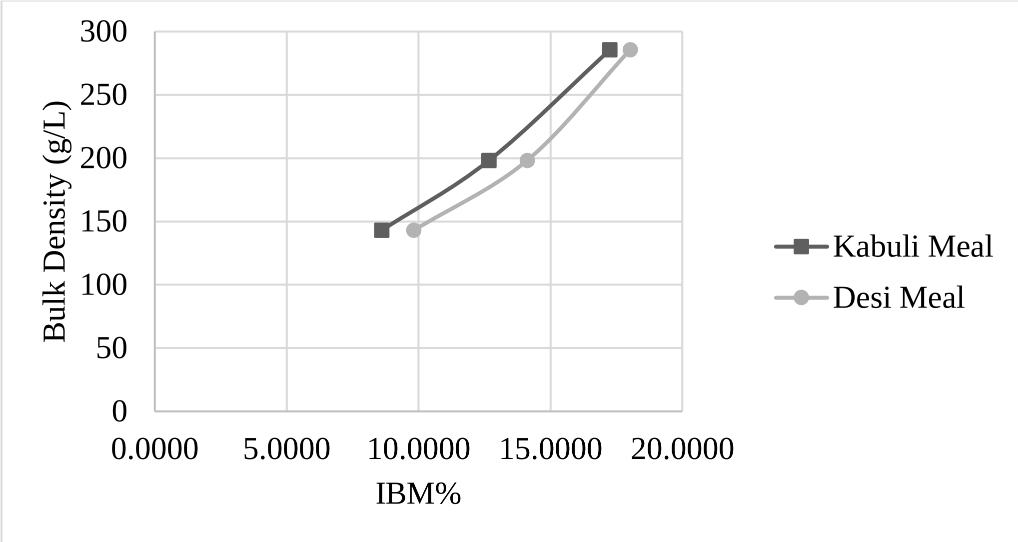


Figure 4.9 Extrusion Data - IBM vs. Bulk Density Off the Extruder

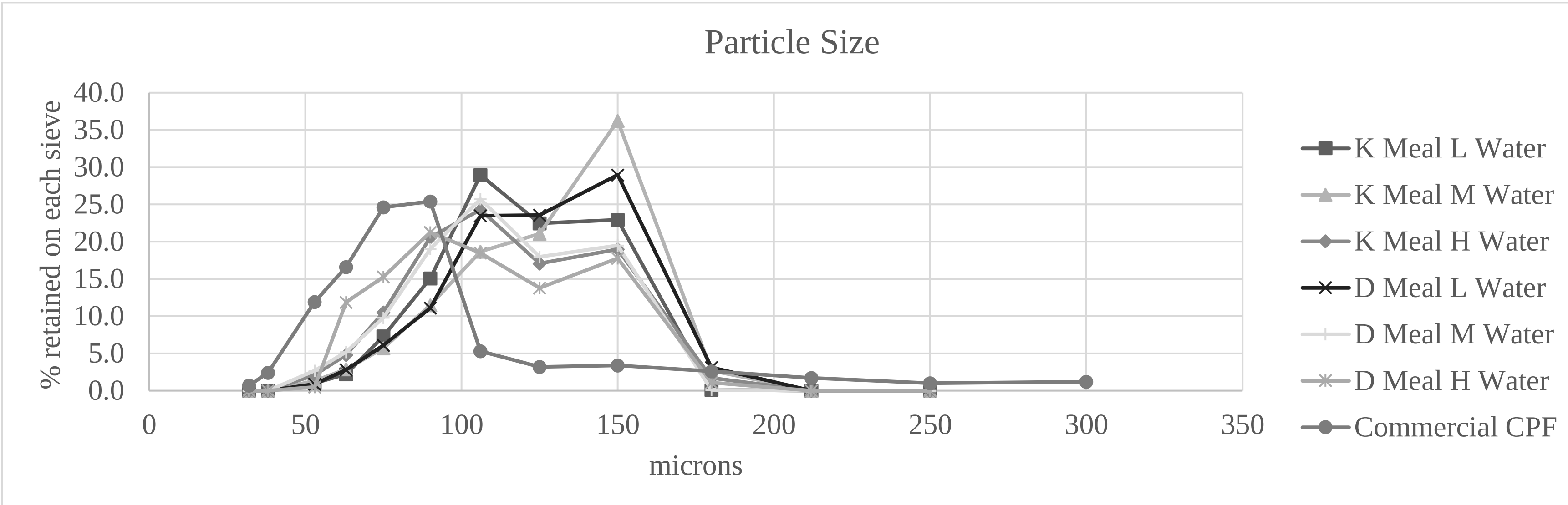


Figure 4.10 Particle Size Data - All Samples

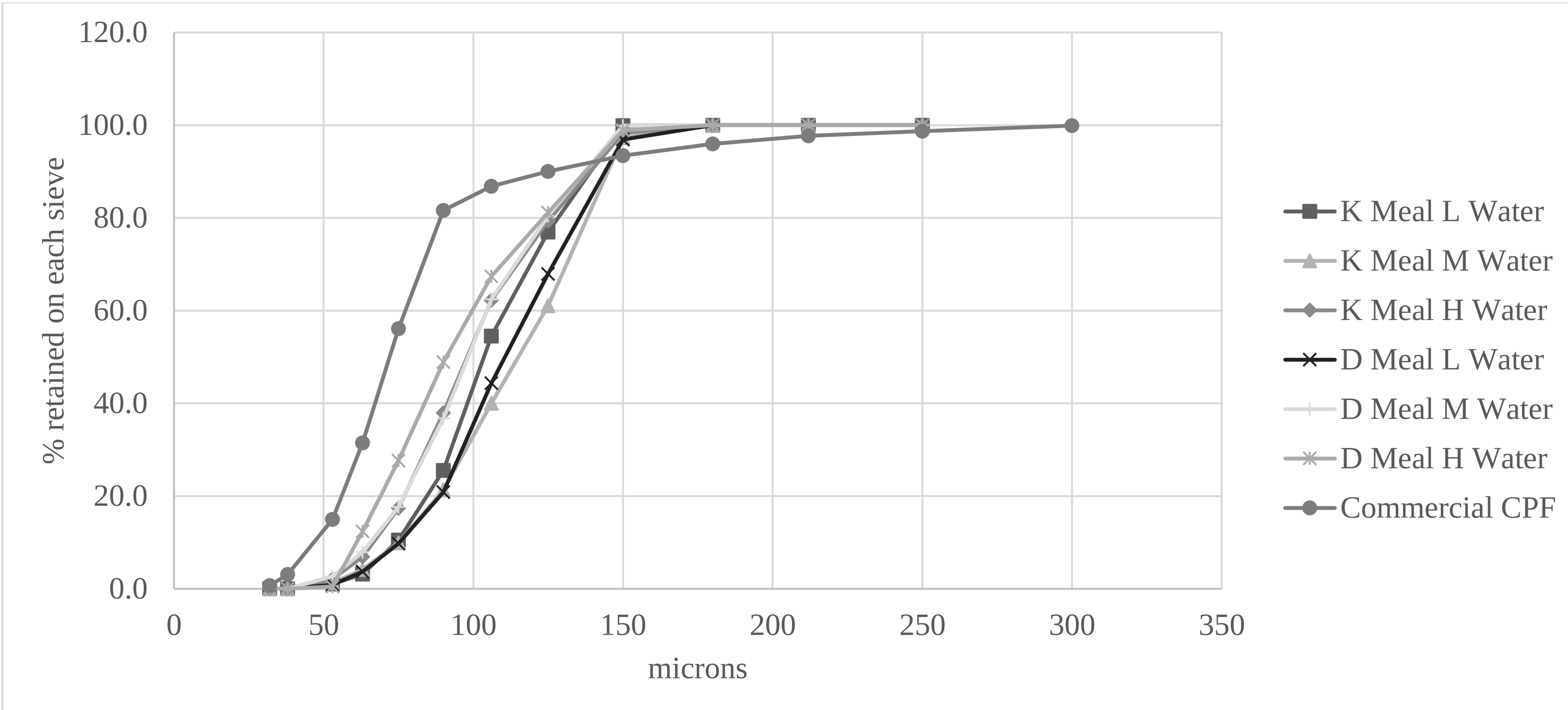


Figure 4.11 Cumulative Particle Size - All Samples

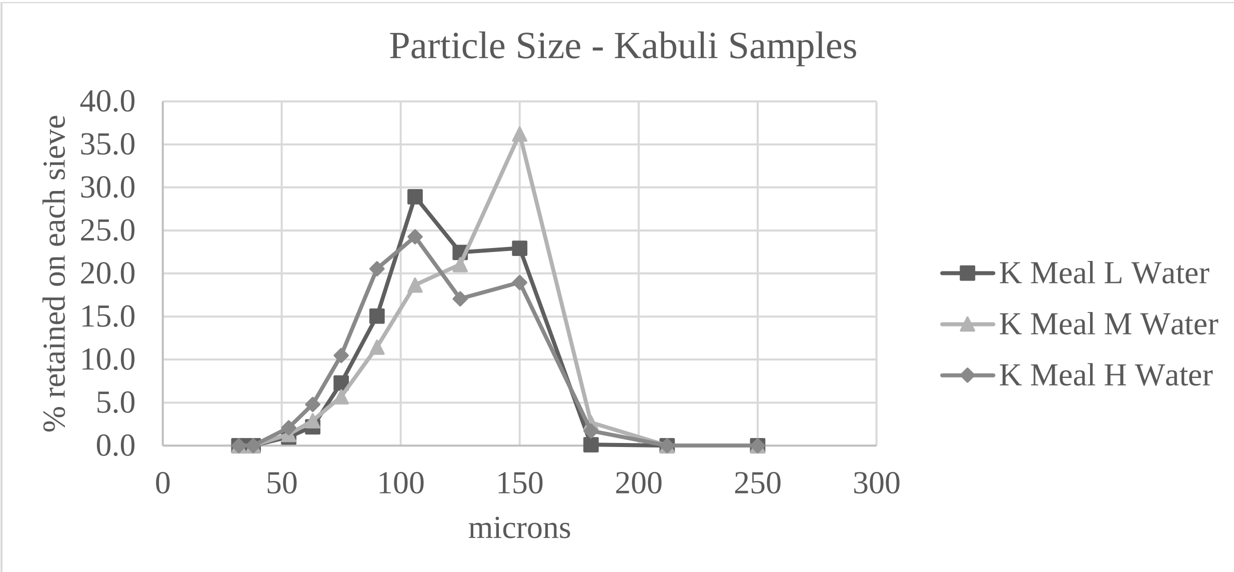


Figure 4.12 Particle Size Data - Kabuli Samples

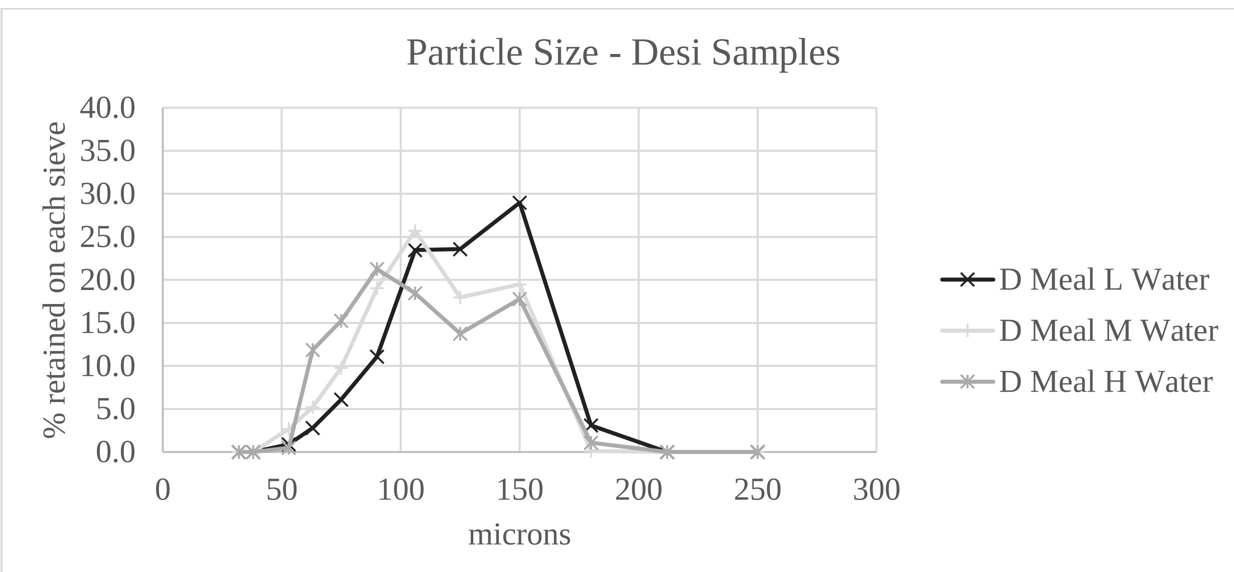


Figure 4.13 Particle Size Data - Desi Samples

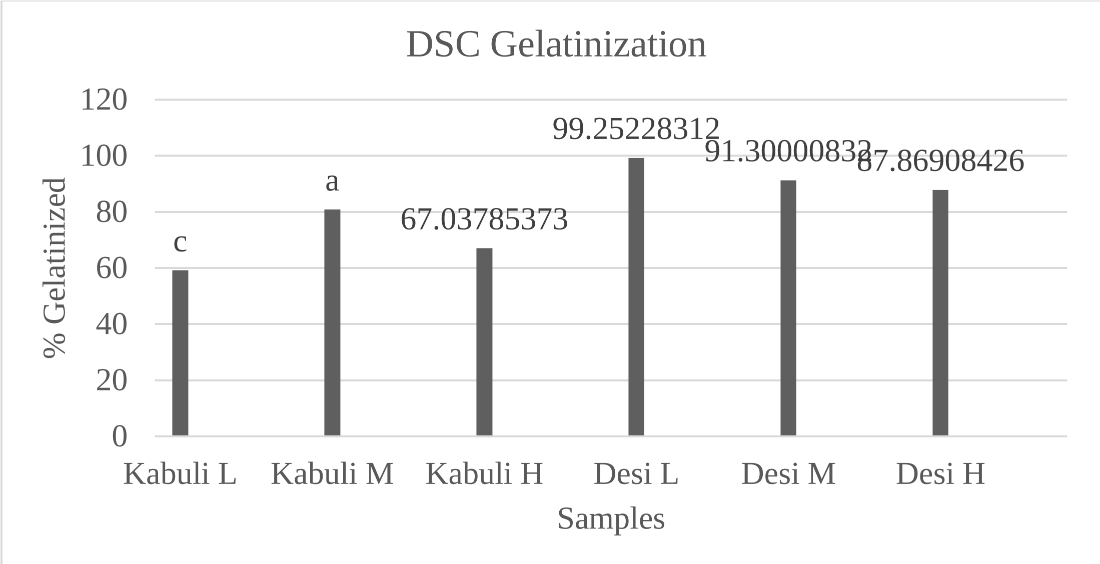


Figure 4.14 DSC %Gelatinization

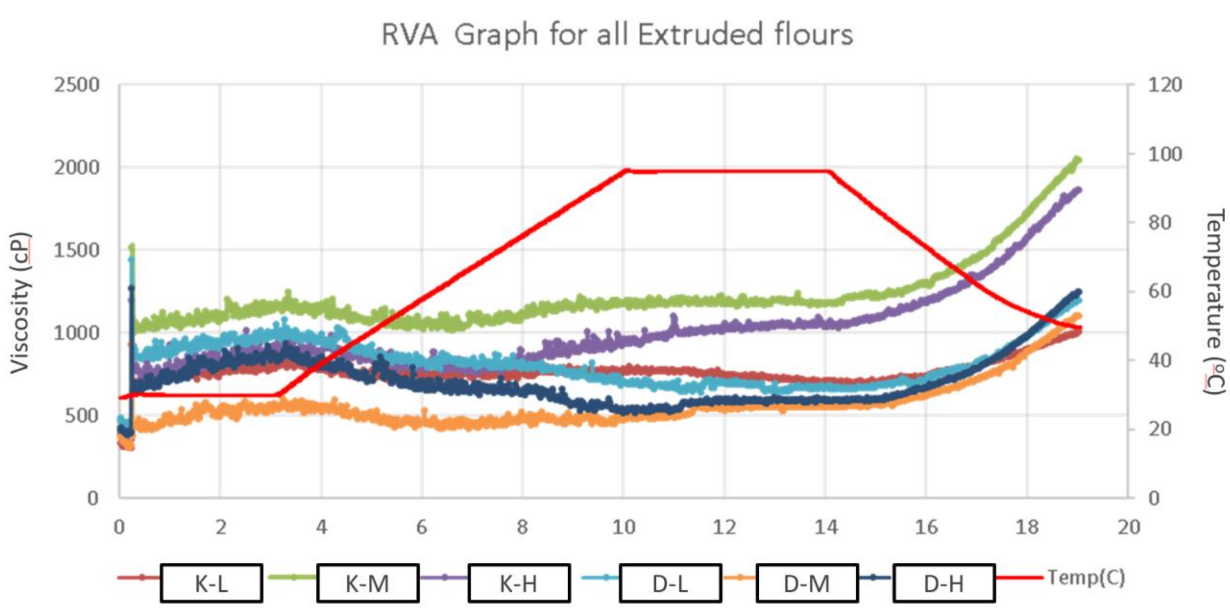


Figure 4.15 RVA Data - Curves

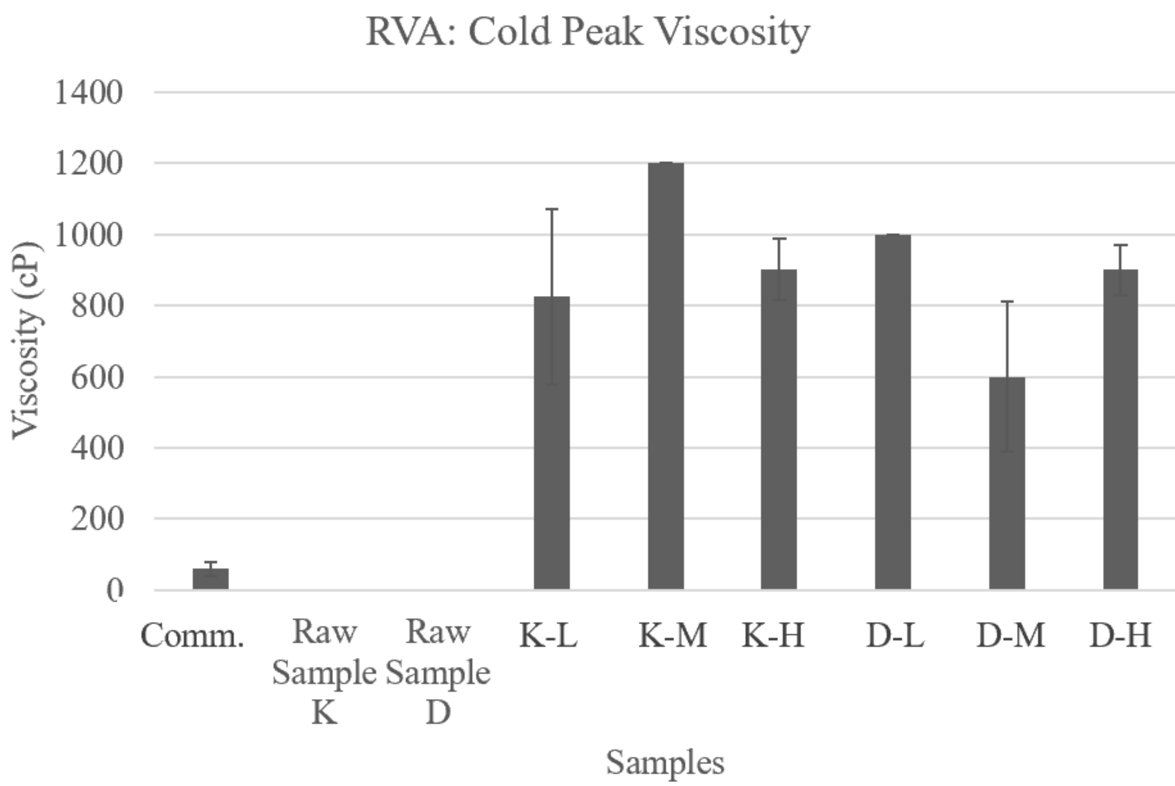


Figure 4.16 RVA Data - Cold Peak Viscosity

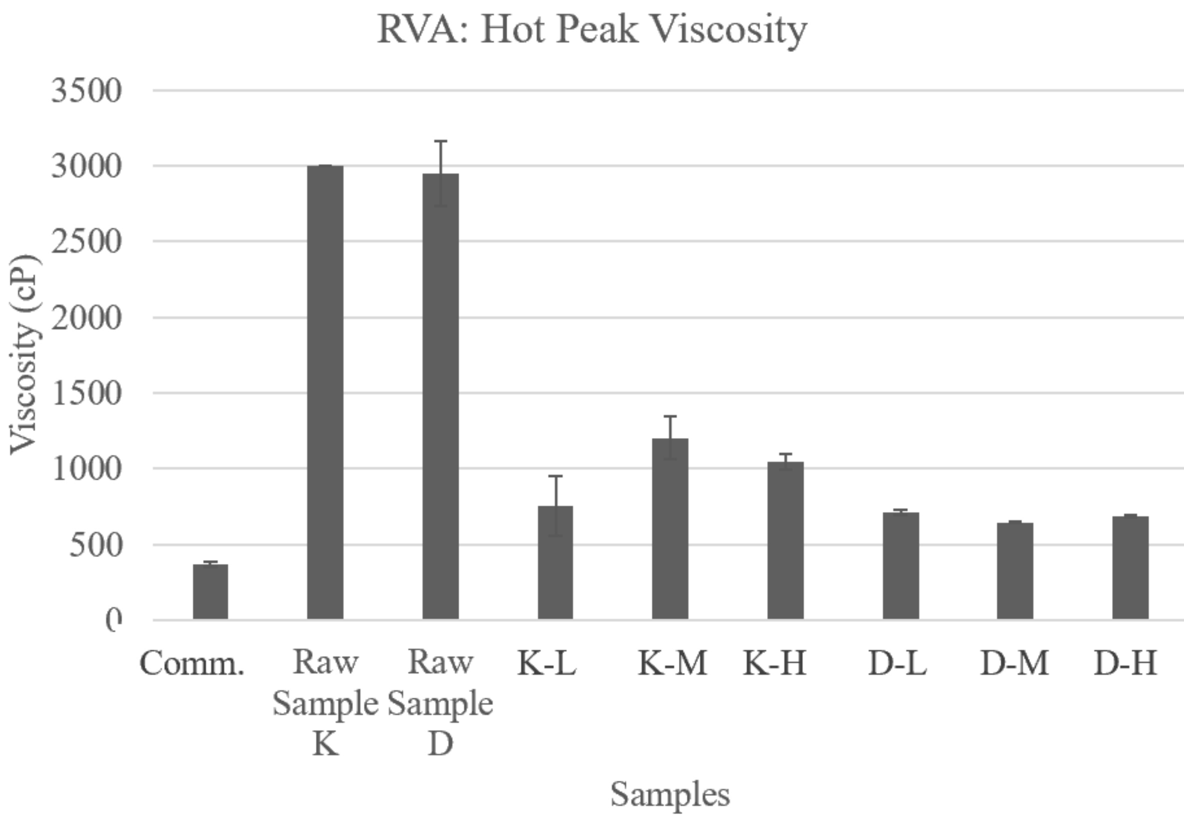


Figure 4.17 RVA Data - Hot Peak Viscosity

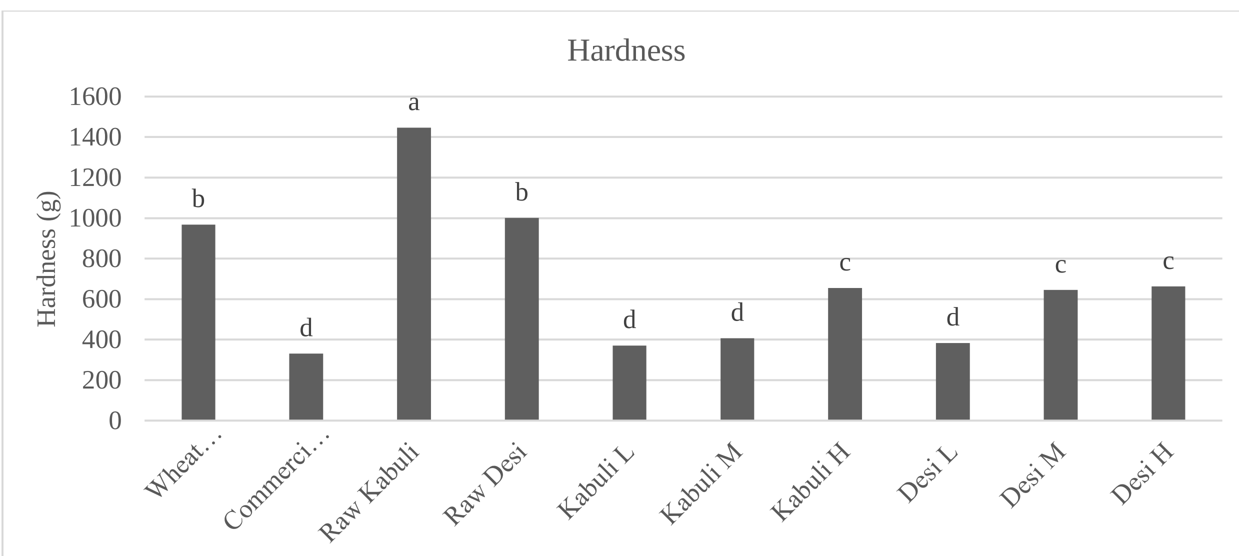


Figure 4.18 Instrumental Data - Cracker Hardness

Chapter 4 Tables

Table 4.1 Experimental Design

Variety	In-Barrel Moisture Level
Kabuli	Low
	Medium
	High
Desi	Low
	Medium
	High

Table 4.2 Flavor Attributes for Sensory Evaluation

Flavor Attribute	Definition
Oil Heated	The aromatics/flavors associated with heated cooking oils that may include olive oil, vegetable oils such as corn or soybean, and other common cooking oils. Characteristics include a lack of freshness, accompanied by slight brown and musty notes.
Overall Beany	A flavor characteristic of cooked beans and bean products, includes must/earthy, musty/dusty, sour aromatics, starchy, powdery feel, and one or more of the following characteristics: green/pea pod, nutty, sweet or brown.
Overall Grain	A general term used to describe flavor associated with grains. It is an overall grainy impression characterized as sweet, brown sometime generic nutty
Sweet	A fundamental taste factor of which sucrose is typical.
Bitter	The fundamental taste factor associated with a caffeine solution.

Table 4.3 Texture Attributes for Sensory Evaluation

Texture Attribute	Definition
Hardness	The force required to bite through the sample with molar teeth (until breaking). Evaluated on first bite down with the molars.
Fracturability	The force with which the sample ruptures. Evaluated on first bite down with the molars.
Initial Crispness	The intensity of audible noise at first chew with molars.
Cohesiveness of Mass	The degree to which the mass holds together during mastication after 5-7 chews.
Gritty	The perception of small, hard, sharp particles reminiscent of sand, or granules in pears.

Table 4.4 Proximate Analysis Data

Sample	Crude Protein	Crude Fiber	Fat	Ash	Total Starch
Kabuli Meal	24.63b	2.72a	4.71a	2.74a	33.25b
Desi Meal	24.64a	2.09b	4.53b	2.59b	37.15a

Table 4.5 Extrusion Processing Data

Sample	In-Barrel Moisture (%)	Moisture OE (%)	Moisture OD (%)	Die Temperature (ºC)	Die Pressure (PSI)	SME (kJ/kg)
Kabuli L	8.6017	3.4730	2.9668	142	1375	341
Kabuli M	12.6705	10.0478	3.9987	125	1450	299
Kabuli H	17.2526	13.5382	4.0969	112	1275	286
Desi L	9.8209	7.0836	3.3315	150	1425	330
Desi M	14.1151	9.8351	3.8572	133	1800	312
Desi H	18.019	12.5793	4.5841	128	2000	330

Table 4.6 DSC Data

Sample	Avg. Gelatinization Energy (J/g)
Raw Kabuli	2.7210
Raw Desi	4.0077
Commercial Precooked Chickpea Flour	0.0000
Kabuli L	1.1105
Kabuli M	0.5206
Kabuli H	0.8969
Desi L	0.0300
Desi M	0.3487
Desi H	0.4862

Table 4.7 WAI and WSI Data

Sample	WAI	WSI
Commercial Precooked Chickpea Flour	3.6489b	10.0585d
Raw Kabuli	1.9509c	26.2789bc
Raw Desi	1.9199c	23.1574c
Kabuli L	4.3125a	24.6783c
Kabuli M	4.2557a	24.8622c
Kabuli H	4.2671a	32.4514ab
Desi L	4.2721a	26.3901bc
Desi M	3.8476b	28.6164bc
Desi H	3.7072b	34.4093a

Table 4.8 Damaged Starch Data

Sample	**% Damage**	**Speed 80% Iodine Absorption (seconds)**
Raw Kabuli	3.6400e	47a
Raw Desi	3.6850e	46.5a
Commercial Precooked Chickpea Flour	10.2850d	19.5b
Kabuli L	12.2600a	17b
Kabuli M	11.7400bc	17b
Kabuli H	11.7550bc	17b
Desi L	11.9650ab	17b
Desi M	11.4150c	17b
Desi H	11.5550bc	17b

Table 4.9 Instrumental Cracker Texture

Sample	**Hardness (g)**	**Fracturability (mm)**
Wheat Cracker	968.23b	21.62c
Commercial Precooked Chickpea Flour	330.54d	20.18e
Raw Kabuli	1446.78a	26.53a
Raw Desi	1000.26b	24.24b
Kabuli L	370.64d	20.21e
Kabuli M	406.59d	20.61de
Kabuli H	655.09c	21.02cd
Desi L	383.20d	20.38de
Desi M	644.79c	20.26f
Desi H	662.61c	20.26f

Table 4.10 Cracker Sensory Data - Texture

Sample	Hardness	Fracturability	Initial Crispness	Cohesiveness of Mass	Gritty
Wheat thins	8.350 ab	7.050 ab	9.500 ab	7.450 a	0.450 b
Good thins	6.950 cd	7.300 ab	10.700 a	5.900 ab	0.650 b
Commercial Precooked Chickpea Flour	4.200 e	3.850 c	6.050 c	2.850 c	2.150 a
Raw Desi Control	8.300 ab	5.800 b	8.100 b	3.750 c	2.050 a
Kabuli L	5.850 d	6.650 ab	9.250 ab	3.500 c	0.350 b
Kabuli M	7.850 abc	7.700 a	9.950 ab	4.200 bc	0.850 b
Kabuli H	8.400 a	6.900 ab	8.850 ab	4.100 c	0.150 b
Desi L	7.250 bc	7.350 ab	9.950 ab	3.800 c	0.250 b
Desi M	8.050 abc	7.800 a	10.150 a	4.050 c	0.450 b
Desi H	7.600 abc	7.300 ab	10.500 a	4.250 bc	0.600 b

Table 4.11 Cracker Sensory Data - Flavor

Sample	Oil-Heated	Overall Beany	Overall Grain	Sweet	Salt	Bitter
Wheat thins	3.750 ab	0.200 c	5.600 a	1.400 a	2.150 a	2.400 a
Good thins	3.400 b	0.900 c	4.350 ab	0.400 b	1.950 a	1.550 b
Commercial Precooked Chickpea Flour	3.800 ab	2.650 b	2.950 c	0.400 b	1.200 a	2.550 a
Raw Desi Control	4.550 ab	3.500 ab	3.350 bc	0.350 b	1.200 a	2.650 a
Kabuli L	5.050 a	4.650 a	4.400 ab	0.650 ab	1.350 a	2.300 ab
Kabuli M	5.000 a	4.300 ab	4.000 bc	0.700 ab	1.950 a	2.350 ab
Kabuli H	4.900 ab	4.700 a	3.450 bc	0.500 b	1.700 a	2.350 ab
Desi L	5.150 a	5.000 a	3.750 bc	0.700 ab	1.550 a	2.500 a
Desi M	4.550 ab	4.800 a	3.800 bc	0.650 ab	1.500 a	2.500 a
Desi H	5.100 a	4.200 ab	3.350 bc	0.600 ab	1.550 a	2.200 ab

Chapter 5 - Final Conclusions and Future Work

Final Conclusions

The work in this thesis can be directly used by the industry and academia. The results showed that roller milling equipment can effectively remove chickpea hull while creating a highly controlled particle size. The benchtop milling research translated very well to pilot scale showing the effectiveness and cost staving ability of this scale of work on novel ingredients. Proximate analysis showed that protein and starch may not be distributed evenly in the endosperm. The extrusion precooking method was proven to be customizable while leading to precooked flours with better functionality than commercial samples. Changing IBM significantly affected the properties of the precooked flours leading to differences in cracker texture. The extrusion process was limited however due to the inherent oil in chickpeas and could not reach the same processing intensity as the commercial precooked sample.

Future Work

Future research could be done to expand the milling flow sheets to include whole Desi chickpeas. More milling research could focus on proximate analysis of every aspect of the milling flow to determine where the best quality of meal and flour could be obtained or where more protein and starch are being collected. Another area of future focus could be on using the newly produced chickpea meal in other processes and formulations, such as pasta.

Further extrusion research at pilot scale could be done to use the flour streams as well, so all streams could be used and therefore increase sustainability and efficiency. This could include comparing flour and meal as well as meal and flour combinations. Another focus of extrusion could be to increase the total energy of the process through preconditioning with steam therefore increasing the thermal energy. The increase in total energy input may result in a flour with closer functionality to the commercial precooked chickpea flour.

References

Adamidou, S., Nengas, I., Grigorakis, K., Nikolopoulou, D., Jauncey, K., 2011. Chemical Composition and Antinutritional Factors of Field Peas (Pisum sativum), Chickpeas (Cicer arietinum), and Faba Beans (Vicia faba) as Affected by Extrusion Preconditioning and Drying Temperatures. Cereal Chem. J. 88, 80–86. https://doi.org/10.1094/CCHEM-05-10-0077

Bhatnagar, S., Hanna, M.A., 1994. Amylose-Lipid Complex Formation During Single-Screw Extrusion of Various Corn Starches'. Cereal Chem.

Bouvier, J.M., Campanella, O.H., 2014. Extrusion Processing Technology: Food and Non-Food Biomaterials, Extrusion Processing Technology: Food and Non-Food Biomaterials. Wiley Blackwell. https://doi.org/10.1002/9781118541685

Candela, M., Astiasaran, I., Bello, J., 1997. Cooking and Warm-Holding: Effect on General Composition and Amino Acids of Kidney Beans (Phaseolus vulgaris), Chickpeas (Cicer arietinum), and Lentils (Lens culinaris). J. Agric. Food Chem. 45, 4763–4767. https://doi.org/10.1021/jf9702609

Chávez-Murillo, C.E., Veyna-Torres, J.I., Cavazos-Tamez, L.M., de la Rosa-Millán, J., Serna-Saldívar, S.O., 2018. Physicochemical characteristics, ATR-FTIR molecular interactions and in vitro starch and protein digestion of thermally-treated whole pulse flours. Food Res. Int. 105, 371–383. https://doi.org/10.1016/j.foodres.2017.11.029

Foster-Powell, K., Holt, S.H., Brand-Miller, J.C., 2002. International table of glycemic index and glycemic load values: 2002. Am. J. Clin. Nutr. 76, 5–56. https://doi.org/10.1093/ajcn/76.1.5

Gil, J., Nadal, S., Luna, D., Moreno, M.T., Haro, A. De, 1996. Variability of Some Physicochemical Characters in Desi and Kabuli Chickpea Types. J. Sci. Food Agric. 71, 179–184. https://doi.org/10.1002/(sici)1097-0010(199606)71:2<179::aid-jsfa566>3.3.co;2-z

Heiras-Palazuelos, M.J., Ochoa-Lugo, M.I., Gutiérrez-Dorado, R., López-Valenzuela, J.A., Mora-Rochín, S., Milán-Carrillo, J., Garzón-Tiznado, J.A., Reyes-Moreno, C., 2013. Technological properties, antioxidant activity and total phenolic and flavonoid content of pigmented chickpea (Cicer arietinum L.) cultivars. Int. J. Food Sci. Nutr. 64, 69–76. https://doi.org/10.3109/09637486.2012.694854

Hoseney, R.C., 1986. Principles of cereal science and technology. A general reference on cereal foods. Princ. Cereal Sci. Technol. A Gen. Ref. Cereal foods.

Jan, R., Saxena, D.C., Singh, S., 2017. Effect of extrusion variables on antioxidant activity, total phenolic content and dietary fibre content of gluten-free extrudate from germinated Chenopodium (*Chenopodium album*) flour. Int. J. Food Sci. Technol. 52, 2623–2630. https://doi.org/10.1111/ijfs.13549

Martin, R., Zhao, J., Siliveru, K., Dogan, H., Watt, J., Chambers IV, E., Alavi, S., 2020. Optimization of benchtop milling and extrusion of chickpeas (Cicer arietinum) into a precooked flour. J. Food Process Eng.

Mekonnen, M.M., Hoekstra, A.Y., 2010. Value of Water Research Report Series No. 48 Value of Water.

Mohammed, I., Ahmed, A.R., Senge, B., 2014. Effects of chickpea flour on wheat pasting properties and bread making quality. J. Food Sci. Technol. 51, 1902–1910. https://doi.org/10.1007/s13197-012-0733-9

Mohammed, I., Ahmed, A.R., Senge, B., 2012. Dough rheology and bread quality of wheat-chickpea flour blends. Ind. Crops Prod. 36, 196–202. https://doi.org/10.1016/j.indcrop.2011.09.006

Normell Jhoe E. de Mesa, Sajid Alavi, Naprinder Singh, Yong-Chen Shi, Hulya Dogan, Y.S., 2009. Soy protein-fortified expanded extrudates: Baseline study using normal corn starch. J. Food Eng. 90, 262–270.

Ravi, R., Harte, J.B., 2009. Milling and physicochemical properties of chickpea (*Cicer arietinum* L.) varieties. J. Sci. Food Agric. 89, 258–266. https://doi.org/10.1002/jsfa.3435

Riley, R.E., Hausner, H.H., 1970. Effect of particle size distribution on the friction in a powder mass. Int. J. Powder Met 6 pp. 17–22.

Sinclair, T.R., Serraj, R., 1995. Legume nitrogen fixation and drought. Nature 378, 344. https://doi.org/10.1038/378344a0

Singh, U., 1988. Antinutritional factors of chickpea and pigeonpea and their removal by processing. Plant Foods Hum. Nutr. 38, 251–261. https://doi.org/10.1007/BF01092864

Soni, B., Sarita, S., 2014. Comparative evaluation of milling bi-products: finger millet seed coat (FMSC), chick pea husk (CPH) and wheat bran (WB) for their nutritional, nutraceutical potential. Int. J. Basic Appl. Agric. Res. 12.

Sreerama, Y.N., Neelam, D.A., Sashikala, V.B., Pratape, V.M., 2010. Distribution of nutrients and antinutrients in milled fractions of chickpea and horse gram: Seed coat phenolics and their distinct modes of enzyme inhibition. J. Agric. Food Chem. 58, 4322–4330. https://doi.org/10.1021/jf903101k

Tavano, O.L., Neves, V.A., Inácio Da, S., Júnior, S., 2016. In vitro versus in vivo protein digestibility techniques for calculating PDCAAS (protein digestibility-corrected amino acid score) applied to chickpea fractions. https://doi.org/10.1016/j.foodres.2016.10.005

Tester, R.F., Debon, S.J.J., 2000. Annealing of starch - A review. Int. J. Biol. Macromol. https://doi.org/10.1016/S0141-8130(99)00121-X van der Weele, C., Feindt, P., Jan van der Goot, A., van Mierlo, B., van Boekel, M., 2019. Meat alternatives: an integrative comparison. Trends Food Sci. Technol. 88, 505–512. https://doi.org/10.1016/j.tifs.2019.04.018

Wood, J.A., Knights, E.J., Choct, M., 2011. Morphology of chickpea seeds (Cicer arietinum l.): Comparison of desi and kabuli types. Int. J. Plant Sci. 172, 632–643. https://doi.org/10.1086/659456

Wood, J.A., Knights, E.J., Harden, S., 2008. Milling performance in desi-type chickpea (Cicer arietinum L.): effects of genotype, environment and seed size. J. Sci. Food Agric. 88, 108–115. https://doi.org/10.1002/jsfa.3053

Xu, Y., Thomas, M., Bhardwaj, H.L., 2014. Chemical composition, functional properties and microstructural characteristics of three kabuli chickpea (*Cicer arietinum* L *.)* as affected by different cooking methods. Int. J. Food Sci. Technol. 49, 1215–1223. https://doi.org/10.1111/ijfs.12419

Yamsaengsung, R., Berghofer, E., Schoenlechner, R., 2012. Physical properties and sensory acceptability of cookies made from chickpea addition to white wheat or whole wheat flour compared to gluten-free amaranth or buckwheat flour. Int. J. Food Sci. Technol. 47, 2221–2227. https://doi.org/10.1111/j.1365-2621.2012.03092.x