Snack food development with single phase extrusion-cooking technology

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Attestation of authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Signed Kristy

Date ________14 April 2016_____________

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Abstract

Extrusion cooking technology is a popular technique for generating a wide range of ready-to-eat products, from snacks, breakfast cereals, pasta and instant noodles to pet food. Extrusion cooking involves inserting raw materials – minimally starchy grains and water – at one end of an extruder barrel. The starch-based raw materials are conveyed through the barrel, typically by a worm drive, to an exit die that forms the final shape. The high pressure, shear forces and friction that develop towards the die end of the extruder generates heat which cooks the product, in turn producing an extruded dry, shelf stable product.

Existing commercial extruders require a three-phase power supply to run the high torque motors, which, are used to provide enough energy to generate the amount of pressure and forces required for industrial production. Millbank Group of Mangere, Auckland has developed a single phase extruder. The advantage of using a single phase powered extrusion cooker is that ready-to-eat snacks can be produced on site by cafes, restaurants or even cinemas, which seldom have a three-phase power supply. Disaster relief is another application, where portable generators are most commonly single phase.

The primary objective of this research is to create products and evaluate their physiochemical properties and to evaluate is consistent viable products can be produced using single phase power.

The first phase of this study was to produce, analyse and compare the extrudates created by this single phase extrusion cooker by using maize, wheat and brown rice as the primary grains.

In the second phase of this study, new grains were introduced to create some new combinations. They were peanut, oat, mung bean, soy and amaranth. Although the addition of the new grains was in a relatively low ratio, ranging from 5 to 10%, they brought a huge impact on the extrudates texture and bulk density.

Extrusion cooking is a rapid yet complex process. There are process parameters, such as screw speed and nose temperature, that impact on the outcome of the extrudate properties which include texture and bulk density. The performance parameters data from Phase 1 and 2 showed variation from a statistical perspective, either due to subtle changes to the extruder and/or changes to the grain specifications. Therefore in the third phase of this study, a designed experiment was conducted which focused on the nose temperature on three basic grains that were often used in Phase 1 and 2, which were brown rice, maize and wheat, to examine whether the physicochemical aspect and texture of the extrudates would be different under the controlled nose temperatures. It was concluded that the higher nose temperatures significantly decreased the moisture content of all extrudates while the lower nose temperatures made the extrudates more difficult to break.

Chapter 1
Introduction

The control of fire was a fundamental advance in human evolution because it allowed the extraction of enhanced nutritional value from foods (Wrangham and Conklin-Brittain 2003). Controlled fire was started by shear forces applied to dry combustible matter. Once created the heat denatured proteins and gelatinised carbohydrates making them more susceptible to digestive enzymes. Shear forces created the heat required to overcome the energy barrier that lead to the exothermic reaction, the heat of which feeds back to maintain what is essentially a chain reaction provided oxygen and fuel are available. However, physical friction itself was never a way of cooking food until the invention of shear extruders.

Extrusion cooks foods by using thermal and mechanical energy created by friction and shearing. This chapter will give an overview on why this research has been carried out, how the extrusion process works and the different types of extrusion cookers that are employed by the food industries.

Purpose of this research

The specific aims of this work are to confirm that a single-screw, single phase extruder can produce consistent extrudates, in terms of physical and chemical properties, with various types of raw materials such as brown rice, maize and wheat. Once the properties of the extrudates have been confirmed to be consistent, meaning the single phase extruder is producing extrudates to a consistent standard, the next hypothesis is that the single phase extruder can be a versatile machine. In Phase 3 of this thesis, each of the selected grains were used to produce extrudates under two different screw temperatures, which were set by the operator, in order to determine the effect screw temperature has on the physical and chemical properties of the extrudates.

History of extrusion

The basic process of a moving liquid via a screw mechanism, typically a mechanical screw within a barrel, was first described before 200 BC the Greek polymath Archimedes. Archimedes used a screw within a barrel to move water from a lower to a higher level, against the force of gravity. This simple design was created with wood and it can be assumed there was no heat produced by this design. Although it is not an example of extrusion as such it was the first step in the direction of an internal screw based machine being used to convey a liquid. (Massoud 2011).

The first example of an industrial style extrusion machine was seen in 1797 when the first patent was taken out for extrusion technology. This basic extrusion machine encompassed a ram-style machine forcing lead through a die to produce lead pipes (Massoud 2011). This would create heat as the lead atoms realigned to create the hollow tube. The first type of food product produced by a single-screw extruder was in the pasta industry in the mid-1930s by a continuous pasta processing method. The pasta produced was in an uncooked form. This pasta required the raw ingredients to be processed into a dough before the machine shaped the product. Undoubtedly some heat would be generated in the region of the die but not sufficient enough to cook the product. By the mid-1940s expanded cornmeal snacks had begun to be produced (Riaz 2000).

Contemporary applications of extrusion technology for food

The basic design of a contemporary commercial extruder consists of a screw(s) in helical and spiral shapes housed within a heated barrel, designed to force the dough through a die (Figure 1). The details of design will be discussed in the next section, but the basic design as stated here is sufficient to allow discussion of the vast range of products made by extrusion.

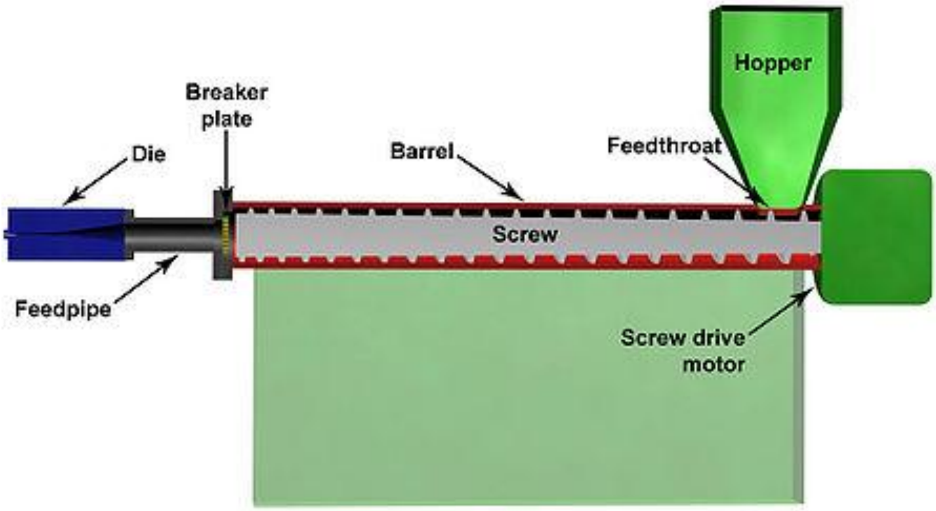


Figure 1 The design concept of a single-screw extruder, the most common commercial design (https://commons.wikimedia.org/wiki/File:Extruder_section.jpg).

When discussing nutrition and food production, it is assumed the focus is solely on human foodstuffs. However, another huge industry in food production is pet food (Figure 2). In modern times pet food is most commonly produced using extrusion technology due to the high production rate and low cost (Lankhorst and Tran et al. 2007). Another benefit to using extrusion cooking when producing pet food is the large variety of ingredients that can be introduced in the processing.

Extruders producing food for human consumption and animal consumption are routinely setup in a similar way. That is to say the machine starts with a feeder which introduces ingredients into the barrel. The ingredients are then pushed along by a screw producing heat through friction, shearing and pressure, with the final product being formed with a die. The process is understandable similar as the requirements of the final product are similar, that is they should be cooked, ready to eat and presentable.

Figure 2 Various small pet food biscuits produced through extrusion (http://www.ddwcolor.com/applications/pet-food/dry-extruded/).

Not only is extrusion a quick way of producing large quantities of ready to eat food it also produces feed that is more digestible than if the ingredients were consumed raw. The process of heating, shearing and the pressure involved in extrusion, not only gelatinises starch, but also deactivates anti-nutritional chemicals that are heat unstable (Moscicki 2010). From a human perspective the most common application of extrusion is the creation of snack foods and breakfast cereals.

Snack foods are commonly thought of as unhealthy, oily, salty types of foods but most importantly they are ready to eat when the urge arises. It is this property that makes snack foods so desirable. Original extrusion snacks were commonly only created from maize but through research and development ingredients such as rice, potato and wheat are now also common raw materials.

Almost all of the snack foods created by extrusion are produced using low moisture extrusion. This makes the product shelf stable and safer for immediate consumption. The extruded products can also go through a secondary phase to further enhance the product and also add flavour through oils or powders. Another process that can be incorporated into the production of snack products through extrusion is the final shape of the product. Using specific dies, precise shapes and textures can be created that are appealing to the consumer (Figure 3).

It is also possible to create snack products that are not considered a fully finished product. The puffing stage, or expansion stage of the production can be done in another factory, shop or even at home using a microwave, deep frying or by simply baking the product. These extrudates are known as half products or can also be called semi products (Wiedmann 1987). A more complex type of extrudate snack is a product made from combining two completely separate and dissimilar types of materials to create one final product. These are produced by co-extruding two different materials simultaneously then combining them to form one product (Fellows 2013).

Figure 3 Various shapes and colours of extrudate snacks (http://www.intechopen.com/source/html/39936/media/image2.jpeg).

Like dried pet foods, breakfast cereals are a major extrusion application. Images of typical cereals are shown in Figure 4.

Figure 4 Four different types of ready to eat breakfast cereals produced by extrusion (http://www.clextral.com/food-feed-2/food/breakfast-cereals/direct-expanded-breakfast-cereals/).

The production of breakfast cereals is most commonly done using extrusion cooking and is commonly made with wheat, corn or a combination of the two. Other grains such as sorghum, rice and oats can also be used and again are occasionally combined to produce multigrain breakfast cereals. Flakes are predominantly associated with breakfast cereals and are the mainstay of most major cereal produces. Products such as corn flakes and bran flakes are almost known to all who consume breakfast cereals and can be seen in many variations. Although these are the most common types of extrudates used as breakfast cereals there are many others on the market. By mixing specific grains the texture and flavour of the cereal can be altered thus producing a new product. Along with texture, a variation of grains can also be used to reduce production cost as well as altering the micronutrients available in the cereal (Camire 2012).

A good example of a ready-to-eat breakfast cereal is Kellogg’s Nutri-grain, which is available in liquid form, snack bar size and cereal form and is sold in many Western markets (Figure 5). Through advertising and other promotion, this extruded breakfast cereal is associated with sports, in particular the Iron Man Triathlon, and is marketed as a nutritious breakfast/snack food that is beneficial to training. Nutri-grain advertising clearly claims that it is high in carbohydrate and protein (Figure 5). Carbohydrates make up the largest component of this product, 69 g per 100 g. Sugar comprises almost half the carbohydrate content. There is, however, no evidence that Nutri-grain is of any unique advantage to an athlete because its ingredients are common to many cereal products.

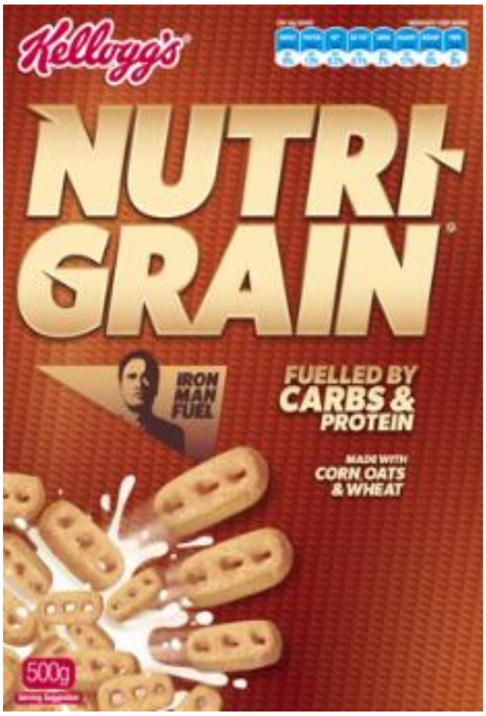


Figure 5 Kellogg's Nutri-grain packaging and an image showing commonly associated advertising (http://www.kelloggs.co.nz/en_NZ/nutri-grain-bar-original-product.html).

Nutrition Information
(AVERAGE)
servings per package - 16
average serving size - 30g (1 metric cup†)

	quantity per serving	% daily intake ▲ per serving	per serve with ½ cup skim milk	quantity per 100g
ENERGY	480 kJ	**6%**	670 kJ	1600 kJ
PROTEIN	6.6 g	**13%**	11.2 g	21.9 g
FAT, TOTAL	0.2 g	**0.3%**	0.3 g	0.6 g
- SATURATED	<0.1 g	**0.1%**	0.2 g	0.1 g
CARBOHYDRATE	20.8 g	**7%**	27.3 g	69.4 g
- SUGARS	9.6 g	**11%**	16.1 g	32.0 g
DIETARY FIBRE	0.8 g	**3%**	0.8 g	2.7 g
SODIUM #	144 mg	**6%**	200 mg	480 mg
		%RDI*		
THIAMIN (VIT B1)	0.55 mg	**50%**	0.60 mg	1.83 mg
RIBOFLAVIN (VIT B2)	0.42 mg	**25%**	0.68 mg	1.42 mg
NIACIN	2.5 mg	**25%**	2.6 mg	8.3 mg
VITAMIN B6	0.4 mg	**25%**	0.4 mg	1.3 mg
VITAMIN C	10.0 mg	**25%**	11.3 mg	33.3 mg
FOLATE	50 µg	**25%**	56 µg	166 µg
CALCIUM	80 mg	**10%**	239 mg	266 mg
IRON	3.0 mg	**25%**	3.1 mg	10.0 mg

† Cup measurement is approximate and is only to be used as a guide. If you have any specific dietary requirements please weigh your serving.
▲ % Daily Intakes are based on an average adult diet of 8700kJ. Your daily intakes may be higher or lower depending on your energy needs.
* % Recommended Dietary Intake (Aust/NZ) per serving.
# 144mg of sodium per serve is equivalent to 0.4g of salt.

Ingredients
Cereals (44%)(wheat flour, oatmeal, maize flour), sugar, wheat gluten, molasses, salt, minerals (calcium carbonate, iron), barley malt extract, mineral salt (sodium bicarbonate), natural colour (paprika, turmeric), vitamins (vitamin C, niacin, thiamin, riboflavin, vitamin B6, folate).
CONTAINS GLUTEN CONTAINING CEREALS.
MAY CONTAIN TRACES OF PEANUTS AND/OR TREE NUTS.
INGREDIENTS: Céréales (44%)(farine de blé, avoine, farine de maïs), sucre, gluten de blé, mélasses, sel, minéraux (carbonate de calcium, fer), extrait de malt d'orge, sel minéral (bicarbonate de soude), la couleur naturelle (paprika, turmeric), vitamines (vitamine C, niacine, thiamine, riboflavine, vitamine B6, folate).
CONTIENT GLUTEN CONTENIR LES CÉRÉALES.
PEUT CONTENIR DES TRACES DE CACAHUÈTES ET/OU NOIX D'ARBRES.

Figure 6 Full nutrition information panel and ingredients of Kellogg's Nutri-grain (http://www.kelloggs.co.nz/en_NZ/nutri-grain-bar-original-product.html).

The ingredient list (Figure 6) shows what was used in the extrusion but will have omitted water. Water is an ingredient at the start but makes up very little of the final product, and so can legally be omitted from the list. The list contains: cereals (44%) (wheat flour, oatmeal, maize flour), sugar, wheat gluten, molasses, salt, minerals (calcium carbonate, iron), barley malt extract, mineral salt (sodium bicarbonate), natural colour (paprika, turmeric), vitamins (vitamin C, niacin, thiamine, riboflavin, vitamin B6, folate). This illustrates the range of materials that can be passed through extruder systems, but usually in combinations. Ingredients are further discussed in the next section.

The discussion above assumes that all the ingredients in the final product pass through the extruder. This is not necessarily the case, because, other ingredients can be added as external coatings.

While cooking fundamentally improves digestibility, the extrusion process may result in some loss of flavour, arising from the pressure and temperature reached during the process. Once the product is released from the die the heated steam that escapes also takes with it flavouring compounds and can result in a bland tasting final product.

Post-extrusion cooking treatments are commonly used to finish a product after the extrusion process. Examples are the process of frying, roasting or toasting to change the texture, appearance and to give a different flavour to the final product (Table 1). A variety of dry coatings may also be added, which contain flavours and other components (Stojceska and Ainsworth et al. 2007).

Table 1 Common post extrusion treatments and raw ingredients used for selected products (Suvendu 2011).

Name of Product	Type of Treatment	Machinery Employed	Raw Materials Used during Postextrusion Treatment
TVP	Drying	Continuous belt dryer	Nil
Low-density cereal/legume/ tuber and root crop based snack	Drying	Continuous belt/rotary inclined dryers	Nil
	Roasting	Air/contact inclined surface roaster	Nil
	Flavoring	Batch inclined drum/enrober/ continuous rotary drum with spray/powder dispensing system	Salt, oil, sugar, flavors, binders, antioxidants, color, minerals, and vitamins
Breakfast cereals	Roasting/ toasting	Air/contact surface roaster/toaster	Nil
	Coating	Batch or continuous drum/enrober	Sugar, malt powder, flavor, liquid glucose, oil
Soy granules	Size reduction and drying	Granulators/disintegrator/rotary slicer and continuous dryer	Flavor, salt

Advantages of modern extrusion systems

Through developments and improvements extrusion has become a very versatile and cost efficient way of producing many types of foods. Advancements such as the inclusion of melt enhancing screws, data collection and analysis and a general understanding of the processes that are involved have all added to the improvement of extrusion.

The cost of production has reduced through this research due to new formulations that have been discovered through which lower cost alternatives have been found for some raw ingredients. In parallel with extruder development, an increased range of ingredients can be used. The advantage of this is that one machine can be designed and built to produce several products that vary greatly in composition, thus increasing the versatility of the machine.

Raw Ingredients

There are several classifications of extrusion ingredients. They are classified by their functional roles during the extrusion process. The groups are as follows:

1. Structure forming materials. These starchy ingredients are used to form the main structure of an extrudate. This structure is created by forming a melt within the extruder from biopolymers which then have bubbles of water vapour passed through to create a product quite similar to expanded foam. The starch component of cereals in Figure 5 is an example of this.
2. Dispersed-phase filling materials. This group includes fibrous materials such as bran that are principally comprised of cellulose and hemicellulose that are a component of cereals. The polymers within these ingredients form separate phases within a continuous starch phase.
3. Plasticising and lubricant materials. Water is commonly the main ingredient under this classification. The purpose of this group of ingredients is to reduce the interactions of the melt within the extruder by plasticising the raw ingredients. This plasticising process transforms the solid ingredients into deformable plastic fluids.
4. Soluble solid materials. Examples are sugar and salt. These ingredients are added to enhance the flavour of a product and/or to lower water activity.
5. Nucleating materials. The use of nucleating materials is to increase the gas bubble nucleation within the melt. This can help produce a product that is less dense and help increase the expansion ratio at the die. Some common nucleating substances include magnesium silicate and calcium carbonate in powdered form. Sodium bicarbonate in Figure 5 appears to fit this description.
6. Colouring materials. Although raw ingredients are commonly the source of colour, yellow maize kernels for example, other colours are often wanted, in for example dried pet food (Durge and Sarkar et al. 2013).
7. Flavouring materials. Although these can be surface added after extrusion – as explained earlier – it is also common to include them in the dough mix.
8. Vitamins. The vitamins stated in Figure 6 are commonly added to formulated cereals and are stable when dried by heat, such as the conditions that occur in extrusion (Athar and Hardacre et al. 2006; Brennan and Brennan et al. 2011; Camire 2012).

The common raw ingredients that are used in extrusion are maize, wheat, brown rice, and soy. Maize is particularly favoured, and the natural yellow pigmentation makes attractive products. The majority of the products produced from maize are further cooked by either baking or frying and have flavour added commonly as a coating. Rice is another preferred ingredient, particularly in areas of the world where rice is in large supply. The production of a clean looking white extrudate is an attractive trait as well as having a bland taste which is less likely to influence the flavour of the final product. Wheat, having higher protein content than the other commonly used grains, is more commonly used in the production of pasta products and breakfast cereals. These cheap starchy and high protein raw materials are the popular choices of extrusion products because their physicochemical properties help facilitate the extrusion cooking process. The advantage of choosing raw materials with a high coefficient of friction, such as maize grits and whole grains, is the development of good drag flow in single-screw extruders (Frame 1999). Oil seeds are not such an attractive ingredient because the oil lubricates reducing friction, which may result in a uncooked extrudate coming out from the exit die.

In terms of human digestion, it is well known that uncooked/ungelatinised starch granules are unable to be significantly digested. With the presence of steam, pressure, heat and the addition of mechanical degradation, the starch granules are gelatinised and dextrinised into a dried form that when rehydrated on eating are accessible to amylolytic enzymes increasing the digestibility of the product.

According to Suvendu (2011), nutritional value is not the only reason high starch foods make an ideal ingredient. Structure, mouthfeel and texture are also affected by starch. Dextrinisation produces dextrin sugars from the starch and gelatinisation helps create the melt viscosity.

The effect that the starch granules will have on the melt is determined by the original ingredient. For example starch from wheat will have the effect of lowering the viscosity of the melt. Starches that are considered waxy, such as those from corn or rice, are used to keep the final product crunchy by reducing the uptake of water during processing. A common food produced with waxy starches are cereals, the waxy starches in the food help prevent the cereals soaking up the liquid, such as milk, so the cereal stays crunchier for longer. Starches that act in the opposite way by encouraging water absorption contain an amylose content of 80%. These high amylose starches create foods that swell in the presence of water and as a powder are commonly used to form gels. Commonly amylose produces lighter products with greater elasticity as well as regulating the surface and texture of an extrudate. Products with a greater concentration of amylopectin on the other hand are harder and have a lower expansion ratio.

Moisture content

Water plays a very important role in the extrusion process. Without water many of the desired processes of extrusion cannot be accomplished, the main one being plasticisation. Along with plasticisation, gelatinisation also relies on the availability of moisture. When looking at raw ingredients to be used in producing a ready to eat product using extrusion there are two aspects that need to take preference over others. Moisture content of the raw ingredients and the amount of water added to the process are the two main factors affecting the cook of the product. When choosing raw ingredients it is important to keep in mind that the moisture content of the raw ingredients will have an effect on cook temperature, the rate at which the product is produced and the final product characteristics. The moisture content of the raw ingredients will have an effect on the density, cooking, expansion and starch gelatinisation of the final product. Along with this is the fact that the products rehydration will be affected which will affect the shelf life and stability of the product.

When describing moisture content in food extrusion, three groups can be formed. The first group, low moisture feed, contains ingredients that have a moisture content of 25% or less. The second group, intermediate moisture feed, involves raw ingredients that have moisture content between 25% and 50%. The final group known as high moisture feed includes any feed that has moisture content above 50%. Below is a brief description of each moisture content group.

Low Moisture Extrusion

Low moisture extrusion is the most common feed group used in the production of extrudates. Products produced with low moisture feed are commonly ready to eat or ready to process foods. In the case of ready to process foods a further cooking step is required, for example frying, baking or roasting can be included to produce the final product.

When low moisture feed is used it is almost always mandatory to include a drying step during the process if the moisture content is above 5 percent. The common feeds or raw ingredients used are legumes, cereals and oilseed meals. Some examples of extrusion products are breakfast cereals and puffed corn balls.

Intermediate Moisture Extrusion

Due to the higher moisture content present in these feeds it is common for the extrusion product to expand when coming out of the die and later collapse to produce a final product with a higher density. The high moisture content of the final product requires that a drying step must be introduced so that safe moisture content can be obtained. If the extrudate has a high moisture content it becomes more susceptible to microbial spoilage and contamination.

The common feeds with intermediate moisture content are cereals such a wheat and flavour, preservative or colour additives. Products produced using intermediate moisture feed include spaghetti and other pasta products. The products require further cooking and are not intended to eat raw so the main function of the extrusion process is to create a shaped product.

High Moisture Extrusion

This form of extrusion is accomplished commonly only with a twin-screw extruder with the inclusion of facilities for cooling as well as specially designed die. Extrudates produced with high moisture extrusion are required to be stored in refrigerated or frozen condition immediately after extrusion for safety reasons.

This type of extrusion can be used to process seafood products such as fish, crab and shrimp meat as well as beef analogs. A good example of a high moisture extrudate is surimi, which is a ready to eat product made from low quality fish meat that can be hard to sell as an individual item.(Eastman and Orthoefer et al. 2001).

Types of extruders

There are two main categories of food extrusion. These categories are product forming and product cooking. These two categories produce two very different products.

The first category of product forming extruders produces foods such as pasta and cold formed snack foods, that are subsequently sold as is (fresh pasta for example) or dried (dried pasta) or fried to dry off the water and include fat (instant noodles). In these cases the extrusion pressures are not high enough to gelatinise the starch.

The second category, cooking, produces cooked products as well as expanded products. This category commonly involves the use of medium to high shear single and twin-screw co-rotating extruders. Shearing refers to the process of deformation of the shape of the material in the extruder.

There are also two types of cooking extruders in terms of screw arrangement. There are extruders that contain a single-screw and ones that have two screws that can either be rotating in the same fashion or in reverse. Both single and twin screw extruders are used to produce food products.

Single-screw extruders

Single-screw extruders commonly have three main sections in terms of the screw. The first section is the feeder or solid conveying section, next the melt/plasticising or melt conveying section, followed by the melt pumping section. The final section included at the end of the extruder is the die (Figure 7). The die section is where the product is finally extruded, discussion of the die section is deferred until after the twin screw description because dies are common to both designs.

Solid conveying section

The solid conveying section, also known as the conveying section, of a single-screw extruder has the largest screw depth of all the sections. This section is used to convey the raw ingredients further along the screw into the melting/plastification section of the extruder. The feeder, in most cases, delivers the raw ingredients directly into the conveying section of the screw.

It is assumed that the channel depth is constant throughout the conveying section. Pressure is slowly developed by the drag induced solids. Groves can be added to the barrel wall to increase friction and therefore increase pressure. This occurs due to the greater surface area now presented by the groves.

Raw solid ingredients are commonly introduced into the barrel in a starved fed fashion. This is to avoid bridging problems which can occur at the feeder port. For this reason it is often the feeder that determines the output of the extruder. The solid ingredients move through this section of the extruder as a solid bed before reaching the melting/plastification stage of the extruder barrel.

Melting section of extruder

The melting/plasticising section in a food extruder is also known as the dough forming section as it is during this part of the extruder that the solid begins to form a dough. Here the channel depth is lower than in the conveying section. Dough formation only occurs if enough water is present in the mix. The water in the mix acts as a plasticiser which reduces the melting temperature of the starch. There are several factors that influence this process, they are as follows: moisture content, temperature, pressure, mean particle size, size distribution, and how well the ingredients were mixed prior to conveying. Once a specific temperature is reached the starch gelatinisation/melting will occur. This process leads to a significant increase in the viscosity of the dough, further raising the pressure.

The penultimate stage of the process takes place in what is known as the melt pumping section of the extruder. In this section the melt that is produced during food extrusion is known to be very similar to that of thermoplastic melts under similar conditions. The melt during the conveying section has a pseudoplastic rheology with the viscosity being influenced mainly by the temperature and moisture content. Chemical and structural changes to the melt can also influence the viscosity of the melt (Waleed 2011).

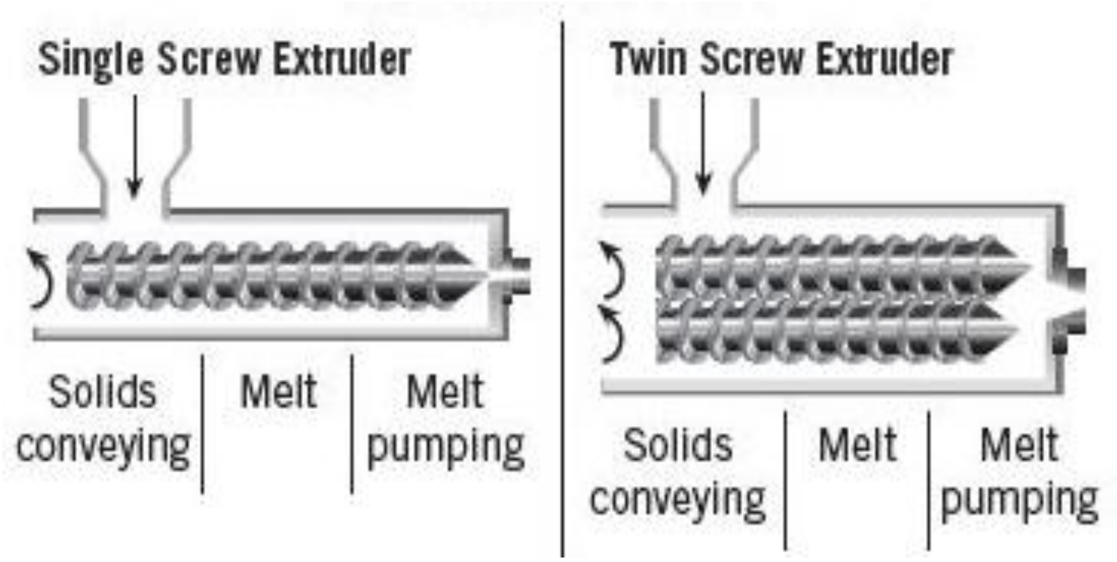


Figure 7 The design concept of single and twin screw extruders, based on the most common commercial designs (http://www.particlesciences.com/images/tb/cross-section-of-single-and-twin-screw-extruder-barrel.jpg).

Twin screw extruders

Twin screw extruders, as the name indicates, contain two screws. They are located side-by-side, and can operate in two ways, co-rotating and counter rotating.

Figure 8 is a good example of a counter rotating twin screw design, where one screw is a mirror image of the other. Twin screw extruders have proved to be more versatile and are therefore adopted when using hard to handle formulations. Single-screw extruders are currently not able to deliver the processing performance required in these situations. However, the principles of conveying, melting/plasticising and melt conveying also apply to these more complex designs.

Figure 8 The design concept of a twin screw extruder, the most common commercial design (http://www.barrel-screw-china.com/en%20parallel-twin-screw-barrel.html).

Dies

When the melt ingredients exit the barrel they are forced through an opening, the size and shape of which can be changed easily to create desired shapes, known as the die. The die is bolted to the end of the barrel so that the melt passes directly through the opening. The pressure that is exerted at this opening is extremely high due to the pressure built up previously in the barrel.

The die shape is important for the final properties of the extrudate. When the melt exits through the die a pressure drop always occurs as atmospheric pressure is established. The boiling point of water drops, and in the case of snack foods, the liberated steam causes the extrudate to expand into the low density forms common in that food class. Less expansion occurs in products like pet food and Nutri-grain (Figure 5), and this will be governed by many factors in their extrusion including the die characteristics. The pressure drop is determined by the flow rate, the die geometry and the viscosity of the melt. The amount of expansion depends on many variables. These include the ingredients used, the amount of moisture present, the speed at which the melt exits the die and also the length of the die (Waleed 2011). Generally speaking, high moisture contents and high die temperatures favour high expansion ratios. Colouring and flavours coatings can be added to the extrudates upon the point of the die. If a cutting blade is present at the exit die it can be coated or sprayed with sugar and colour, for example maple syrup and sprinkles. This can enhance the appearance and acceptance of the extrudates to the consumers. This colouring and flavouring coating technique might be used to add vitamin and mineral to the extrudates to compensate their relatively low content (Burns and Caldwell et al. 2000).

Comparative advantages of single and twin screw extruders

Twin screw extruders have many functional advantages over single-screw. They are significantly better in terms of the ingredient feeding, the mixing of ingredients, and heat transfer within the extruder, and less variable extrusion. The one disadvantage of twin screw extruders over single-screw is the cost. The maintenance costs of a twin screw extruder are greater than those of single-screw extruders (Fellows 2000). On the other hand, single-screw extruders have the benefit of costing less to purchase and maintain. As technology has developed, single-screw extruders have become more reliable due to variable screw speed drive and the introduction of improved instrumentation (Waleed 2011).

Energy consumption and supply

During the process of creating an extrusion product most of the energy is consumed by the product itself. Although the majority of the energy is consumed by the product some energy is lost through the barrel, the motor as well as the gear box. The changes that occur during the consumption of energy by the product include:

1) A rise in Enthalpy. The increase in enthalpy accounts for the maximum consumed energy.

2) Heat from molecular break down and the gelatinisation of the starch granules. Different starches require different amount of energy but it is estimated to be between 10-20 KJ per Kg. During the processing of high viscosity products, such as ones that have low moisture content, the starch and biopolymers present undergo a fractionation. This process is also known as depolymerisation. The process of depolymerisation is also considered to consume energy.

3) Potential energy. In most cases the kinetic energy of the material is ignored as it is such a minute value. If a liquid is being used in a jacket surrounding the barrel this contributes to energy loss. Loss of energy can occur through convention by the process of the heated barrel losing heat energy into the surrounding air. The gear box and motor also consume energy in the form of forced cooling. This is required so that the equipment can maintain a normal work speed and efficiency. In most cases the energy loss caused by equipment cooling is 5-15% of the total motor energy.

Mechanical energy supplied by the extruder motor is consumed mostly by the material within the filled section of the barrel. The energy is mostly consumed by the friction created within the barrel and by the viscous heat dissipation.

Extruders are supplied energy for the material they contain in several different ways. The material is supplied energy by barrel heat transfer, the extruder motor and depending on the machine design sometime direct steam injection (Meng, Threinen et al. 2010).

Energy is lost through heat transfer. The loss is less in portions of the barrel that are not filled as there is less contact between the material and the barrel surface. Heat loss however increases as the viscosity of the material decreases and the screw speed increases.

When the ingredients or food produced has a high moisture content, low viscosity or is high in fats or sugars it is more essential that barrel heating is used. In these cases the mechanical energy input is less. When the material is that of a high viscosity nature the main source of energy input is mechanical. In some cases heat can be transferred out of the material via cooling of the barrel. As the material cools however the viscosity typically increases and this in turn increases the mechanical energy requirement.

Steam injection is used as another way to introduce water and energy into the extrusion process. The injection of steam can be used as a way to substitute or supplement the energy requirements of the extrusion process. When steam injection is used it often dramatically reduces the amount of energy required by other processes such as mechanical and heat. Commonly the steam is injected into the non-filled sections of the barrel. To prevent any flow back from occurring there should be a filled section prior to the steam injection and after.

General effects of design and operating conditions on the performance of extruders

Effect of Extruder Diameter

The diameter of the extruder is most commonly dependent on the intended screw speed of the extruder itself. As the intended screw speed of the extruder decreases the diameter of the extruder increases. The minimum diameter size of the extruder can also be influenced by factors such as the die pressure and how much torque is going to be applied on the screw shaft. The most common extruder diameters range from between 15mm up to 300mm depending on the purpose of the extruder.

Length to Diameter Ratio

There are several factors that determine the length of the extruder, these are listed below:

Steam usage -The use of steam as a means of introducing water and or energy

Viscosity - The viscosity of the melt and the formula being used

Total Energy - How much energy is required to produce the desired product

Motor Power - What is the available motor power and limiting screw speed?

Pressure - What pressure will be created within the extruder?

Functional Requirements - Is the extruder going to be a straight forward conveying, melt and forming extruder or will it have other functions that require the use of ventilation etc.

Optimum Screw and Barrel Design - In the case of an extruder being used to produce more than one product the length will be reliant on the product that requires the larger length.

To summarise the above factors it is common practice to use or create an extruder that is a relatively short length if the viscosity of the raw ingredients and melt is high. In these cases the production is mainly reliant on the power of the motor. More powerful motors can produce a greater screw speed and thus generate heat energy over a shorter length. The use of steam can help in the production of a shorter extruder due to the heat introduced by the high temperature vapour. As more functions are introduced to an extruder the total length will increase, this may be due to increased retention times or the need to introduce more physical parts to the extruder.

Screw Pitch

With an increasing screw pitch the conveying capacity will also increase. With the increasing conveying capacity a shorter retention time will occur in the non-filled sections of the screw. In non-filled sections of the screw it is common to have a larger screw pitch. These sections are can be found at venting stages as well as solid conveying regions. In the regions of the screw where melting and melt conveying are required screws with a medium pitch are used. In sections of the screw when a high pressure is required over a short distance, such as that just before the die, a short screw pitch is used.

Screw channel depth

The channel depth plays an important role in the drag flow created by a Newtonian fluid. The screws used within a single-screw extruder can be independently chosen, this helps to deliver optimum results and desired performance within a specific area. In solid conveying regions it is common for screws to have a relatively deep channel depth whereas metering regions usually have a shallow channel depth. In regions where a high pressure is being achieved, such as at the die, it is common for a shallow depth screw to be used as it provides a more stable performance as well as output due to the fact that it will be less vulnerable to pressure flow fluctuations(Waleed 2011).

In twin screw extruders that use intermeshing twin screws the screw channel depth is not independent and is set by the manufacturer of the extruder. The depth is relatively deep in these extruders as it provides a good balance between shear rate, volumetric output and shaft torque.

In the case of an extruder using a conical screw over the length of the entire machine, the channel depth is variable however these extruders are not commonly used in food production.

Quantity of flight screws

In terms of a single-screw-extruder the number of flight screws present and the flight width work as two independent variables. With the increase in the number of flight screws or increase in flight width, a decrease will occur in the channel volume as well as a decrease in conveying capacity.

Each screw section of the extruder has a different independent number of flight screws. This is due to the function of the section and how the quantity of flight screws may affect production and efficiency. In the solid conveying section of the extruder a single flight screw is most commonly used. Within the melting section of the extruder a double or in some cases a triple flighted screw can be used. The increase in the flight screw number causes a greater retention time which can be desirable within this section of the extruder. At the discharge end of an extruder multiple flight screws, from between 2-4, are used as this can reduce extruder output oscillation which is caused by the rotation of the screw itself.

Mixing and Restrictive Screw Elements

The purpose of having mixing and restrictive screw elements can be many. The main reasons are to change the pattern of the flow, to increase the fill degree of the extruder and finally to increase the mixing efficiency of the extruder. Other effects that can be caused by introducing this screw element include a change in the distribution of the material residence time and the input energy requirement. There are several types of screws created to have varying effects. Below is a list of the more common screw designs that have a variety of effects.

Reverse Screws

Reverse screws have the main purpose of creating a back-flow which in turn creates an increase in the flow resistance. Occasionally reverse screws and forward screws are used together to create a mixing section. The reverse screw section within the extruder is usually quite short to avoid excess restriction(Mahmut 2011).

Cut Flight Screws

A cut flight screw is commonly a standard screw that has been cut in such a way that the leakage flow is increased. These screw alteration can be done to forward screws as well as reverse screws. In forward screws the increase in the leakage flow reduces the drag flow which in turn increases the residence time distribution. When used on reverse screws the same net drag flow decrease is observed which results in a decrease of power consumption, residence time and a decreased pressure drop.

Throttle valve

The throttle valve is located at the end of the extruder just before the die. The throttle valve gives greater control over the extruder fill prior to the die which cancels out the need to alter the screw. The inclusion of a throttle valve can be quite valuable in extruder machines that are used to produce a variety of products.

Screw design

The retention time can be influenced by the introduction of reverse and neutral screws, and other machined modifications. Some of these modifications can be seen in (Figure 9). These modifications cause an increased internal flow resistance. However, by increasing the internal flow resistance more energy is required which means a more powerful motor producing more torque. This greater energy requirement also increases the temperature of the melt. The greater temperature creates a lower viscosity at the die resulting in a lower die pressure. But with increased temperature of the melt, there is greater vapour expansion which creates extrudates with lower density.

The channel depth of the screw is also important. As previously mentioned in the solid conveying regions it is common for screws to have a relatively deep channel depth whereas melt regions usually have a shallow channel depth (Meng and Threinen et al. 2010).

Figure 9 Various screws and barrel parts with the purpose of increasing and decreasing barrel retention time.

Screw speed

The shear rate across all the melt-filled sections of the extruder can be increased by increasing the screw speed, this however requires a greater energy input. The melt pumping sections of an extruder are effectively reduced in length with the increase in screw speed because the residence time is lower. Increased screw speed results a higher melt and product temperature, lower die pressure, and a higher product expansion(Waleed 2011) (Table 2).

Barrel temperature

By increasing the temperature of the extruder barrel – by steam injection through channels in the barrel – the melt viscosity is decreased due to the increase in melt temperature. The reduction in the melt viscosity reduces the mechanical energy required. It is expected that with an increase in the barrel temperature the product density will decrease due in part to the lower viscosity of the melt and in part due to the greater expansion of water as steam when the extrudate cools(Maskan and Altan et al. 2012).

Die design

The die resistance to the melt flow can obviously be increased by the reduction in the size of the die outlet. By increasing the die resistance the pressure drop across the die increases (Table 2). As mentioned before a greater product temperature at the die would create a lower density product which increases radial expansion of the extrudate. All other variables increase in response to a decrease in die size (Table 2).

Table 2 The effect of independent variables on extrusion properties. From (Maskan, Altan et al. 2012)

Independent Variable	Mechanical Energy Input (kWh/kg)	Motor Torque (Nm)	Die Product Temp. (°C)	Die Product Pressure (psi)	Expanding Product Density (g/l)
Screw design, increasing restriction to the flow "stronger screw"	↑	↑	↑	↓	↓
Die design, increasing resistance to the flow	↑	↑	↑	↑	↓
Increasing barrel temp	↓	↓	↑	↓	↓
Increasing screw speed	↑	↓	↑	↓	↓
Increasing feed rate	↓	↑	↓	↑	↑
Increasing moisture content	↓	↓	↓	↓	↑
Increasing fat content	↓	↓	↓	↓	↑
Increasing sugar content	↓	↓	↓	↓	↑
Increasing high water absorbing fiber content	↑	↑	↑	↑	↑
Increasing low water absorbing fiber content	↓	↓	↓	↓	↑
Increasing high water absorbing protein content	↑	↑	↑	↑	↑
Increasing low water absorbing protein content	↓	↓	↓	↓	↑

Motor characteristics

The decision on what size/power motor depends on several independent variables shown in Table 2. Clearly, the higher restriction due to the melting section and the die and the greater the power that is required per kilogram of extrudate, the greater the torque will be. Higher barrel temperatures – due to steam jacket heating for example – are related to higher melt temperatures and therefore lower viscosities, explaining the lower mechanical energy input and torque required. The opposing effects of increasing screw speed and feed rate on mechanical energy input and torque are not so easy to explain.

When the ingredients have a high moisture, fat or sugar content, the mechanical energy input and torque content are reduced (Table 2), because those ingredients are lubricating the barrel. In the case of sugar it melts to a lubricating caramel. Where these ingredients are in high concentrations, the barrel has to be heated – and this requires energy – because the mechanical energy input and torque is lowered. Moisture has a complex relationship with motor requirement because protein and fibre absorb different quantities of water (Table 2).

Because three phase motors requiring 400 V rms[1] have three times the power and torque of single phase motors requiring 230 V rms, the former are the motors of choice in existing extruders. Industrial areas always have a three phase power supply, but the supply is usually not available in other commercial or residential areas. Therefore, extrusion technology is currently limited to industrial areas.

Effect of wear on extrusion machines

As a summarisation an extruder functions as a thermo mechanical reactor as well as a pump. The screw design within the extruder has a great effect on these functions. Over time the screw and barrel material are worn down and this has an effect on the way the extruder functions.

The amount of wear that occurs to the extruder is dependent on several things such as the material being used, the original construction material of the extruder and what conditions the machine is operated under.

An example of the effect wear can have on a machine is the increase of the gap dimensions present at the forward conveying section of the extruder. As the gap dimensions increase the pumping efficiency of the extruder decreases. The decrease in pump efficiency causes back mixing which increases the retention time of the material. To compensate for the back mixing the mechanical energy input needs to increase. This can also have an effect by decreasing the output of the extruder(Moscicki 2011).

When the food product being developed is sensitive to thermal change the impact of reduced flow resistance can affect the final product. The product can deteriorate due to the stagnation of the raw material within the barrel and also cause blockages to occur at the die. This can lead to the final product becoming inedible and therefore unsalable.

Although wear is expected to occur it is in some cases possible to reduce the amount of wear that occurs. Changes to the product formula, such as the alteration of the water flow, can reduce the impact of wear on an extruder. Another way to possibly reduce wear on an extruder is by altering the operating conditions.

[1] rms means root mean square, another name is the quadratic mean. The root mean square is the value of a periodic current that is equal to the DC current that delivers the same average power to a resistor as the periodic current.

Some extruders may be longer than is necessary. This length can be an advantage when wear starts to occur. This is due to the fact that with enough knowledge the screw position can be altered so that the filled sections of the extruder are moved away from the parts where wear has occurred. The new position of the filled sections can be created where the barrel is still in satisfactory condition.

It is inevitable that parts will eventually need to be replaced within the extruder as wear will occur even with the best standards of care. As new parts are introduced into the extruder, adjustments are required so that the machine can continue to reach its specific output requirements.

Venting within the extruder

The use of venting during the extrusion process can provide many benefits. These benefits include the rapid cooling within the extruder as well as being able to provide certain changes to the product within. For venting to occur within the non-filled section of the extruder a specific and specially designed screw is required. In most cases the use of a high volumetric flow capacity screw section is implicated. This section is positioned at a venting port after a high restriction or low flow screw section. The high restriction screw section acts as a gas tight seal(Waleed 2011).

There are two main factors that can have an effect on venting during extrusion. The temperature and the melt rheology can play a major part in the effectiveness of venting. Foods that have a low viscosity, such as high initial moisture content, are easily vented. In the case of ingredients and material that have low fat content, low initial moisture content or can produce excessive amount of vapour venting can be difficult. This difficulty occurs due to the ingredients having the potential to produce a highly expanded mass; this mass is difficult for the extruder to convey forwards.

In cases when the product is already half cooked or only half cooking is required it is important that rapid cooling can take place. The use of venting to rapidly cool the product is essential as it helps prevent expansion, this in turn can be used to produce a good face for die cutting.

When a larger temperature is required for the final product, occasionally, two separate extruders are used. The first extruder is used to cook the product whilst the second machine is used to compress and form the material into the final product. In this case venting commonly takes place between the two extrusion machines.

In the case of the use of two separate extrusion machines a higher rate of production can be achieved. Each of the extrusion machines can be used independently for its designated task such as cooking or product forming. In this way each machine is used in the manner intended and thus allows it to work at its maximum potential.

Chemical changes during extrusion cooking

Starch

Very large portions of ready to eat extruded snacks are composed of grains either entirely or partially, with starch levels being considerably high. It is therefore important to look at the effect that extrusion has on starch during processing. Starch is found natively as a crystalline structure with its exact shape and size depending on what plant it is formed in (Starch Metabolism and Structure, page 61-90). During the extrusion process the starch crystalline structure can be destroyed completely or partially, along with starch polymers being fragmented on a molecular level (Effects of processing on physical properties of extruded snacks with blends of sour cassava starch and flaxseed flour).

During extrusion it is believed that the starch molecules are degraded mainly due to the shearing force within extruders. It has been shown that mechanical energy plays the major role in the reduction of the molecular size of starch molecules as well as starch crystallinity. Although thermal energy plays a major role in the degradation of other nutrients, in starch it only causes partial gelatinisation and has very little effect on the molecular size.

Protein

Proteins can be relatively easy to denature and the denaturing can be caused by various elements. During cooking it is commonly heat that denatures proteins with the possibility of physical shearing during preparation. Extrusion incorporates heat and shearing in a much greater amount than regular cooking. The pressure produced during extrusion causing a greater shearing force to be applied to the food within the extruder as well as a greater heat being produced. These greater energies combine to greatly increase the denaturation of proteins during extrusion cooking, the energies produced as so high in fact they are known to break the covalent bonds present with the biopolymers (Singh and Gamlath et al. 2007).

The nutritional value of protein is determined by three factors, they are the digestibility of the protein, the quantity of protein consumed and the availability of essential amino acids within the food. Of those three factors the digestibility of the protein is considered to be the primary dependent in deciding the nutritional value of protein (Cheftel 1986). Table 3 below shows the effect of processing parameter on protein digestibility.

Processing parameter	Protein digestibility	Food source	References
Process temperature	↑ with increasing extrusion temperature	Corn gluten–whey blends, sorghum and fish–wheat blends	Fapojuwo *et al.* (1987), Bhattacharya & Hanna (1985), Bhattacharya *et al.* (1988)
Feed ratio	↑ with increasing animal protein	Fish and wheat flour	Bhattacharya *et al.* (1988) & Camire *et al.* (1990)
Screw speed	Insignificant effect	Fish and wheat flour	Bhattacharya *et al.* (1988)
	↑ with increasing screw speed	Corn gluten–whey blend	Camire *et al.* (1990)
Length to diameter ratio	Insignificant effect	Fish and wheat flour	Bhattacharya *et al.* (1988)

↑, increase.

Table 3 The effect of processing parameter on protein digestibility (Singh and Gamlath et al. 2007).

It is believed that one of the major factors that can cause a reduction in protein digestibility is the presence of anti-nutritional factors such as enzyme inhibitors (Cheftel 1986). Extrusion cooking has ability to inactivate these enzyme inhibitors thus creating more binding sites for enzymes to utilise, improving protein degradation and absorption by the body. Enzyme inhibitor inactivation combined with the denaturation of the proteins, as mentioned above, increasing the protein digestibility when compared to traditional methods of cooking.

Protein degradation is another way of increasing the availability of nutrients within extrusion products. One form of protein degradation happens naturally due to the shearing of the proteins during the extrusion process. The great amount of force used to crush and form a melt within the machine is strong enough cause alterations to the protein structure (Brennan, M. A. 2013)

Fat content

During the food extrusion cooking process, the raw materials of choice usually contain relatively low fat content, this is to ensure the retention time of the raw material is long enough for cooking, or the raw material will not be extruded too soon due to the lubrication of the screw from fat content. Low fat content materials are preferred for extrusion cooking to minimise fat oxidation of the long shelf life extrusion products.

Popular raw materials of selection for cereals, for examples, wheat, maize have a low fat content at 2%, while oats and soybean may contain up to 10% and 50% by seed weight, respectively (Singh and Gamlath et al. 2007).

Possible applications of extruders using single phase power

There is practically no food shortage in Western countries. Besides commonly consumed food such as meats, vegetables and fruits which are readily available, snack foods are also present in perhaps greater amounts and in more convenient locations. Snack foods are easily found in bars, cinemas and almost every entertainment venue. They are almost always high in saturated fats and/or sugars which are responsible for improving the mouth feel and flavour of the products.

An extruder which can plug directly into a single phase domestic plug would have good potential in entertainment venues due to the high demand of snack foods and the ease of production. Snack foods could be made on site and too order reducing waste and possibly improving customer satisfaction as they can see their snacks being produced. Arguably, however, a greater potential application in the use of single phase extruders would be to provide nutrition to third world and famine affected regions. The possibility of plugging an extruder into a simple diesel generator could open the doors to sanitary, ready-to-eat energy sources.

Many regions of the world are not able to provide the healthy daily requirements of essential minerals and vitamins to their population. This can be due to many reasons including lack of financial ability or due to natural disasters. The diets in these areas often rely heavily on cereals with only small amount of animal products and vegetables being available.

In other areas of the world there are many food by-products created during production that are high in protein and other vitamins but go unused. The production of oil from many seed crops for instance produces a cake that is commonly up to 50% protein. These by-products usually become animal feed or fertiliser due to the current cost of producing anything edible and the high risk of toxins being present naturally in the raw materials.

It is possible to incorporate these commercial by-products into the extrusion process and in doing so incorporate protein, minerals and vitamins (Marsmana and Gruppen et al. 1995) without creating an expensive food product. By producing extrudates with higher nutritional value at a lower cost the advantages to lower income areas and disaster relief becomes enormous. Low cost materials combined with the relatively low cost production by extrusion means that foods with higher nutritional value can be provided to the population for the same price as low cost but low nutritional value products.

Possible implication of using single phase power for extrusion

Understandably, it is common that when a lower energy supply is used in machinery, several aspects of the processing will be effect. It is therefore logical to assume that this should also be the case in extrusion cooking. When only a third of the energy is being used to power an extruder several parameters will be affected.

One major implication of producing extrudates with a smaller single phase motor is the drastic reduction in the production rate. Larger three phase extruders are capable of producing between 272 – 3600 kg per hour as stated by the manufactures of Insta-Pro (http://www.insta-pro.com/products-services/extruders.html). It is unlikely that these types of production rates could be reproduced with a single phase powered extruder. This production rate seems unachievable due to the lower shaft speed and the size of the barrel and screw. The lower screw speed and sizes are due to the decreased torque produced by the single phase motor. An extruder the size of those used for industrial production could realistically not be run with a single phase motor and still produce an edible product.

The types of amounts of raw ingredients used will also be affected. The lower torque being produced by the single phase motor would most likely be unable to process the same size raw materials as an extruder with a more powerful motor. Larger ingredients such as whole kernels from maize of perhaps harder ingredients like prawn shells are likely to cause a jam between the screw and the barrel unless pre-treated into smaller and uniform sizes.

Previous studies have found that with scaled down extruders it becomes hard to create consistent products. Smaller scale extruders have been found to lack repeatability with results scattered over a wide range. To go with this extruders designed and built on a smaller scale have been found to produce a great volume of stress on the screw (Penner, A. L. 2008).

Problems encountered and further development of extrusion cooking

Current extrusion technology employs three phase power (400 V rms), however this supply is not widely available. Moreover, industrial scale extruders are expensive, NZD$30,000 for a typical model. Millbank Group of Mangere, directed by Mr. Bruce Cliffe, has designed and built a simple and an economical extruder that can be installed at a much lower cost, and at the same time uses single phase power (230 V rms). The high torque required for extrusion is made possible by a phase inverter, which converts single phase power back into three phase power, but obviously lacking the energy of genuine three phase power at 400 V rms.

According to Millbank's website (http://fricitioncooker.com/friction-cooking/): the technology *"could provide a way to broaden the* use *of extruders by allowing the production of a large range of cooked foods, in many different price bands, and in a much wider variety of roles and locations. We believe that our Friction Cooker is such a machine. It is a lower cost, simple, portable food cooking device that can be used to process food in circumstances where it may otherwise be impossible to cook extruded foods. This may be for food manufacturing in an isolated community, an on-farm food processing plant, soup production, a health food factory, a bakery, a large commercial kitchen, in catering operations, for poverty diets, or for emergency or famine relief. The products produced could range from soups to health snacks, from raw materials blends, to chocolate coated biscuits."*

AUT has access to this new extruder and the immediate issue is what are the textural properties of the sorts of products that can be generated by this simplified technology.

Design of experiments

The research conditions

In an ideal experimental situation, the researcher has complete control over all known factors that determine outcomes. In an industrial environment this is seldom possible and the researcher has to adapt experimental conditions to suit the environment. There were many factors that were beyond control in this study. Millbank continually upgraded its extrusion equipment, and this often happened with minimal or no notice. Changes included making different screws and machines aimed at exploiting a continuous flow of empirical data. For example, these machines worked using a specific screw and barrel for their particular grain or grains (Figure 18). These barrel-screw combinations were created to overcome the problem of uncooked grain creating blockages in the barrel. Problems arising from blockages were undercooked extrudates as well as grain wastage and decreased product capacity of the extruder. Another factor was that it led to intensive mechanical wear and tear on the barrel. New exit dies and rotating cutters were developed and trialled throughout the study. Thus the shapes of the extrudates varied from the nominally cylindrical shape (Figure 18) to small ball-shaped (Figure 18) and elongated wavy shaped extrudates (Figure 18). The idea was that consumers might prefer a snack product with an irregular shape. Although the extrudate morphology had no effect on the chemical analysis, it did, however, affect the way in which the physical tests, included bulk density and texture analysis, could be carried out.

Another issue that occurred during this study was the lack of consistency of the grains. Millbank group had little control over the grains they received. For example, multiple types of wheat were used to produce extrudates for this study. Moreover, brown rice was rarely available on site which meant extrudate produced by brown rice were rare. With so few brown rice extrudates available reproducible date was impossible to obtain.

Millbank group's first priority was to perfect the extrusion equipment, unfortunately and unintentionally with little regard to experimental integrity. Necessarily, my data are snapshots of with Millbank’s experimental progression. Moreover, some data within trials could not be obtained in the experimental environment.

Chapter 2

Materials and Methods

Phases of the work

The object of this study was to obtain fundamental data of the single-phase extruder. This information included the screw speed, barrel temperature, power and the feed rate for different types of grains during the extrusion process and also the characteristics and consistency of the extrudates produced.

Chapter 2 describes the materials and methods used.

Chapter 3 first describes **Phase 1** work where the extrudates were produced solely using wheat, brown rice, maize and pearl wheat. **Phase 2** is also reported here, where extrudates were made from single grains and a combination of grains. These included the addition of mung beans, soy beans, oats, peanuts and amaranth.

Chapter 4 describes an experiment with single grains where extrusion conditions were better controlled and more amenable to conventional statistical analysis. This is **Phase 3**.

Chapter 5 is the Conclusion.

Extrusion equipment

The core equipment designed and built by Millbank is a single-screw extruder operating from a single phase power supply. Single phase power supplies at 230 V rms, alternating current, can only produce 1/3 the torque of the more expensive 400 V rms three phase power supply. To overcome this problem Millbank has developed several ways to ensure production can continue.

Outline of Millbank's Design

Millbank designed this single-screw extruder operated by single phase power supply equipped with a removable 3 mm cylindrical exit die. It is small enough to fit in the boot of a car. This extruder is equipped with a control panel. There is an adjustable vibrating feeding hopper that controls the rate of grain feed entering the barrel. A tachometer records the speed of barrel rotation and an ammeter records the power. The barrel and screw design(s) is proprietary knowledge. The system has an option for the addition of water, but this is seldom used. The barrel has no cooling system, which makes this design inherently simple.

Figure deleted for reasons of confidentiality

Figure 10 A current model of the 3 mm cylindrical exit die.

Figure 11 The last step of extrusion cooking, extrudate emerging from the die and expanding as steam escapes.

The Millbank extruder is designed to run with an inverter. The purpose of this inverter is to produce controllable levels of power to the machine and to ensure that the machine itself does not use more power that it can handle. One of the major functions of this inverter is to produce an ac current from a dc power supply, such as that from a single phase power outlet. This provides a constant uninterrupted voltage to the motor (Lihua and Taotao et al. 2008). Large spikes in power due to large amount of stress placed on the machine can cause damage to the screw and machines structure. The overall structure of the extruder is designed to withstand a certain amount of pressure placed on it, if this pressure is exceeded catastrophic failures might occur. If power spikes occur exceeding 12 A the inverter will shut off the power supply to the extruder and in doing so will prevent damage.

Due to the lower torque being provided by the motor running on a single phase power supply, Millbank has designed a smaller screw requiring less power to run. The shorter screw length still creates the temperature and pressure required to produce ready to eat extrudates, however as a consequence of shorter proportions the production rate is lower than that of a three phase extruder. Secondly, the single phase extruder has a carefully controlled feed rate. If the feed rate becomes too high a backlog of product can occur which can cause the motor to cut out due to the high torque required to overcome the blockage. Not only must the flow rate be controlled but the consistency of the feed should be uniform in terms of size and shape. This reduces the fluctuations of torque that can occur when processing.

Figure deleted for reasons of confidentiality

Figure 12 Layout of the single phase extruder showing major parts.

Figure 12 shows a typical assembly, with labelled parts. The control panel has a display screen with switches for setting and adjusting programs as well as a power switch.

Details deleted for reasons of confidentiality

As discussed in the Introduction, the speed of the screw rotation is governed by several factors, but within limits is strongly affected by the power that is displayed on the ammeter. Speed of screw was recorded by the tachometer. The speed can be increased by increasing the amperage provided to the motor. A safety shut off is set at a certain amperage so that the single phase motor is not damaged by the large current.

Details deleted for reasons of confidentiality

Figure deleted for reasons of confidentiality

Figure 13 Control panel of the extruder.

Details deleted for reasons of confidentiality

Figure deleted for reasons of confidentiality

Figure 14 In this picture the exit die is covered by a rotating cutter mounted on the shaft. Pellets of varying lengths can be produced, depending on the number of cutting blades.

The screw design changed three times during the experiments that were conducted over a 15 month period, and the details of changes are hazy. The final screw design most commonly used – and most importantly used for the definitive Phase 3 work –is made up of (Figure 15).

Details deleted for reasons of confidentiality

Figure deleted for reasons of confidentiality

Figure 15 Close up view of the single-screw. Product flow is from left to right.

Figure deleted for reasons of confidentiality

Figure 16 Details deleted for reasons of confidentiality

Due to the confidentiality reason, details and pictures related to the single phase extruder have to be removed. Below is a picture of a single-screw extruder with the labelled parts to aid with understanding of the machine described in the later parts of this thesis. Although the single-phase extruder used did not have all the parts shown in the image below it is a good representation of the many similar parts present.

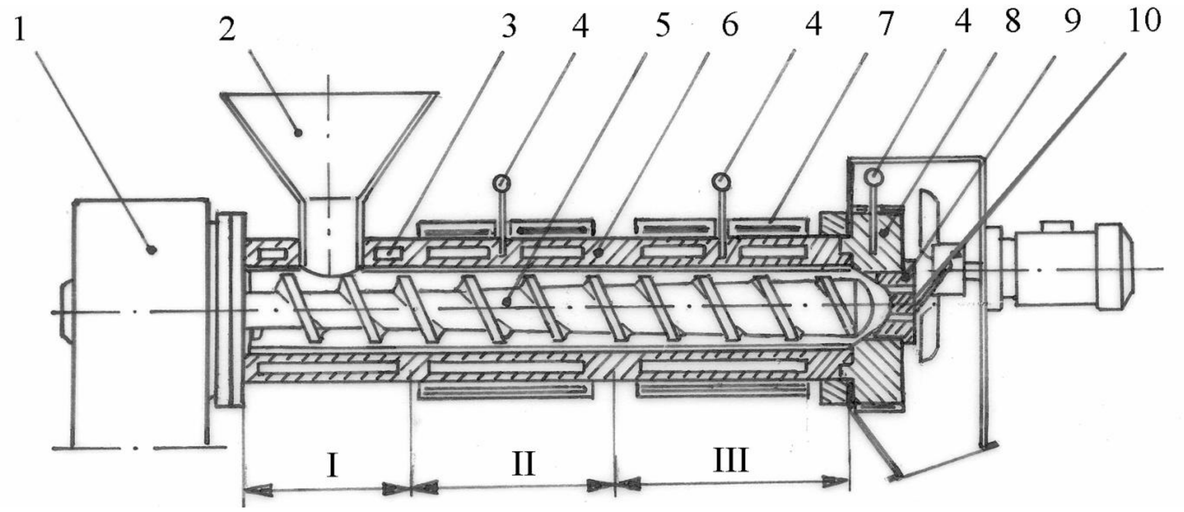


Figure 17 The above is a cross-section of a single-screw extruder showing several parts: 1) Motor, 2) Feeder, 3) Cooling jacket, 4) Thermocouple, 5) Screw, 6) Barrel, 7) Heating jacket, 8) Head, 9) Die, 10) Nose. The sections correspond to I) Transport, II) Melt conveying, III) Melt/Plasticising (Moscicki 2010)

Grains

Grains used in this project were brown rice, maize, wheat and pearl wheat. Brown rice and maize was obtained from Davis Trading and was of a human consumption grade. The wheat used was animal grade and was obtained from Goodman Fielder. Other additional ingredients, peanut, amaranth, oat, soy and mung bean, were available at local supermarkets and were fit for human consumption.

Range of extrudates made and tested

Extrudates made and tested in this project contained brown rice, maize, wheat and pearl wheat, along with a range of combinations. The additional ingredients were peanut, amaranth, oat, soy and mung bean. Apart from the various combinations of extrudates produced, different die shapes and extrudate cutters were installed to produce different shape extrudates other than the traditional cylindrical extrudates. They were ball shaped and long wavy shaped extrudates. Various extrudates were continuously produced throughout this thesis, yet only the ones listed above were tested for the purpose of this thesis. Photographs of the wide range of the extrudate products are in the Appendix.

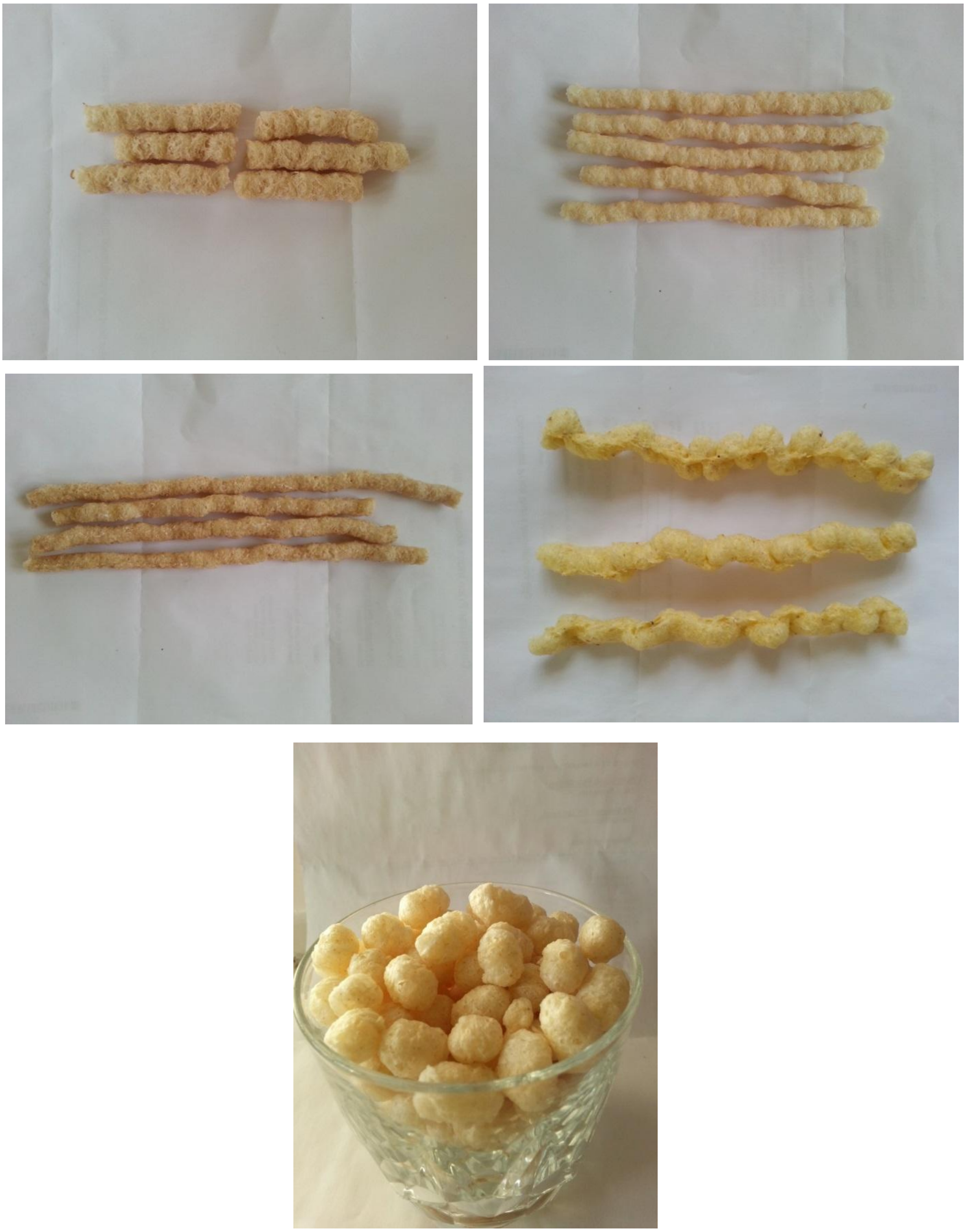


Figure 18 A range of extrudates produced and tested included extrudates of 60% brown rice, 35 % oats and 5% soya bean (top left), brown rice extrudates (top right), wheat extrudates (middle left), wavy maize extrudates (middle right) and ball shaped brown rice extrudates.

Finished product proximate and physical analysis

Proximate analysis covers, ash and moisture content, protein, fat, and water activity of the grains and extrudates whereas physical properties of extrudates include size, shapes, volume, density, texture and colour.

Moisture

The moisture content of triplicate extrudate samples were determined by gravimetric analysis after drying in a conventional gravity laboratory air oven at 135°C for 1 hour and cooling in a desiccator before reweighing (AACC 2000). The percentage of moisture content was calculated using the following formula:

$$\text{Moisture } (\%\ \text{m/m}) = \frac{\text{Loss of weight (g)}}{\text{Original weight of sample (g)}}\ x\ 100$$

Water activity

Water activity (Figure 19) is defined as the ratio between the vapour pressures of water in the headspace above a material to that of pure water under the same condition. It measures the free water existing in a material that is not bound to molecules and therefore available for the growth of microorganisms, such as bacteria, moulds and yeasts. The water activity of most food changes with temperature, for example, the solubility of solutes to which the water is bound. The water activity level for most food ranges from 0.01 for very dry dehydrated foods to 1.0 for pure water (Sahin and Sumnu 2006).

Water activity of the extrudates was determined by a Novasina water activity meter (Figure 19). It is based on the free water vapour of the extrudate humidifying the air volume inside the chamber prior to water activity measurement. After calibrating the water activity meter at 25 °C, three 1-cm-long extrudates were placed in the sampler dishes in the water activity meter. The sample chamber lid was then sealed air-tight over the sample. Once the readings had stabilised, the water activity results were recorded. 10sets of three 1-cm-long extrudates had Water activity measured and the means and standard deviations were calculated and displayed as results in later chapters of this thesis.

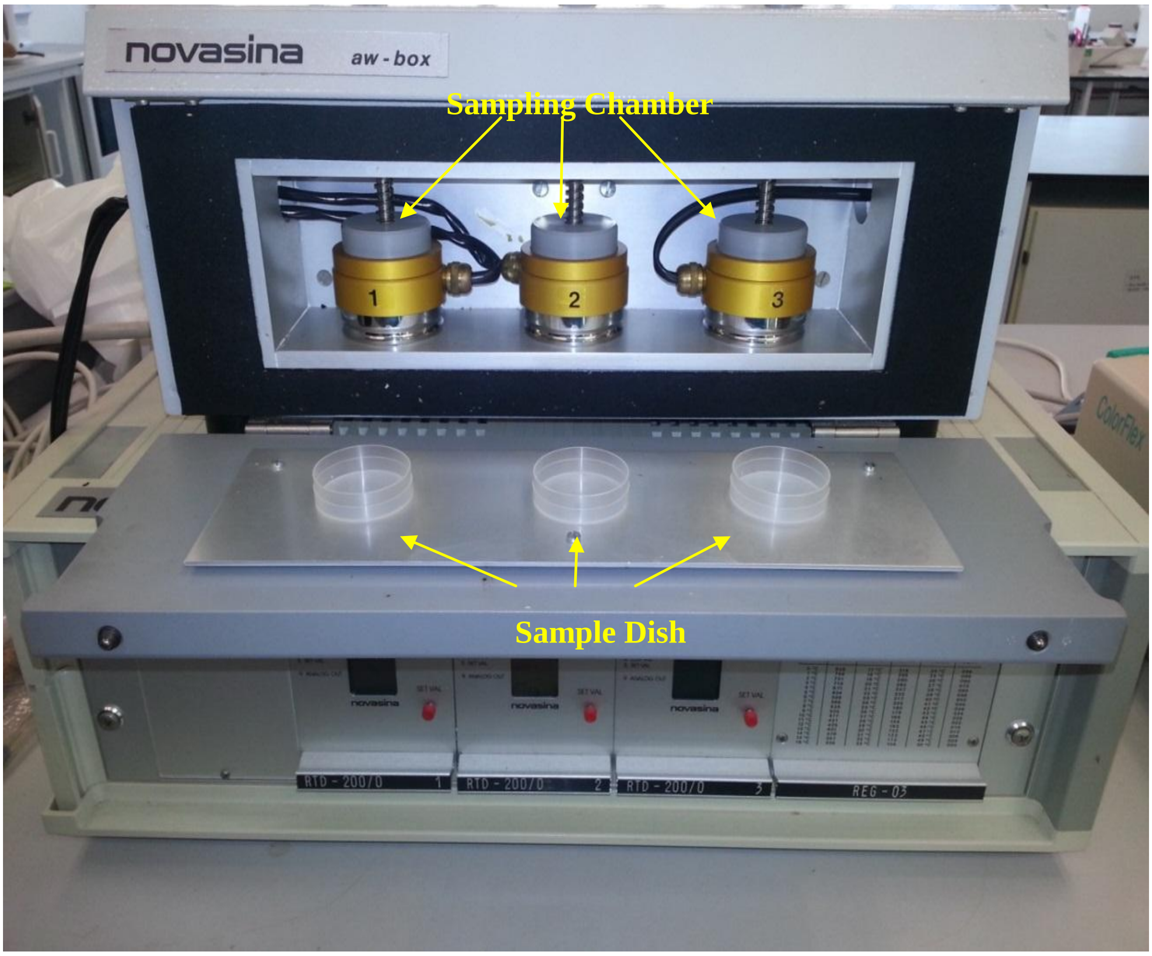


Figure 19 The Novasina water activity meter. The photograph shows the sample dish that held the extrudate pieces (not shown) which were placed evenly in the sampling chamber.

Ash

The ash content was determined by initially blending the extrudates into a fine blend then accurately weighing triplicates of the extruded sample, 2g each, into a previously ignited, cooled and weighed crucible. The crucibles were placed in a muffle furnace heated to 600°C for 2 hours, then cooled in a desiccator before reweighing.

The percentage of ash content was calculated by the formula below:

$$\text{Ash } (\%\,\text{m/m}) = \frac{\text{Weight of residue}}{\text{Initial sample weight}}\ x\ 100$$

Fat

Soxhlet extraction is a solid-liquid extraction method that is employed commonly for finding the amount of fat in foods. The method involves dissolving the fat with solvents such as diethyl ether, chloroform and petroleum spirit. The solvent is separated by gravity from the food residue and is evaporated to waste using a Soxhlet apparatus. What remains after evaporation is the extracted fat that is determined gravimetrically.

Weighed accurately, 8 g of finely ground extrudate samples are added to the extraction thimble and held in place with glass wool. To match the sample size required a weighed 250 mL round bottom flask is used and 100 mL of petroleum spirit is added. The flask is added to a Soxhlet apparatus and left to extract for 3 hours. The flask containing the petroleum spirit and fat was reflux evaporated over a 100°C water bath in the fume hood for 3 hours. The flask was then dried in an oven at 105°C, cooled in desiccators and reweighed.

The fat concentration in the food was calculated by the following formula:

$$\text{Fat } (\%\ \text{w/w}) = \frac{\text{weight of flask with fat} - \text{weight of empty flask}}{\text{Initial sample weight}}\ x\ 100$$

Protein

A combination of Kjeldahl digestion and colorimetric determination is a classic method to determine the nitrogen content of the food sample (Stojceska and Ainsworth et al. 2008). When nitrogenous materials are digested with sulphuric acid, the nitrogen in protein, and other nitrogenous compounds, is converted to ammonium sulphate. The concentration of nitrogen or protein can be determined colorimetrically from this (Baethgen and Alley 1989; AACC 2000).

0.5g of ground extrudates were accurately weighed into Kjeldahl digestion tubes and digested with 3 mL of concentrated sulphuric acid and 1.1g of Kjeldahl mixture (100:10:1 mixture of K_2SO_4:$CuSO_4$:Se) at 420°C for 2 hours. Once digestion is complete the solution is a straw colour. Digests were then transferred to a 100 mL volumetric flask and filled to the mark with water[2] of a known volume. The reagents described by Baethgen and Alley (1989) – buffer solution, salicylate/nitroprusside solution and hypochlorite solution – were

[2] All water used in this project was deionised.

added and the mixture was vortexed, then incubated in a water bath at 37°C for 15 minutes before reading the absorbance at 650 nm.

Standards were prepared at the same time and in the same manner but dried ammonium sulphate was used instead of the finely ground extrudate samples. 4.715g of dried ammonium sulphate is dissolved and made up to 1000mL, as 1000mg L^{-1} NH_4 N stock, it is labelled as diluent solution. Then 100mg L^{-1} of NH_4 N is prepared by diluting 10mL of 1000mg L^{-1} NH_4 N stock (diluent solution) to 100mL. A series of NH_4 standards were made by diluting 0ml, 10ml, 20ml, 30ml, up 100ml, with an interval of 10ml, of 100mg L^{-1} to 100mL with the 1000mg L^{-1} NH_4 N stock (diluent solution). The standard series contains 0 mg L^{-1}, 10 mg L^{-1}, 20 mg L^{-1}, 30 mg L^{-1}, 40 mg L^{-1}, 50 mg L^{-1} up to 200 mg L^{-1}, with an interval of 10, mg L^{-1} of NH_4 N, this is to ensure the standard series is wide enough to cover the unknown nitrogen content of the extrudates. For the standards containing above 100 mg L^{-1} NH_4 dilution procedures were carried out using 250ml flasks and diluting accordingly. A standard curve was constructed in the range 10 to 200 mg nitrogen L^{-1}, that usefully matched the nitrogen in the extrudate that was recovered in the volumetric flasks.

Bulk density and expansion ratio

The bulk density (g cm^{-3}) of extrudates was calculated by measuring the dimensions of the extrudates according to the formula $\frac{4m}{\pi d^2 L}$, where m is mass (g) of a length L (cm) of extrudate with a diameter d (cm). The diameter and length of the extrudates were measured using vernier callipers. Ten pieces of extrudate were randomly selected for these measurements (Ayadi, Rosentrater et al. 2011; Majumdar, Venkateshwarlu et al. 2011).

The expansion ratio is defined as $\frac{\text{Diameter of a extrudate sample (cm)}}{\text{Diameter of the die exit (cm)}}$ and was calculated from the same raw data (Rzedzicki, Szpryngiel et al. 2000; Majumdar, Venkateshwarlu et al. 2011), knowing the die diameter, 3 mm.

Colour

The colour of the grains and extrudates were assessed using a Hunter-Lab ColorFlex 45/0 colorimeter (Figure 20), with the illuminant D65 light source and the standard 10° observer measuring angle. The colorimeter is designed to measure the colour of flat surfaces, for example, fabrics and painted surfaces. Because the extrudates were of a similar shape, it was decided that by filling the dish with 1 cm pieces, a colour image would be recorded that was at least indicative of the colour. In this instance it proved to be the case because maize extrudates were found to be much yellower than other extrudates, as might be expected from the raw material.

After calibration, the colour of a clear glass crystallising dish, 6.4cm in diameter and 4cm high, was measured five times in Hunter colour space, L*, a* and b*, after covering the dish with the cylindrical black shroud, shown in the figure, to exclude all external light. The dish was manually rotated between measurements. The mean values of this blank reading were calculated. 1cm pieces of extrudate were used to fill the dish, and another five measurements were taken, rotating the dish slightly between each measurement. These data were each corrected for the blank by subtraction, and the corrected data were the basis for statistical calculations.

Figure 20 The Hunter Lab ColorFlex 45/0 colorimeter. The photograph shows the crystallising dish that held the extrudate pieces (not shown), and the shroud to shield ambient light.

Texture profile analysis

The objectives were to quantitatively determine the force required to compress extrudates to a set distance, and to determine the force required to fracture extrudates. A compression test is commonly used to measure the hardness of a food product, it is defined as the force required to compress a extrudate to a fixed distance, or as the distance a fixed force will compress an extrudate (AACC 2000) . A brittleness test determines the peak force required to fracture the extrudate into two parts.

The compression of the extrudates was determined with a TA.XT *Plus* single column texture analyser (Stable Micro Systems Ltd.). The analyser was fitted with a 500 N load cell and calibrated. The probe was a 50mm-diameter flat-end aluminium compression probe (probe P/50) that compressed 10cm long, 1cm width extrudates, to within 4 mm of the heavy duty platform's aluminium plate (Figure 21). Force data were recorded from when the probe first contacted the extrudate piece at a continuous speed 3 mm sec^{-1}. The force-time (distance) curves were analysed by Texture Exponent 32, which calculated the work required to crush the extrudate. Peak force data were also recovered. This force is considered to be the hardness of the sample(Gambaro, Varela et al. 2002; Stojceska, Ainsworth et al. 2008). Peak force and work were calculated for 10 replicates. Peak force was determined with a three-point bend rig (Figure 22).

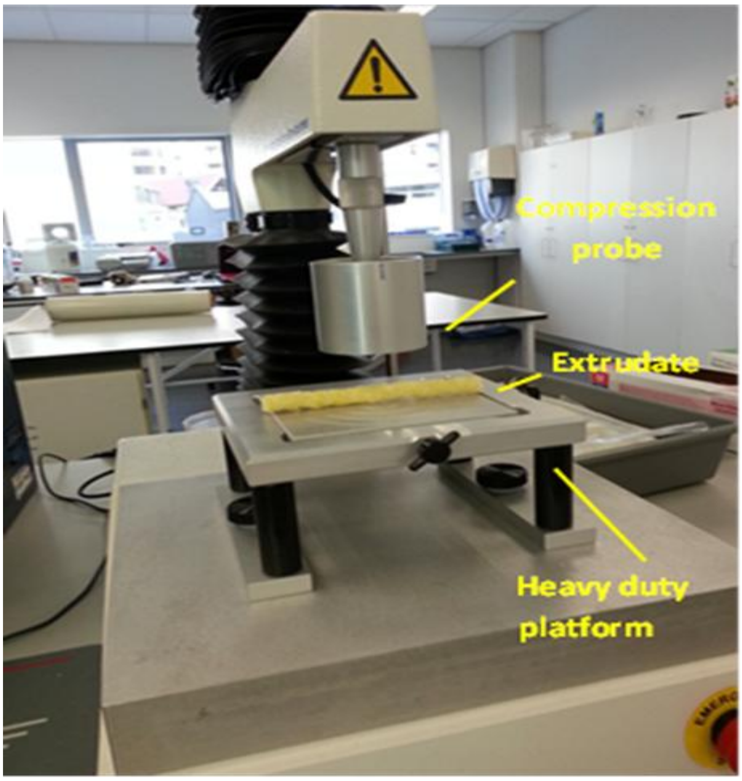


Figure 21 The TA.XT Plus texture analyser. The photograph shows the 50 mm flat aluminium compression probe with an extrudate sitting on a heavy duty platform

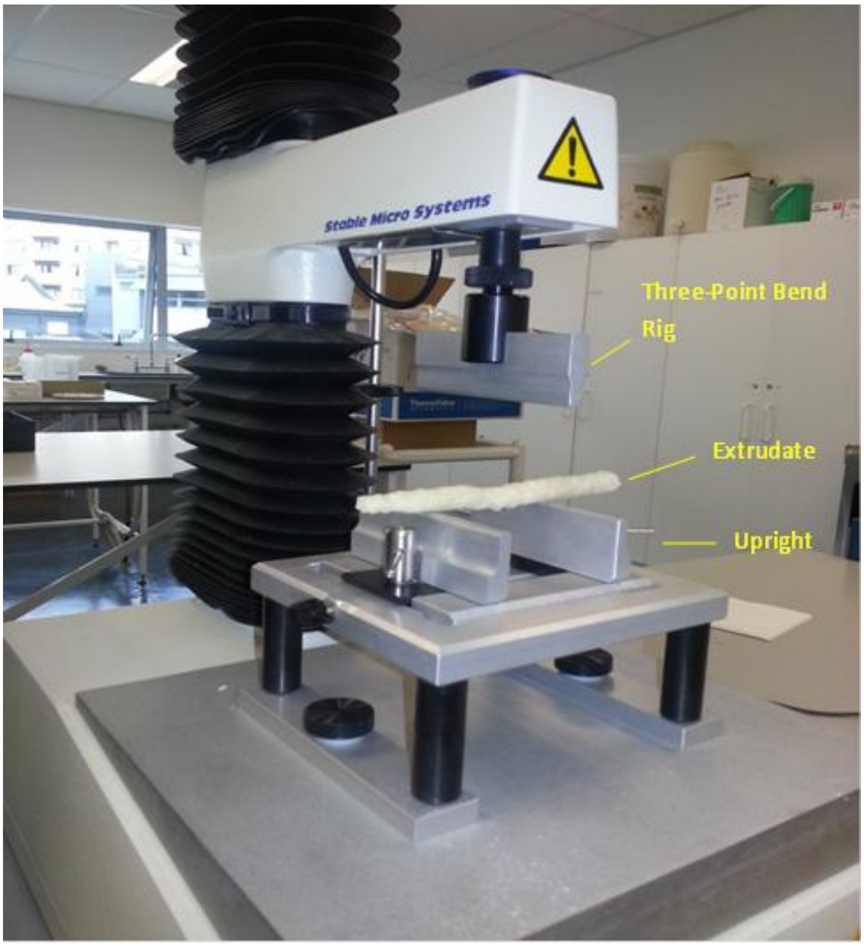


Figure 22 The TA.XT Plus single column texture Analyser used for the brittleness test. The photograph shows the extrudate sitting on the 2 uprights with the three point bend rig positioned above the extrudate.

A 10 cm-long piece of extrudate was placed on the two uprights, 5.5 cm apart, and the blade was centred above the extrudate. Each sample was broken in two by the lowering probe. The pre-test speed was 2mm sec^{-1} and the test speed 3mm sec^{-1}. Peak force and work were calculated for 10 replicates. The work in this content means the force of the displacement direction of the probe or rig applied to break the extrudate (W=F x d). The peak force and work results were calculated and displayed by the TA.XT Plus software programme Texture Exponent 32.

Data analysis and reproducibility

Chemical analyses had three replicates, colour five and texture 10. Replication in this context means repeating the analysis three, five or ten times with different batches of extrudates. The data were analysed for variance using routines in Microsoft Excel and XLSTAT (Microsoft Office XP software) and Analysis of variance (ANOVA) in Minitab (Version 16). Results are expressed as means and standard deviations (± SD).

Chapter 3

Phases 1 and 2 Experiments

Phase 1

Experimental

In the first stage of this study, multiple types of grains were used, they were brown rice, maize, wheat and pearl wheat. Extrudates made from these grains were collected during the period of August 2012 to July 2013. All the extrudates were stored separately in heavy duty plastic bags at room temperature prior to chemical composition analysis and physical characteristics tests. The details of these tests and their methods are described under Chapter 2 of this thesis.

During this 11 month period, the extrusion process for each of the four grains was about an hour long. During the extrusion process physical performance extrusion data was collected, they were production capacity of extrudates per hour, power consumption, screw speed and nose temperature (Table 5). The single phase extruder screw was mechanically modified during this time but details could not be obtained. The descriptions of the cylinder extrudates production are shown in Table 4.

Table 4 Cylindrical extrudates produced in Phase 1

	Brown rice	Maize	Wheat	Pearl wheat
August 2012	✓	✓	✓	
October 2012	✓	✓	✓	✓
November 2012		✓	✓	✓
July 2013	✓[1]	✓[1]	✓[1]	
July 2013	✓	✓	✓	

[1] The modification involved an addition of a mould at the end of the exit die in order to produce spherical shaped extrudates. There was a single session of producing ball shaped extrudates of brown rice, maize and wheat on 4 July 2013.

Altogether in Phase 1 several batches of extrudates were produced. They were brown rice (4 runs), maize (5), wheat (5) and pearl wheat (2).

Results and Discussion

Physical performance for extrudates produced from four different grains.

In five production sessions of extrudates over 11 months, data were obtained for production, power, screw speed and nose temperature. The results are shown in Table 5. The choice of operating conditions was governed by the operator's experience, and the only clear distinction between the grains was the lower screw speed and nose temperature chosen for brown rice by the operator. The two variables are likely to be linked.

Table 5 Physical performance over five production days for cylindrical extrudates. Data are means ± SD. Means within a column with different superscripts are significantly different ($P < 0.05$).

Grain	Replicate Runs	Production (kg h^{-1})	Power (kW)	Screw speed (r.p.m.)	Nose temp. (°C)
Brown rice	4	8.25 ± 0.87^{a}	1.58 ± 0.26^{a}	147 ± 18^{b}	107 ± 15^{a}
Maize	5	8.58 ± 1.56^{a}	1.39 ± 0.16^{a}	208 ± 4^{a}	122 ± 5^{a}
Wheat	5	6.84 ± 2.94^{a}	1.43 ± 0.26^{a}	195 ± 23^{a}	124 ± 4^{a}
Pearl wheat	2	5.98 ± 0.19^{a}	1.20 ± 0.05^{a}	219 ± 20^{a}	117 ± 10^{a}

The production capacity, the power usage and the nose temperature (Table 5) data for all four grains were not significantly different from each other ($P > 0.05$). However, even though it might not be significant there does appear to be a slight difference in production rate between maize and pearl wheat and brown rice and pearl wheat. There was a significant difference between some of the grains in regards to the screw speed during production ($P = 0.003$). The mean screw speed when producing brown rice extrudates was significantly different from the other three grains as shown by the Tukey test. After removing the brown rice data from the one way analysis of variance, statistics show that there is no significant difference in the screw speed between the remaining three grains ($P = 0.460$).

Table 6. Physicochemical properties of cylindrical and spherical extrudates over several production days for four grains in Phase 1. Data are means ± SD. Means within a column with different superscripts are significantly different (P < 0.05).

Grain	Replicate runs	Moisture content (% m/m)	Ash content (% m/m)	Fat Content (% m/m)	Water activity (Aw)	Bulk density[¶] (g cm^{-3})	Compression [¶] force (N)	Compression work[¶] (mN m)	Triple point[¶] force (N)	Triple point work[¶] (mN m)
Brown rice	4 (3[¶])	8.8 ± 1.5[a]	1.4 ± 0.14[a]	0.2 ± 0.11[a]	0.19 ± 0.05[a]	0.19 ± 0.03[ab]	109 ± 21[a]	313 ±40[a]	7.1 ±1.27[a]	20.5 ±0.94[a]
Maize	5 (4)	8.9 ± 1.0[a]	1.1 ± 0.10[b]	0.5 ± 0.29[a]	0.19 ± 0.04[a]	0.14 ± 0.01[a]	101 ±52[a]	330 ±32[a]	4.4 ±0.84[a]	19.7 ± 4.22[a]
Wheat	5 (4)	8.1 ± 2.0[a]	1.5 ± 0.09[a]	0.6 ± 0.53[a]	0.21 ± 0.01[a]	0.23 ± 0.04[b]	143 ± 18[a]	352 ±51[a]	7.3 ±1.8[a]	21.2 ± 2.20[a]
Pearl wheat	2	6.2 ± 0.2[a]	1.5 ± 0.09[a]	0.2 ± 0.02[a]	0.18 ± 0.00[a]	0.20 ± 0.00[ab]	130 ± 6.9[a]	305 ±94[a]	6.2 ± 0.35[a]	19.0 ± 1.00[a]

[¶] Bulk density and texture data – the last five columns – have fewer (replicates) because only cylindrical extrudates could be usefully compared.

Please note: Protein results were not available due to the VELP machine malfunctioning and a Kjeldahl method had not yet been fully developed at this stage. Please refer to page 68 of this thesis for the complete protein analysis results.

Although data were limited, linear correlations were derived for the cylindrical extrudates of brown rice (4 replications testing with different batches of extrudates) maize (5) and wheat (5) (Table 7, Table 8 and Table 9). As explained in Chapter 2, it was not strictly valid to statistically compare data where they were potentially confounded by changes to the extruder and grain specification. However, it is argued that if the statistical outputs were not significant, this would be some confirmation that statistical methods were of limited value.

Two of the correlations were significant, that between production and screw speed for brown rice (r = 0.96; P = 0.05), and that between production and nose temperature for maize (r = 0.90; P = 0.04). Inspection of the non-significant correlations shows some unexpected differences. For example, power and nose temperature were negatively correlated for brown rice but positively correlated for maize and wheat. It is emphasised that the details of the particular brown rice, maize and wheat grain used was beyond my control. Attention was then directed at the physical properties of the extrudates produced.

Table 7 Correlations between production, power, screw speed and nose temperature for brown rice extrudates. Bold data are correlation coefficients and italicised data are P values.

Variables	Production	Power	Screw speed	Nose temp.
Production	**1**	*0.36*	*0.05*	*0.83*
Power	**-0.64**	**1**	*0.17*	*0.48*
Screw speed	**0.96**	**-0.84**	**1**	*0.63*
Nose temp.	**0.17**	**-0.52**	**0.37**	**1**

Table 8 Correlations between production, power, screw speed and nose temperature for maize extrudates. Bold data are correlation coefficients and italicised data are P values.

Variables	Production	Power	Screw speed	Nose temp.
Production	**1**	*0.19*	*0.69*	*0.04*
Power	**0.70**	**1**	*0.86*	*0.44*
Screw speed	**0.24**	**-0.11**	**1**	*0.31*
Nose temp.	**0.90**	**0.45**	**0.58**	**1**

Table 9 Correlations between production, power, screw speed and nose temperature for wheat extrudates. Bold data are correlation coefficients and italicised data are P values.

Variables	Production	Power	Screw speed	Nose temp.
Production	**1**	*0.14*	*0.50*	*0.25*
Power	**0.76**	**1**	*0.67*	*0.37*
Screw speed	**0.41**	**-0.27**	**1**	*0.55*
Nose temp.	**0.64**	**0.52**	**0.36**	**1**

Physicochemical data of extrudates of four grains for Phase 1

The moisture content of all extrudates was less than 9% m/m (Table 6), indicating that no water was added in the process and that moisture was possibly lost as steam at the exit die. Importantly the water activities were less than 0.22, indicating microbiologically stable products. For these two parameters there were no significant differences between grains, likewise for fat content. All fat values were less than 0.7% m/m. The ash content was lowest for maize and was significantly different from the other grains ($P < 0.05$).

Where cylindrical extrudates were produced, mean bulk density and texture data were determined. Although there were no significant differences between the grains for compression force, compression work, triple point force and triple point work, the mean values for the wheat extrudate were always the highest. Moreover, the bulk density of the wheat extrudates was significantly different from the other extrudates. The high gluten content in wheat grain may be responsible for the highest bulk density.

With the data available it was realistic to determine Pearson correlation coefficients between physical performance and physicochemical data of extrudates of brown rice, maize and wheat. (Pearl wheat had only two replicates) These results are presented in Table 10, Table 11 and Table 12, but presenting only correlations of the 78 possible that were significant ($P < 0.05$). For brown rice (Table 10) there was an obvious positive relationship between production and screw speed. The strongly negative relationship between nose temperature and compressive force may reflect some undefined state of starch at high temperatures, yet to be discovered for this extruder. The positive relationship between ash content and the 3 point bend test cannot be explained at this time and may be a random event.

Table 11 shows that there was a strong positive relationship between nose temperature and production rate for maize extrudates. This relationship may have occurred by chance as it was only found for maize extrudates and not the other extrudates. There were strong negative relationships between ash content and screw speed, compression force and 3 point bend force and compression work and 3 point bend force. The ash content of maize extrudates was negatively related to screw speed. No literature could be found to explain this relationship.

More unexplained relationships are shown in Table 12 for wheat extrudates. Water activity and fat content were positively associated whereas ash content and moisture content, 3 point bend work and power and compression work and production were all negatively related. These relationships could have occurred by chance. They do not have any cause and effect relationships with each other.

Table 10 Significant correlations between physical performance data and physicochemical tests for brown rice extrudates. Bold data are correlation coefficients and italicised data are P values.

Variables	Product-ion	Screw speed	Nose temp.	Ash content	Compression force	3PB force
Production	**1**	*0.045*				
Screw speed	**0.955**	**1**				
Nose temp.			**1**		*0.011*	
Ash content				**1**		*0.001*
Compression force			**-0.989**		**1**	
3PB force				**0.999**		**1**

Table 11 Significant correlations between physical performance data and physicochemical tests for maize extrudates. Bold data are correlation coefficients and italicised data are P values.

Variables	Product-ion	Screw speed	Nose temp.	Ash content	Compression force	Compression Work	3PB force
Production	**1**		*0.037*				
Screw speed		**1**		*0.047*			
Nose temp.	**0.901**		**1**				
Ash content		**-0.884**		**1**			
Compression Force					**1**		*0.019*
Compression Work						**1**	*0.022*
3PB force					**-0.937**	**-0.930**	**1**

Table 12 Significant correlations between physical performance data and physicochemical tests for wheat extrudates. Bold data are correlation coefficients and italicised data are P values.

Variables	Produc-tion	Power	Moisture	Ash content	Fat content	Water activity	3PB work	Compression Work
Production	**1**							*0.048*
Power		**1**					*0.010*	
Moisture			**1**	*0.022*				
Ash content			**-0.930**	**1**				
Fat content					**1**	*0.016*		
Water activity					**0.944**	**1**		
3PB work		**-0.959**					**1**	
Compression Work	**-0.881**							**1**

The colour of the extrudates are shown in Table 13, this also includes the spherical exudates for brown rice, maize and wheat. These were included because the sizes of the cylindrical extrudates were cut to approximately the same size as the spherical extrudates to evenly fill the crystallising dish used for determining colour.

Table 13 Colour characteristics of all four extrudates. Data are means ± SD. Means within a column with different superscripts are significantly different ($P < 0.05$).

	L*	a*	b*
Brown rice	59.65 ± 7.48[a]	1.89 ± 0.77[a]	16.65 ± 2.75[a]
Maize	53.00 ± 9.99[a]	3.37 ± 1.61[a]	30.34 ± 6.71[b]
Wheat	50.77 ± 6.13[a]	3.43 ± 0.88[a]	14.05 ± 2.10[a]
Pearl wheat	49.22 ± 0.30[a]	2.76 ± 0.79[a]	14.18 ± 1.24[a]

There is no significant difference between the lightness (total light reflectance of the extrudates (L*) or between the redness, which is represented by a positive a* value. There was however a major difference between the yellowness of the samples. Yellowness, represented by a positive b*, was significantly higher in maize compared to the other three grains. This was no surprise because maize kernels are markedly yellow. Moreover, this result confirms the utility of the method adopted.

Phase 2

Experimental

In the second stage of this study, new ingredients were tested along with brown rice, maize and wheat that were tested in Phase 1. These new ingredients were soy, peanut, mung bean, oat and amaranth to variously mix with brown rice, maize and wheat. Availability of the new ingredients occurred only once phase 1 was complete. Extrudates made from these grains were collected between July and October 2013 (Table 14). All the extrudates were stored in the same way as in Phase 1, separately in heavy duty plastic bags in the cupboard at room temperature prior to chemical composition analysis and physical characteristics tests. The details of these tests and their methods were described in Chapter 2.

During these 4 months, each of the extrusion processes for all extrudates were about an hour long. The same set of physical performance extrusion parameter data was collected during the extrusion process. These were production, power, screw speed and nose temperature. The single phase extruder was constantly mechanically modified during this period of time but no record of this was available. Thus the data give only a broad picture of the extruder performance with no true replication.

Table 14 Extrudates produced in Phase 2

Date in 2013 (session)	July (1)	August (2)	Septem. (3)	Septem. (4)	October (5)
Grain and (%)					
Brown rice (100)	✓	✓			✓
Maize (100)	✓	✓	✓	✓	
Wheat (100)	✓		✓	✓	✓
Maize (95), soy (5)	✓				
Wheat (95), soy (5)	✓				
Brown rice (90), peanut (10)		✓			
Maize (95), mung (5)			✓		
Brown rice (60), oat (35), soy (5)					✓
Maize (90), oat (10)					✓
Maize (90), amaranth (10)					✓

The new combinations created in Phase 2 are shown in Table 14, where the effects of pure grains and combinations were explored. These combinations were produced as single experimental runs. Replication of grain used was limited to brown rice (3 replicates), maize (4) and wheat (4), but as noted there were subtle undescribed changes to the screw during these four months, although the overall dimensions of the extruder were unchanged. It is argued, however, that if correlations emerge that are consistent between grains and/or consistent with equivalent Phase 1 correlations, then cause and effect may be inferred.

Therefore, the data are presented in two ways, first limited to these three grains in table format with statistical tests, then as bar graphs for the entire data set. The object of the latter was to gain a broad picture of the range of properties generated.

Linear correlations were derived for the cylindrical extrudates of brown rice (3 replications) maize (4) and wheat (4) (Table 15, Table 16 and Table 17).

Table 2 (P.29) shows that there are relationships between the independent variables of extrusion. While there is no information in this table that suggests these are simple linear relationships between the variables, linear correlations were investigated as a first step.

Table 15 Correlations between production, power, screw speed and nose temperature for brown rice extrudates. Bold data are correlation coefficients and italicised data are P values.

Variables	Production	Power	Speed	Nose temp.
Production	**1**	*0.25*	*0.39*	*0.12*
Power	**0.92**	**1**	*0.14*	*0.13*
Screw speed	**0.82**	**0.98**	**1**	*0.27*
Nose temp.	**-0.98**	**-0.98**	**-0.91**	**1**

Table 16 Correlations between production, power, screw speed and nose temperature for maize extrudates. Bold data are correlation coefficients and italicised data are P values.

Variables	Production	Power	Screw speed	Nose temp.
Production	**1**	*0.04*	*0.12*	*0.38*
Power	**0.96**	**1**	*0.03*	*0.43*
Screw speed	**-0.88**	**-0.97**	**1**	*0.60*
Nose temp.	**-0.62**	**-0.57**	**0.40**	**1**

Table 17 Correlations between production, power, screw speed and nose temperature for wheat extrudates. Bold data are correlation coefficients and italicised data are P values.

Variables	Production	Power	Screw speed	Nose temp.
Production	**1**	*0.64*	*0.65*	*0.55*
Power	**-0.36**	**1**	*0.27*	*0.80*
Screw speed	**-0.35**	**-0.73**	**1**	*0.67*
Nose temp.	**0.45**	**0.20**	**-0.33**	**1**

Statistically significant correlations were very few, and only occurred for maize. There was a significant positive relationship between production and power (r = 0.96; P = 0.04), and a strong negative relationship between screw speed and power (r = -0.97; P = 0.03). It was useful to compare these two significant correlations with the equivalent correlations form Phase 1. Inspection of Table 8 shows that the two equivalent correlations were in the same numerical direction, respectively positive (production, power: r = 0.70) and negative (screw speed, power: r = -0.11), but neither was significant (P > 0.05). Now, taking the reverse position of comparing the single significant correlation in Phase 1 (brown rice: screw speed, production: r = 0.96, P = 0.05) with the equivalent correlation in Phase 2 (r = 0.82), the numerical direction was certainly the same, but not significant (P = 0.39).

Turning now to the bigger picture (Figure 23,Figure 24, Figure 25, Figure 26), the overall physical performance data for all extrudates in Phase 2 were relatively consistent, where data were available. For example brown rice, maize and wheat extrudates production capacity was similar within grain between sessions (Figure 23). This suggests that any modification made were having little effect on production capacity. The production capacity of grain combinations where recorded were generally in the same range as for single grains. The overall mean production rate for all trials was 7.2 ± 0.8 kg h^{-1}.

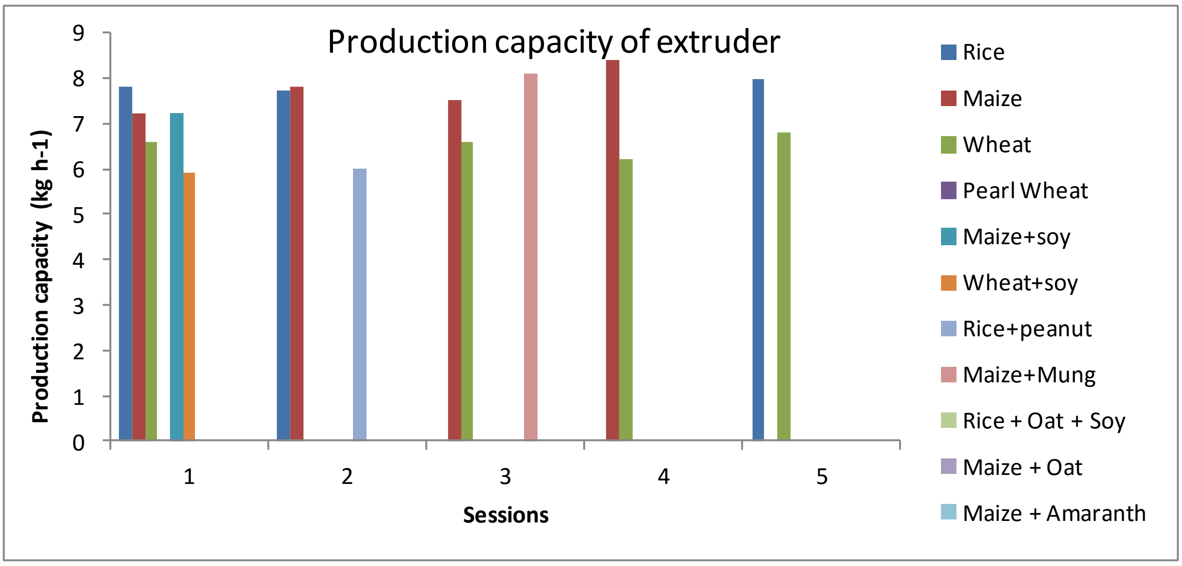


Figure 23 Production capacity of Phase 2 extrusions. Numbers 1 to 5 refer to production sessions (Table 14). Data for brown rice/oat/soy and maize/oat and maize/amaranth were unavailable.

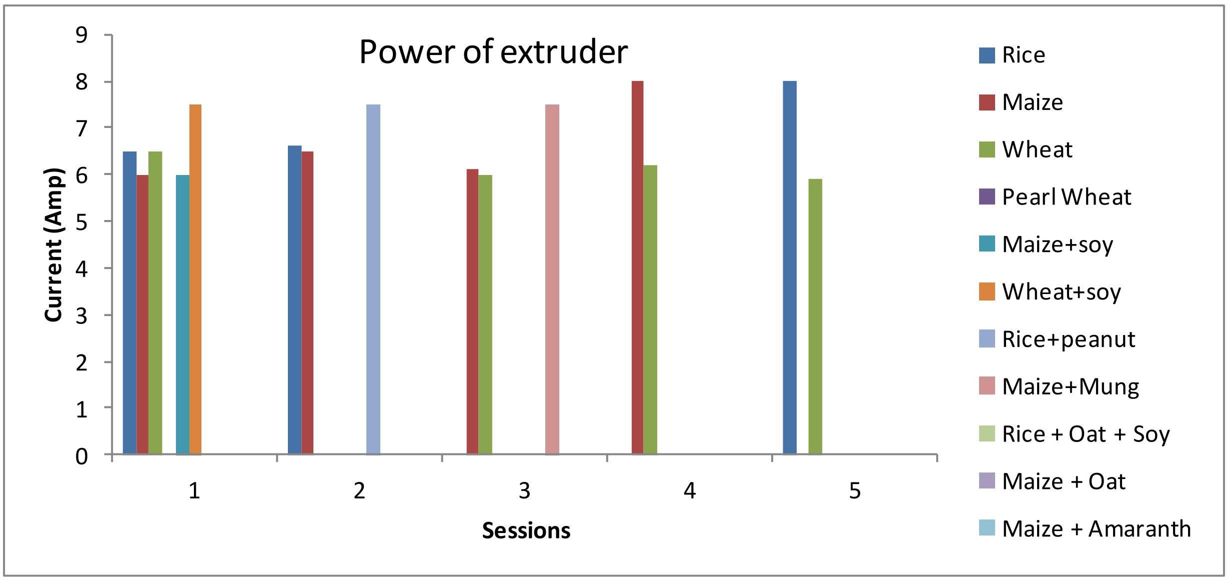


Figure 24 Electric power of Phase 2 extrusions. Numbers 1 to 5 refer to production sessions (Table 14). Data for brown rice/oat/soy and maize/oat and maize/amaranth were unavailable.

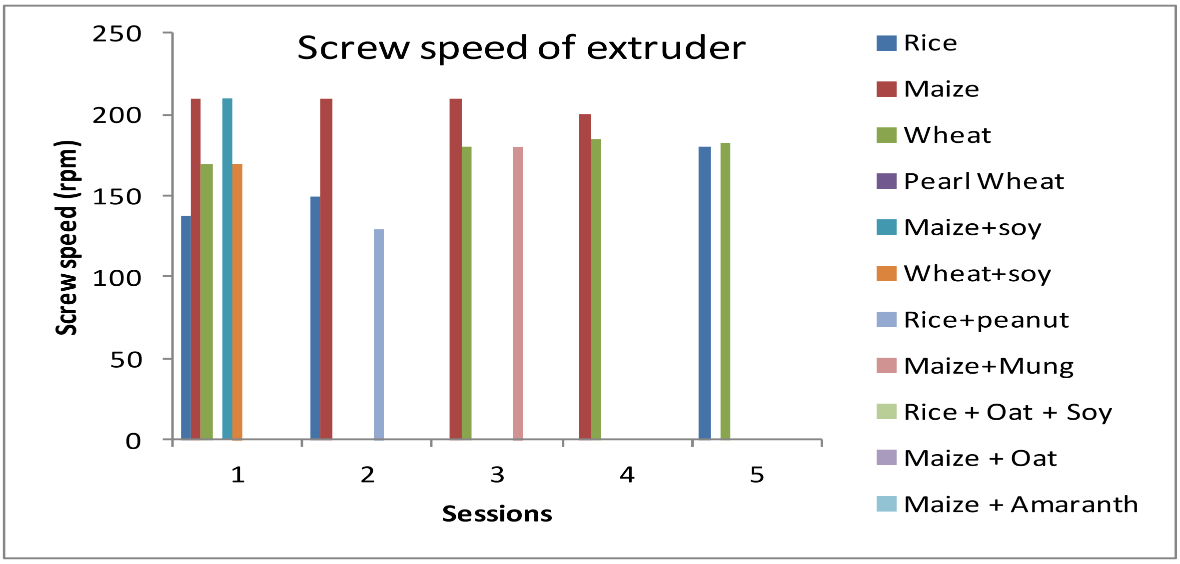


Figure 25 Screw speed of Phase 2 extrusions. Numbers 1 to 5 refer to production sessions (Table 14). Data for brown rice/oat/soy and maize/oat and maize/amaranth were unavailable.

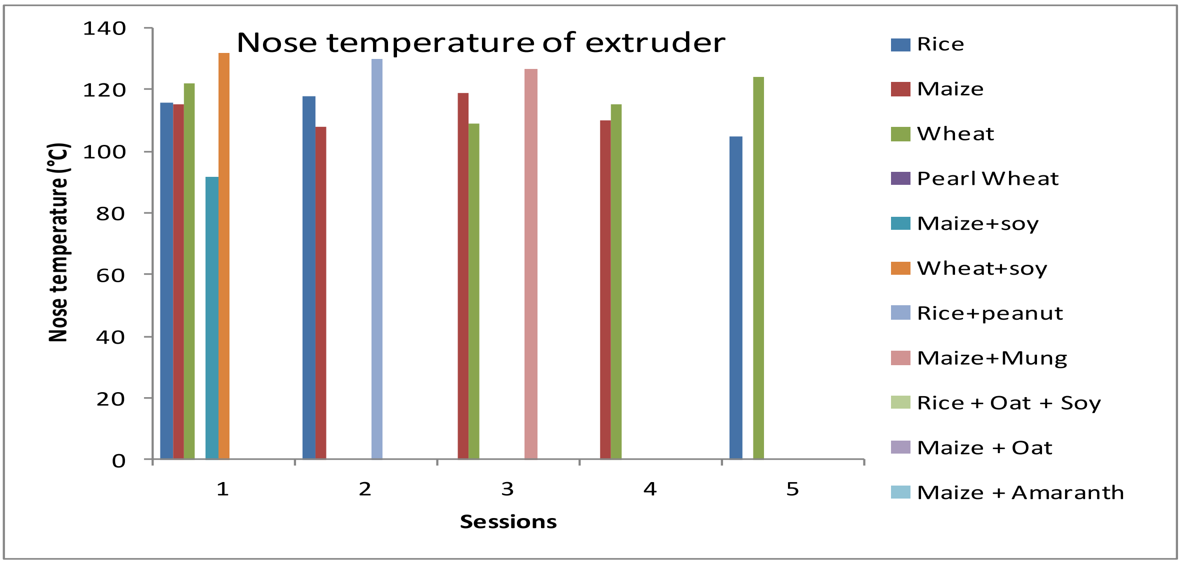


Figure 26 Nose temperature of Phase 2 extrusions. Numbers 1 to 5 refer to production sessions (Table 14). Data for brown rice/oat/soy and maize/oat and maize/amaranth were unavailable.

Figure 24,Figure 25, and Figure 26 show the other performance parameters for the production capacity in Figure 23. Inspection of these bar charts suggests a correlation for at least production capacity and power. Table 18 shows the correlation coefficients between all these parameters considering all grains and their combinations as one data set.

Table 18 Correlations between production, power, screw speed and nose temperature for all extrudates in Phase2. Bold data are correlation coefficients and italicised data are P values.

Variables	Production	Power	Screw speed	Nose temp.
Production	**1**	*0.37*	*0.31*	*0.13*
Power	**0.25**	**1**	*0.30*	*0.41*
Screw speed	**0.28**	**-0.29**	**1**	*0.05*
Nose temp.	**-0.41**	**0.23**	**-0.52**	**1**

Only the nose temperature (Figure 27) and screw speed were significantly (inversely) correlated. As the screw speed increased, the nose temperature decreased. This is probably counter intuitive because kinetic energy not used to cause phase changes grains is dissipated as heat.

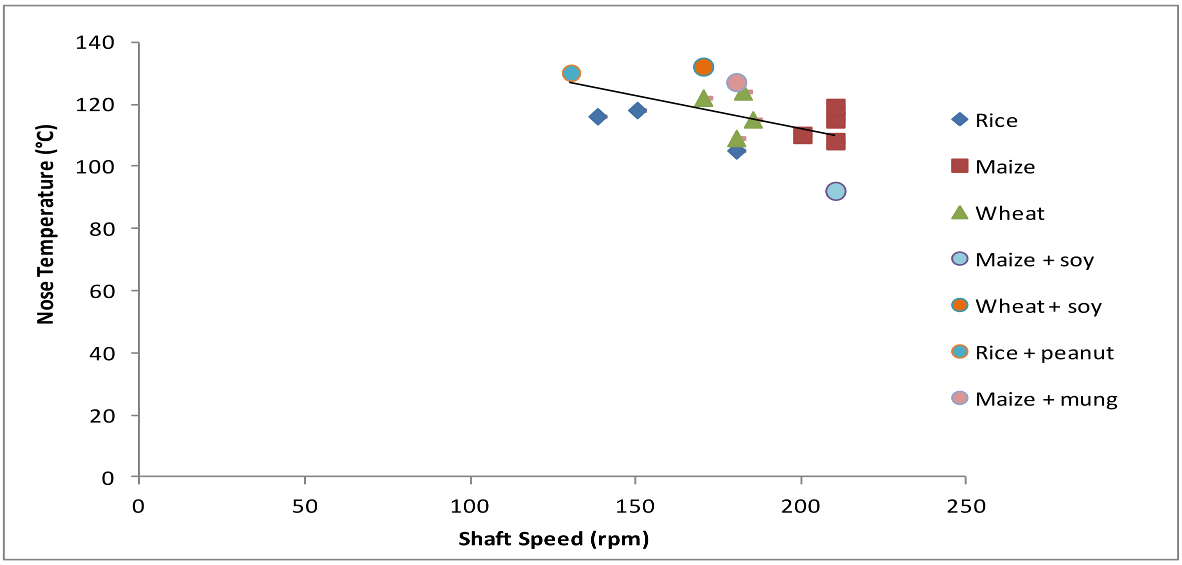


Figure 27 Scatterplot of nose temperature and shaft speed of Phase 2 extrusions. Numbers 1 to 5 refer to production sessions (Table 14). Data for brown rice/oat/soy and maize/oat and maize/amaranth were unavailable.

The obvious negative slope in Figure 27 supports the significant negative correlation in Table 18. However, inspection of the plot shows that the negative correlation is largely determined by the grain type rather than screw speed, and must be ignored as a causal effect.

It can be concluded that the reported production data for Phase 1 and the replicated part of Phase 2 were not amenable to standard statistical tests, either due to subtle changes to the extruder and/or changes to the grain specifications.

Physicochemical data of extrudates of three grains for Phase 2

There was little difference between the extrudates from different grains in Phase 2 (Table 19). The ash content was the only chemical property that was significant different, highest for wheat. This can only stem from the composition of the original grain.

The moisture content and water activity were both low for all the grains, and the data were comparable with data in Phase 1 (Table 6). Maize was shown to have the lowest bulk density and wheat has the highest bulk density, again consistent with Phase 1 data. The higher bulk density of the wheat extrudates will be discussed in the conclusion and other differences between Phase 1 and Phase 2 physicochemical data will be discussed in a later section, Statistical comparison of Phase1 and Phase 2 results on page 72.

Table 19 Physicochemical properties of Phase 2 cylindrical extrudates over several sessions for three grains. Data are session means ± SD. Means within a column with different superscripts are significantly different ($P < 0.05$).

Grain	Replicate runs	Moisture content (% m/m)	Ash content (% m/m)	Fat Content (% m/m)	Water activity (Aw)	Bulk density (g cm^{-3})	Compression force (N)	Compression work (mN m)	Triple point force (N)	Triple point work[¶] (mN m)
Brown rice	3	9.4 ± 2.1[a]	1.4 ± 0.2[ab]	1.2 ± 1.5[a]	0.23 ± 0.04[a]	0.28 ± 0.06[a]	76 ± 35[a]	234 ± 80[a]	8.2 ± 8.0[a]	27.6 ± 31.3[a]
Maize	4	8.8 ± 1.2[a]	1.1 ± 0.0[b]	0.6 ± 0.3[a]	0.26 ± 0.05[a]	0.19 ± 0.05[a]	72 ± 57[a]	204 ± 111[a]	5.8 ± 0.3[a]	24.9 ± 6.0[a]
Wheat	4	9.0 ± 3.0[a]	1.6 ± 0.4[a]	0.2 ± 0.1[a]	0.21 ± 0.07[a]	0.35 ± 0.16[a]	80 ± 29[a]	235 ± 43[a]	10.1 ± 7.1[a]	33.4 ± 23.0[a]

Please note: Protein results were not available due to the malfunction of the VELP machine and the Kjeldahl method had yet been fully developed at this stage.
Please refer to page 68 of this thesis for the complete protein analysis results.

Graphical representation of physicochemical data of all extrudates in Phase 2.
In this section the focus will be on means that differ greatly from typical values.

Moisture content

The moisture content is relatively consistent amongst the samples with little variation between the grains over the period of five sessions. Brown rice plus peanut had the lowest moisture content possibly due to the fat contribution from peanut. The third session produced extrudates with the highest moisture content. Because water was not used in any of the extrusions, it is likely that the moisture content of the original grain was relatively high.

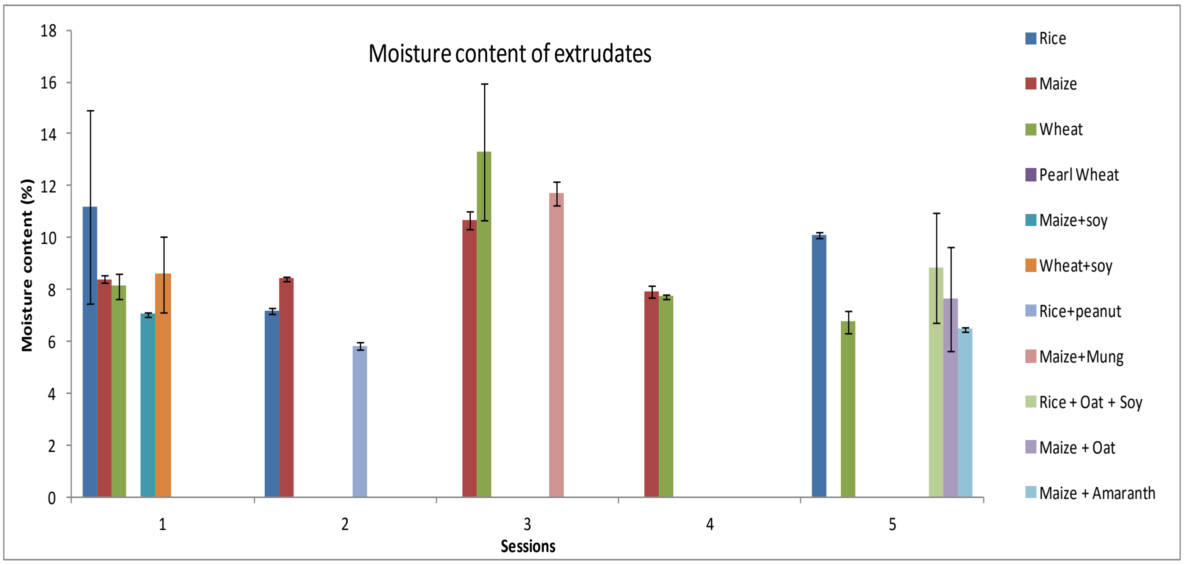


Figure 28 Moisture content of Phase 2 extrusions. Numbers 1 to 5 refer to production sessions (Table 14). Data are means of replicates within session ± SD.

Ash content

Wheat extrudates tended to have the highest ash content of all the grains and combinations, probably due to the original grain. Certainly in Phase 1 (Table 6), wheat extrudates had the highest ash content. The maize plus mung bean combination had the lowest ash content, derived at least in part by the low ash content of maize (Table 6 and Table 19). Inspection of Figure 29 shows that soy addition was particularly effective in raising the ash content of extrudates. This reflects the known relatively high ash content of soy (Marshall 2010).

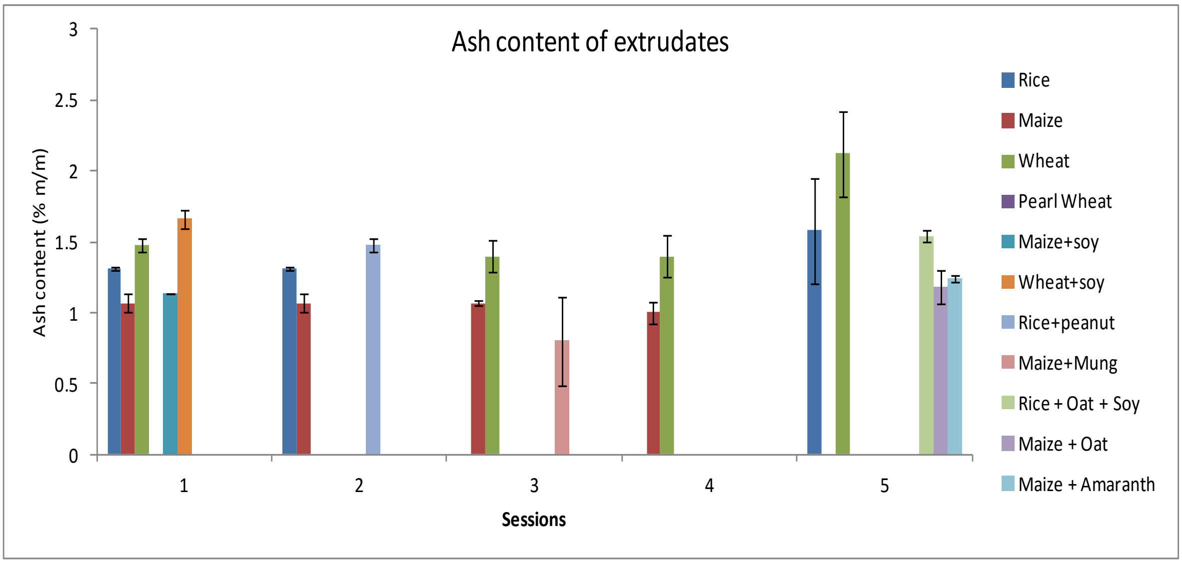


Figure 29 Ash content of Phase 2 extrusions. Numbers 1 to 5 refer to production sessions (Table 14). Data are means of replicates within session ± SD.

Water activity

The highest water activity was of maize in combination with mung bean (Figure 30). Maize and amaranth had the lowest water activity but was not significantly different from wheat in Session 5. All the extrudates will be microbiologically stable with water activities low enough to inhibit the growth of spoilage organisms (Ray 1996; Gustavo V. Barbosa-Cánovas, Anthony J. Fontana et al. 2007).

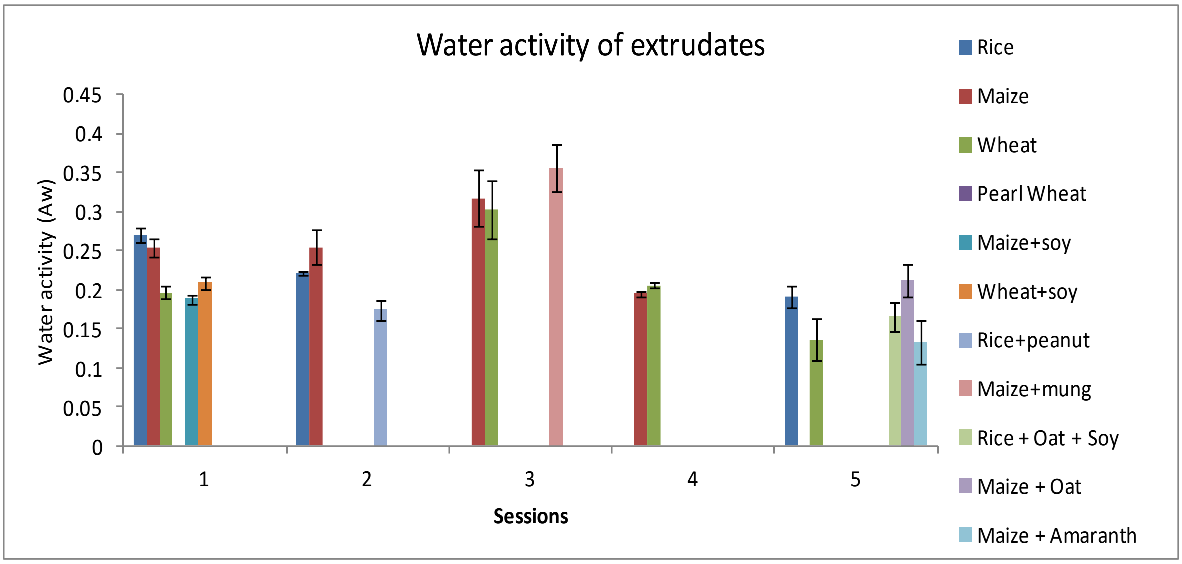


Figure 30 Water activity of Phase 2 extrusions. Numbers 1 to 5 refer to production sessions (Table 14). Data are means of replicates within session ± SD.

Bulk density

Bulk density was greatest in wheat extrudates, while maize + soy and maize + amaranth had surprisingly very low bulk densities. (Reinspection of the original data indicated the results were accurate. Mass of the 10cm replicates was found to be unusually low, while diameters were similar to those of pure grains.) Maize alone produced extrudates with low bulk densities but the addition of other grains further reduced the bulk density, with the exception of maize + mung. The bulk density of brown rice + peanut was lower than that of pure brown rice extrudates. The addition of other grains might tend to disrupt/prevent within-grain bonding, with amaranth being the best example. It may be significant that the grain size of amaranth is minute compared with the size of a maize kernel. In this respect microscopy might be useful to understand this phenomenon, however due to time constraint, microscopic cross-sections of the grain structure was not performed.

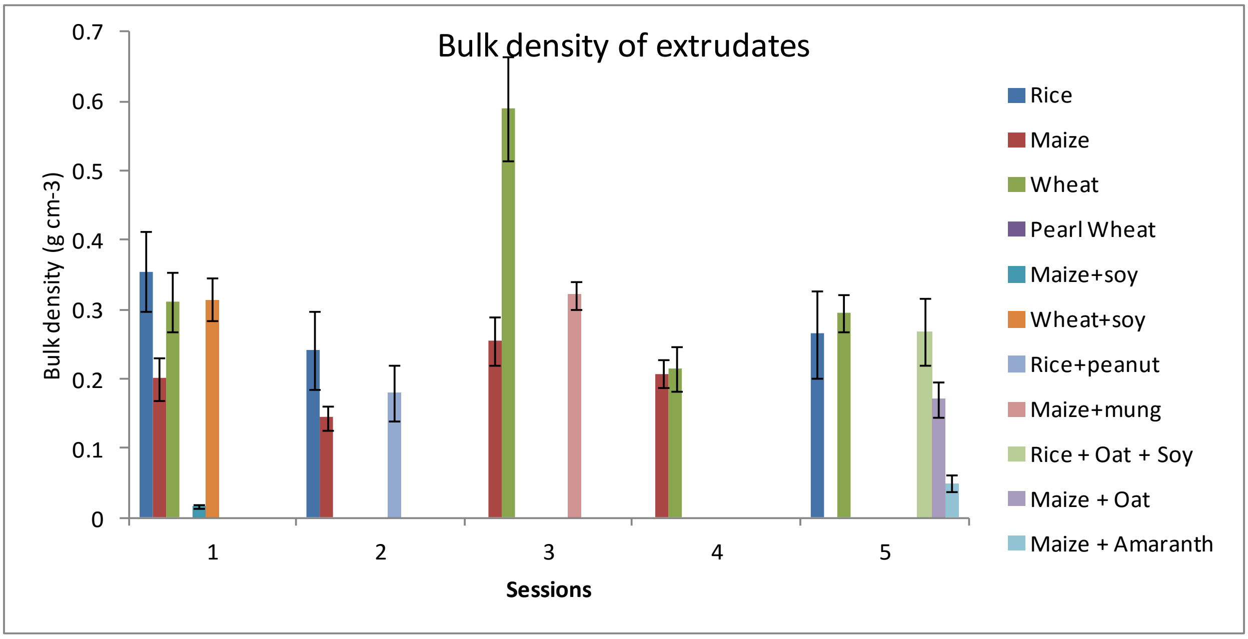


Figure 31 Bulk density of Phase 2 extrusions. Numbers 1 to 5 refer to production sessions (Table 14). Data are means of replicates within session ± SD.

Compression force and work

Maize + amaranth produced extrudates with a lowest compression force, which was consistent with the low bulk density. However, in Session 3 maize produced the least hard extrudate, but this is not consistent for maize. In Sessions 2 and 4, particularly Session 4, maize is the hardest.

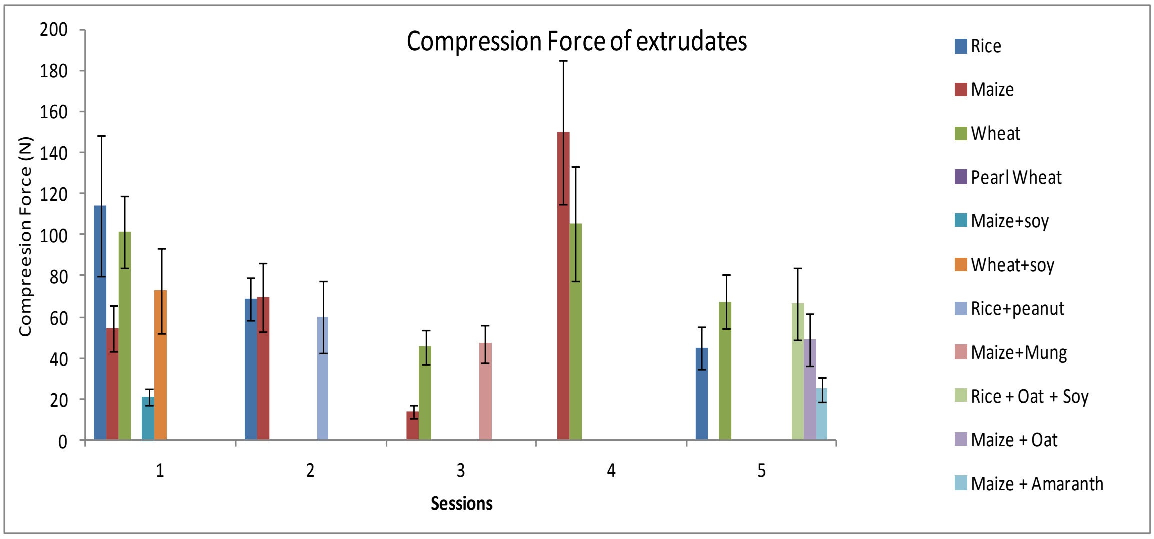


Figure 32 Compression force of Phase 2 extrusions. Numbers 1 to 5 refer to production sessions (Table 14). Data are means of replicates within session ± SD.

The relationship between bulk density and compression force was explored by plotting the two sets of data irrespective of grain (Figure 33). The relationship was very weak, with an $r^2 = 0.039$, more or less random.

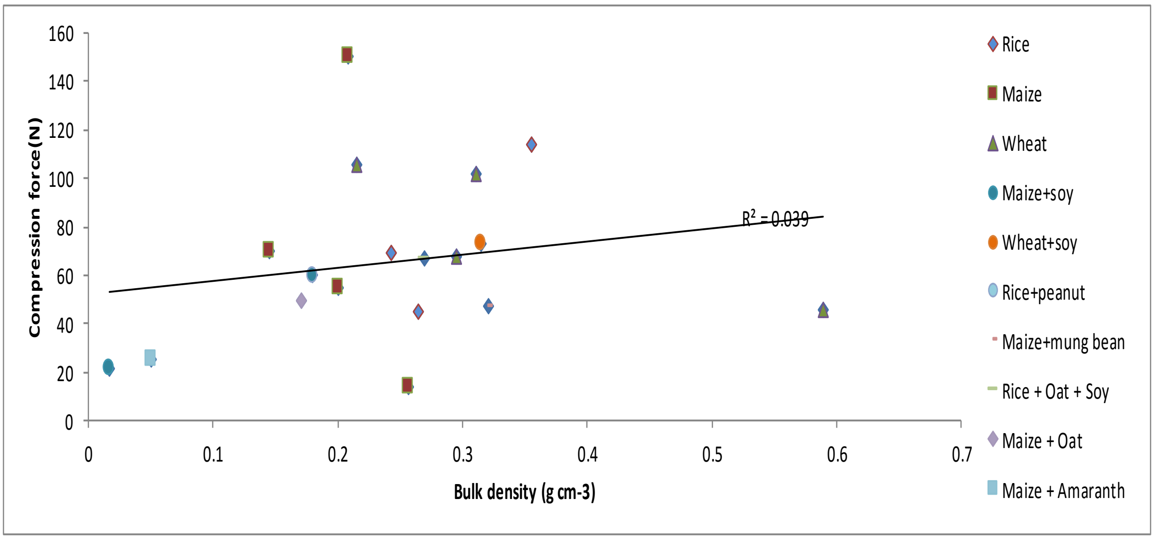


Figure 33 Correlation relationship of compression force of Phase 2 extrusions.

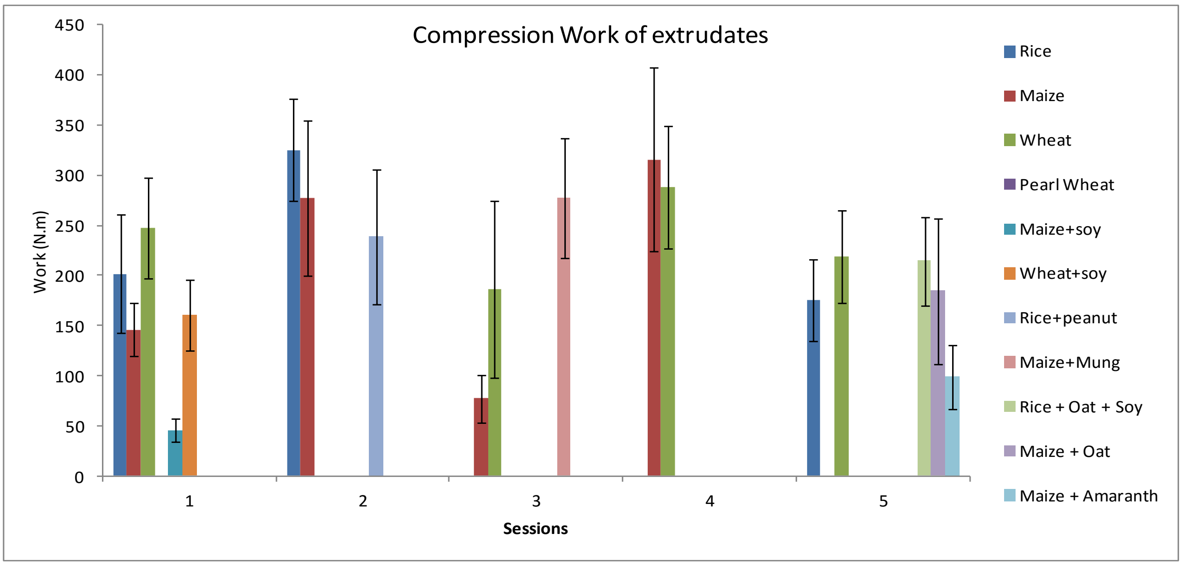


Figure 34 Compression work of Phase 2 extrusions. Numbers 1 to 5 refer to production sessions (Table 14). Data are means of replicates within session ± SD.

Three point bend force

As shown with bulk density and the compression tests, the addition of other grains usually resulted in reduced force of break. Thus the force-to-break brown rice + oats + soy along with maize + oats, and maize + amaranth was greatly decreased compared with single grain brown rice and maize extrudates. However, maize + mung was an exception, the mung having little effect of force, and reflected the high bulk density result. Wheat requires the greatest force-to-break (Figure 35 and Figure 36).

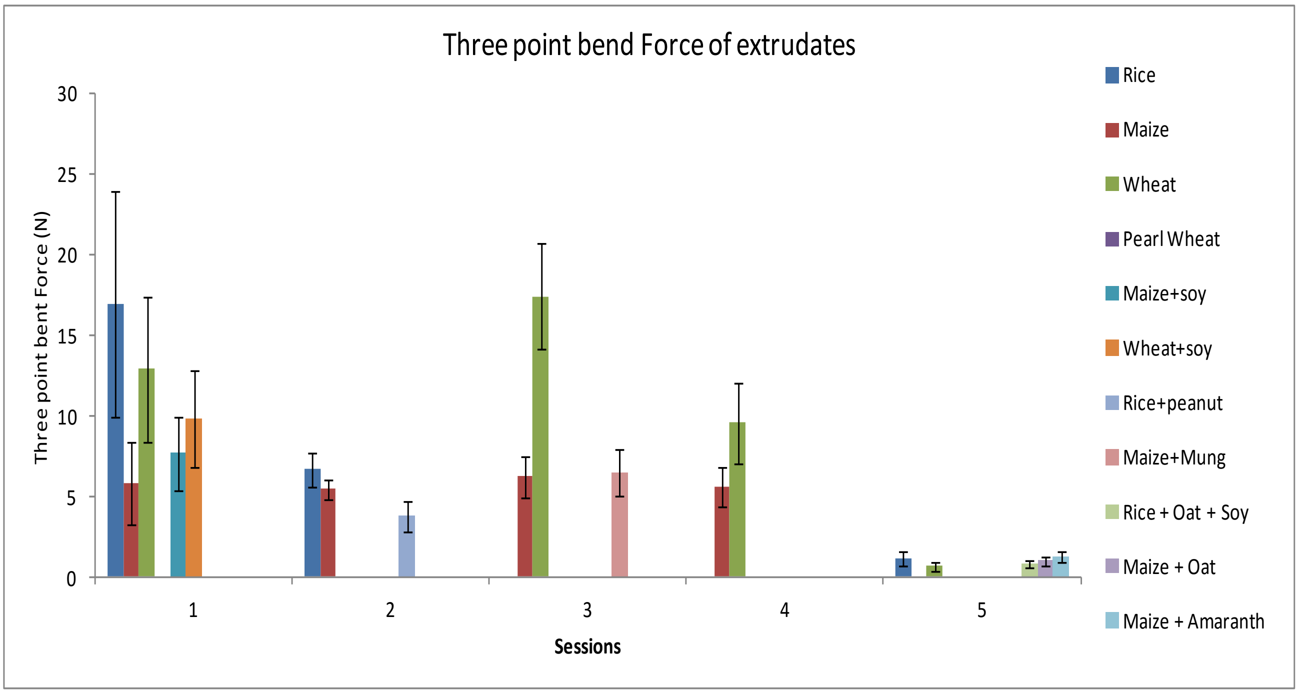


Figure 35 Three point bend force of Phase 2 extrusions. Numbers 1 to 5 refer to production sessions (Table 14). Data are means of replicates within session ± SD.

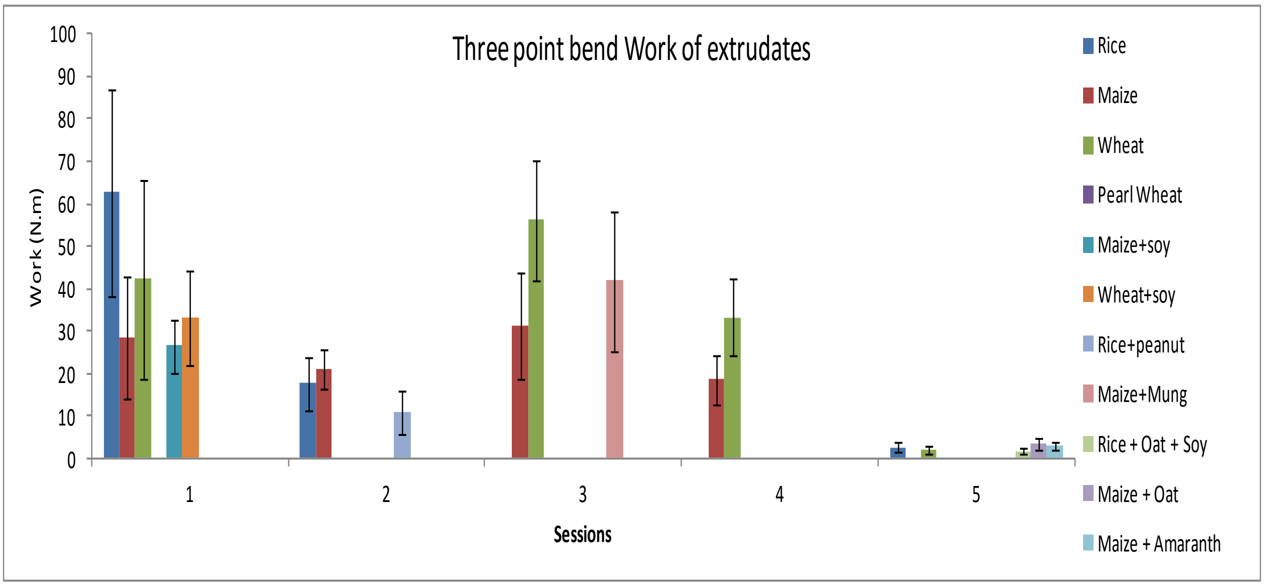


Figure 36 Three point bend work of Phase 2 extrusions. Numbers 1 to 5 refer to production sessions (Table 14). Data are means of means of replicates within session ± SD.

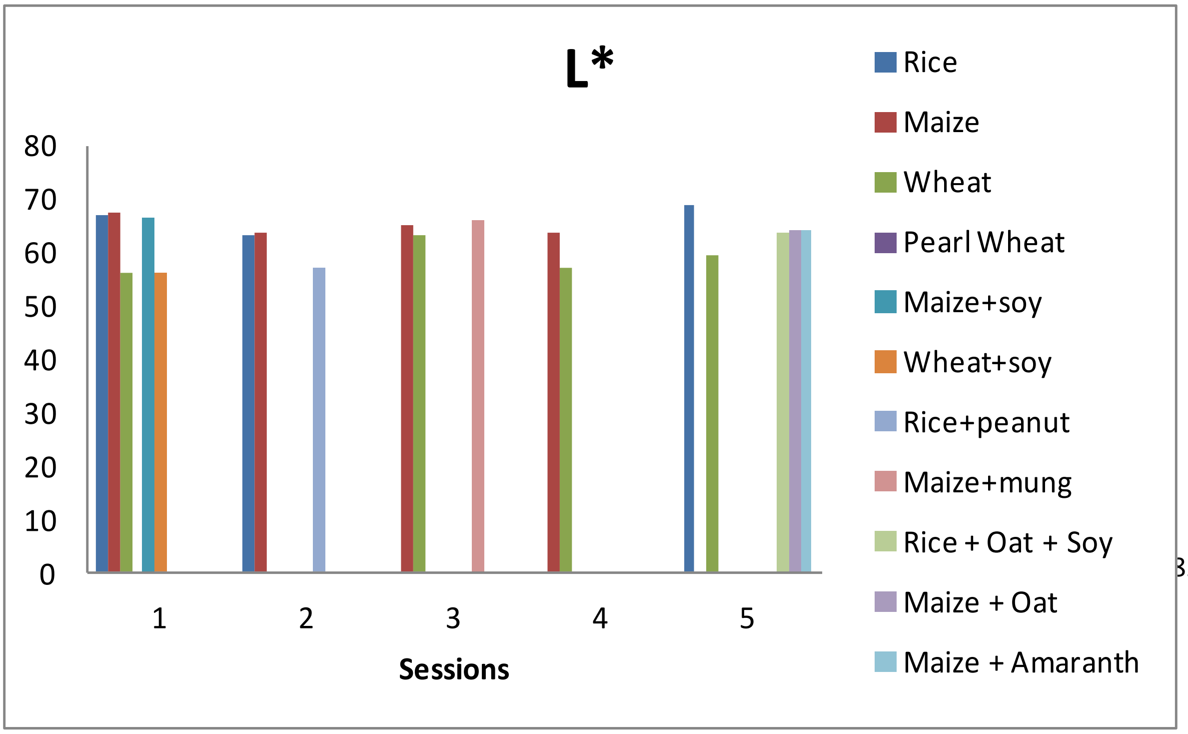
Colour

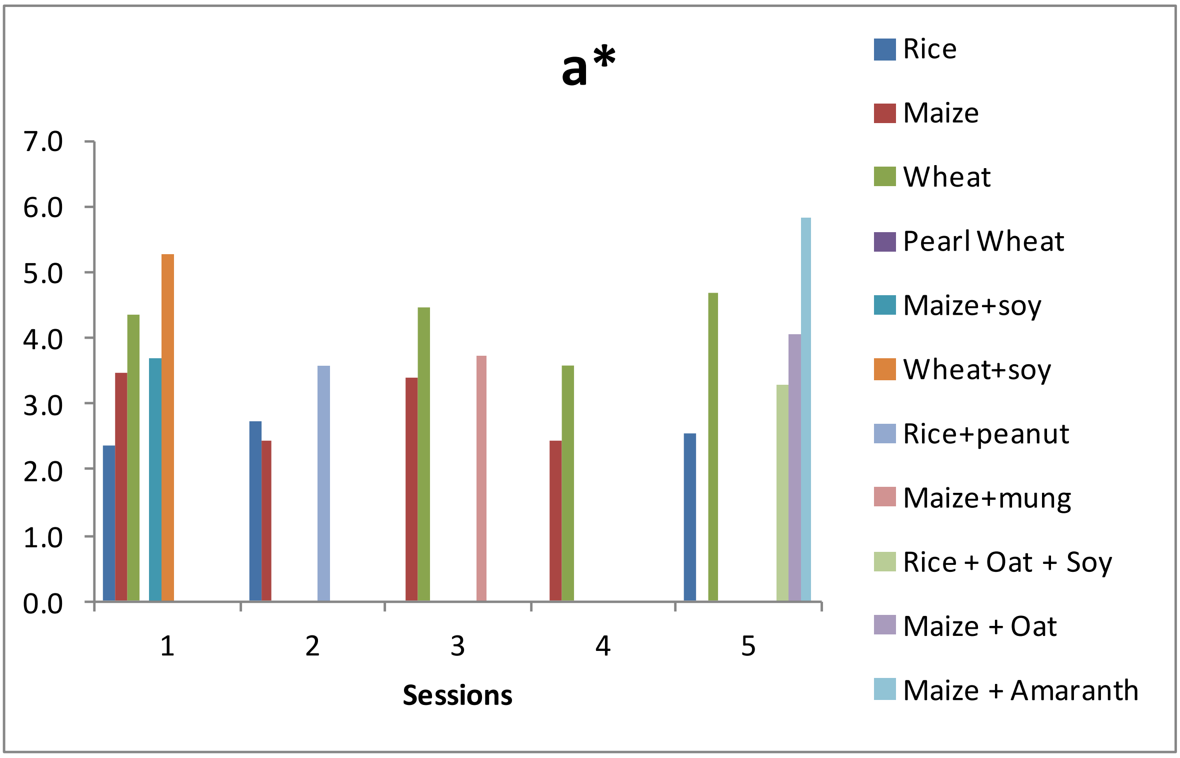
The colour of extrudes are shown in Table 20 for brown rice, maize and wheat.

Table 20 Colour characteristics of three extrudates. Data are means ± SD. Means within a column with different superscripts are significantly different ($P < 0.05$).

	L*	a*	b*
Brown rice	66.2 ± 2.8^{a}	2.55 ± 0.2^{a}	18.1 ± 0.3^{a}
Maize	64.9 ± 1.9^{a}	2.94 ± 0.6^{a}	30.6 ± 1.7^{b}
Wheat	59.0 ± 3.2^{b}	4.28 ± 0.5^{b}	17.4 ± 3.1^{a}

There were significant differences between the lightness and redness in wheat from brown rice and maize. It shows that wheat extrudates were slightly darker than brown rice and maize extrudates. Yellowness, which is represented by a positive b*, was significantly higher in maize compared to the other two grains, paralleling the results obtained in Phase 1, arising from maize's yellow kernel. Figure 37 shows the colour data for all Phase 2 extrudates. L* values, the fraction of reflected light, was roughly similar across all extrudates. Values for a*, redness in all these extrudates, are rather different for different extrudates. However, because the a* values were all less than 6.0, it would be difficult for the human eye to detect redness on the 0 to 100 scale of redness in L*, a*, b* colour space (CIELAB) (Sahin and Sumnu 2006; Kuehni 2012). For b*, by contrast, the values lay between 15 and 33 on the 0 to 60 scale, and the yellowness due to maize was obvious to the eye.





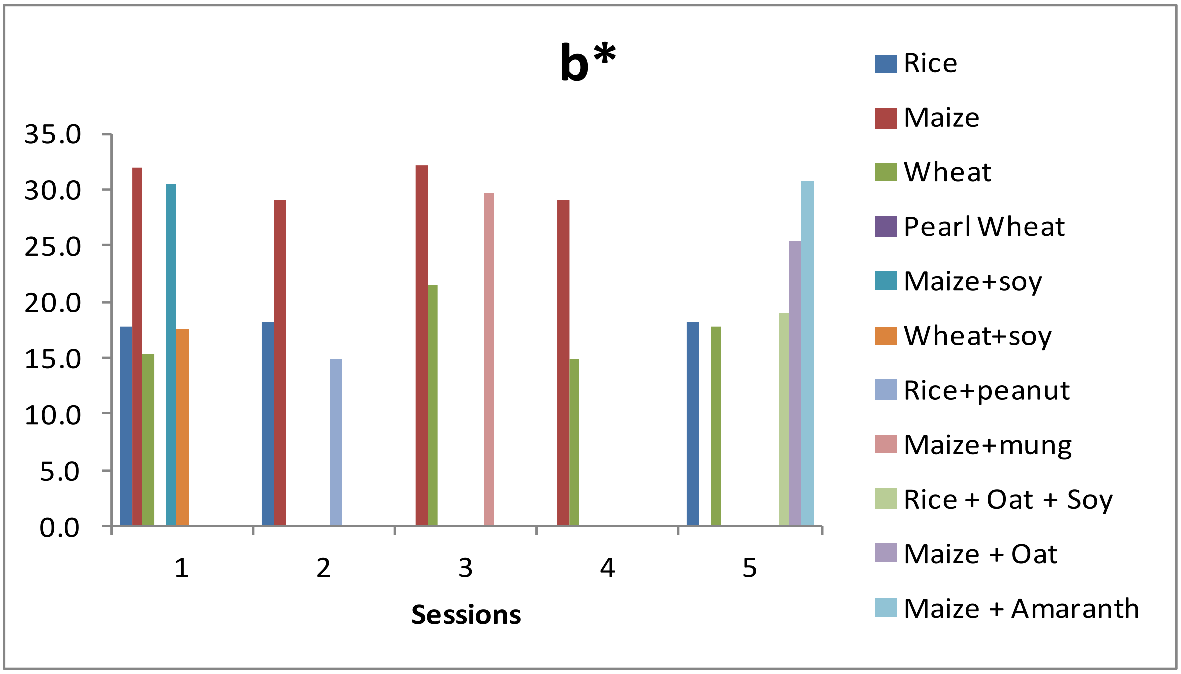


Figure 37 Colour characteristics of Phase 2 extrusions. Numbers 1 to 5 refer to production sessions (Table 14). Data are means of means of replicates within session ± SD.

Comparisons between Phases 1 and 2

Table 21 shows the diameters of single grain extrudates from Phases 1 and 2, where all extrudates were formed by the same exit die (3 mm diameter). Within-grain between- Phases variation was not significantly different, while within-Phase between-grain variations were highly significant. The diameters of wheat extrudates were narrower than brown rice and maize equivalents. Whereas the variables relating to starch will almost certainly affect gelatinisation, protein(s) are also likely to be involved. In particular, wheat has a high protein content, mostly in the form of gluten (Wieser 2007). It was therefore of interest to measure the protein content of extrudates.

Table 21 Diameters of the extrudates during Phase 1 and Phase 2 showing the mean values and the standard deviations. Statistical comparisons between grains-within Phase, and within grain- between Phases are also shown.

	Extrudate diameter (cm)		
Grain	Phase 1	Phase 2	P value within grain
Brown rice	1.03 ± 0.15	1.01 ± 0.09	0.858
Maize	1.04 ± 0.06	0.99 ± 0.01	0.200
Wheat	0.89 ± 0.02	0.89 ± 0.07	0.945
P value within Phase	0.065	0.048	

Protein content in Phase 1 and 2 extrudates

The protein content of the extrudates from both phases were tested at the same time in the later stage of the study. The Kjeldahl distillation equipment had failed and therefore a nitrogen determination method had to be developed based on the method of Baethgen and Alley (1989) as described in Chapter 2. This proved to be successful in that the results were believable, with consistent replicate results. Although the exact composition of grains within species used to produce the extrudates was unknown and possibly variable, the protein content of brown rice, maize and wheat extrudates between Phase 1 and Phase 2 were not significantly different from each other (data not shown). Therefore the data could be pooled within grain (Figure 38).

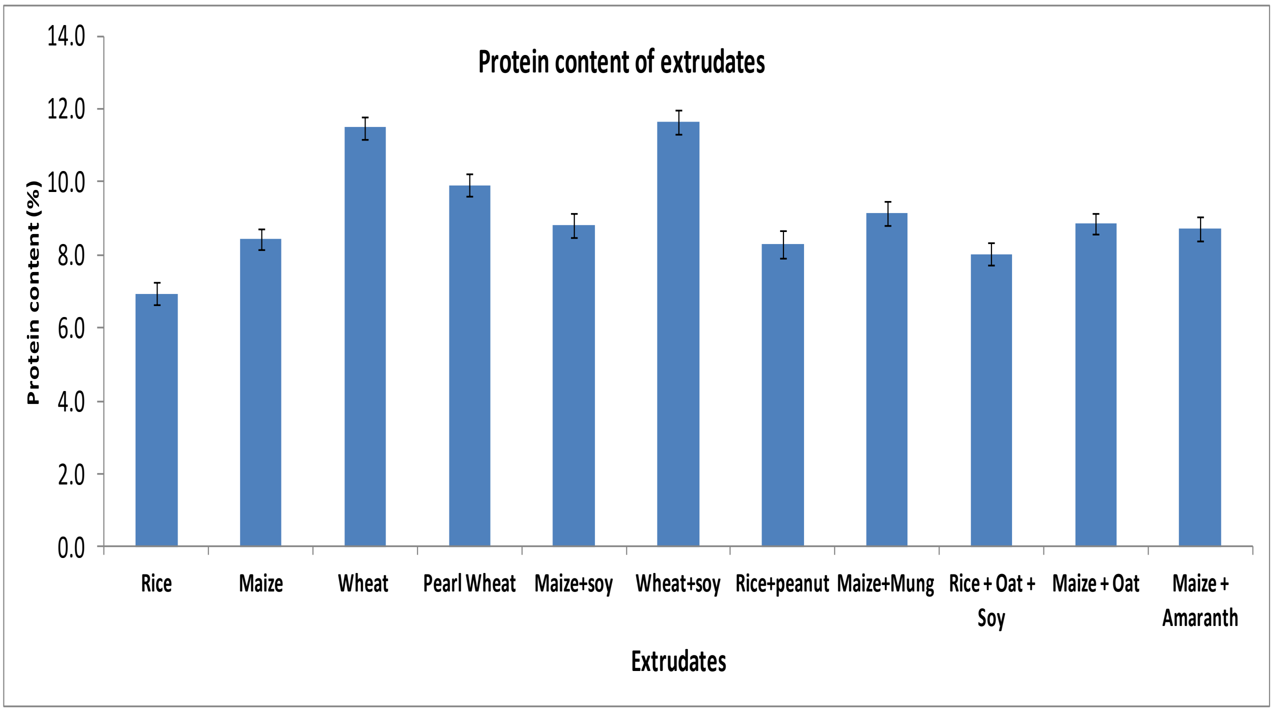


Figure 38 Protein content of Phase 1 and 2 extrusions combined. Data are means of means of replicates ± SD.

Wheat and a wheat mix containing 10% soy produced extrudates that had the highest protein content among all the extrudates, around 12% (w/w). Pearl wheat extrudates, which is wheat without the hull and bran, had the third highest protein content at about 10% (w/w). On the other hand, brown rice extrudates had the lowest protein content among the extrudates, which was only 7% (w/w). In seeking to explain why wheat extrudates had the highest bulk density (Table 19 Phase 2), it is tempting to ascribe it to wheat's high protein content (Andersson and Hovmöller 2000). However, the comparative density of dry protein is around 1.3 g cm^{-3} (Andersson and Hovmöller 2000; Quillin and Matthews 2000) and that of dry starch is around 1.5 g cm^{-3} (Dengate, Baruch et al. 1978; Marousis and Saravacos 1990). Thus, less protein should lead to a higher bulk density, so the densities of these two components cannot be the answer. It is more likely that the protein in wheat in some way minimizes radial expansion of extrudates, thus accounting for the higher bulk density.

The addition of small amounts of other grains to brown rice, maize and wheat had little effect on the protein content, which was not surprising due to the small volumes added. One exception was the increase of protein when a 10% mixture of peanut is used with brown rice grain (Figure 38).

A comparison between Phase 1 and Phase 2 statistics results

Between the two productions phases, minor unknown modifications were made to the extruder screw and the grains used were undefined beyond species. In this section the two production phases have been compared to see if these two variables had any significant effect of the extrudates produced. Comparisons between the two phases were only carried out on brown rice, maize and wheat because not enough data was collected for pearl wheat and other new combination extrudates in Phase 2. The P values of a one way analysis of variance are shown in Table 22.

There were no significant differences between the two phases for most of the physicochemical tests, the exceptions being compression force and work for wheat, and the three point bend test for maize. This suggests that the modifications that were made to the screw and the possible variations in grain characteristics had few effects on physiochemical properties of the extrudates. However, the inputs to produce Phase 1 and Phase 2 outputs were poorly controlled – as discussed earlier – and there remains the need to make more systematic comparisons between grains and operating conditions. This has been attempted in Phase 3.

Table 22 P values of comparisons between Phase 1 and Phase 2 physicochemical properties of cylindrical extrudates for three grains. Comparisons that are significantly different ($P < 0.05$) are bolded.

Grain	Replicate runs	Moisture content (% m/m)	Ash content (% m/m)	Fat Content (% m/m)	Water activity (Aw)	Bulk density[¶] (g cm^{-3})	Compress. force (N) [¶]	Compress. work (N m) [¶]	Three point force (N) [¶]	Three point work (N m) [¶]
Brown rice	3	0.62	0.78	0.21	0.39	0.08	0.23	0.20	0.82	0.71
Maize	4	0.96	0.82	0.56	0.07	0.08	0.48	0.07	**0.02**	0.21
Wheat	4	0.60	0.50	0.24	0.99	0.19	**0.01**	**0.01**	0.46	0.33

[¶] Bulk density and texture data – the last five columns – have fewer (replicates) because spherical extrudates were excluded in this analysis, only cylindrical extrudates could be usefully compared.

Summary of results for Chapter 3

The first phase results provided some interesting initial data on the extrudates produced with the primary four grains. Statistically significant correlations were found between the production of brown rice extrudates and the screw speed of the extruder as well as the production of maize extrudates and nose temperature of the extruder. Other production information of interest was that of brown rice, this having a significant difference to the other three grains in terms of screw speed when producing extrudates. However, there were no consistent patterns in the data indicating that production data were not amenable to standard statistical tests.

In terms of physical properties, it was found that maize had significantly lower ash content from the other three grains, and that can only reflect the composition of the original grain. Maize was shown to have a significantly greater b* value than that of the other extrudates which indicates the product is yellower than the extrudates produced from the other grains. This was expected on the basis that the bran fraction of maize is yellow. Other properties were not significantly different with the exception of bulk density which showed wheat to be significantly different from the other extrudates. All extrudates had a low moisture content, water activity, and fat content.

There were a few unexplained strong relationships between physical performance data and physicochemical tests for brown rice, maize and wheat extrudates. These relationships can most likely be explained due to the fact that, at this early stage of experimentation, there was little knowledge of how the machine would respond to operating parameters. Modifications were made after these initial runs leading me to believe the operator made improvements based on these unexpected results.

Phase 2 provided a variety of data showing the effects of several mixtures of grains, and the variability of single grain extrudates prepared in different sessions. The single grains gave results comparable to Phase 1 as seen above in Table 22. The addition of one or more different grains frequently had profound effects on bulk density and texture.

When comparing the density of the rice extrudates with those produced on a scaled down industrial modelled machine a similarity in bulk density can be seen. Literature values show a range between 0.21g cm^{-3} and 0.29 g cm^{-3} over various cooking temperatures (Gat and Ananthanarayan 2015). The extrudates produced with the single phase extruder had a similar bulk density 0.28 g cm^{-3} falling within that range. The literature states the samples were produced with a twin screw extruder and with rice flour rather than whole grains used as the raw ingredients. The results indicate that, at least with rice grain, extrudates can be produced that are similar in bulk density to those manufactured with industrial standard extruders.

The rice extrudates can also be compared to other extrudates produced with single-screw extruders. Similar values are shown for protein content and fat content of extruder rice products. The literature values shown for a single-screw extruder show the protein content of rice extrudates to be between 7.91% - 8.46% and fat content to be between 1.35% - 1.39% (Liu, Zhang et al. 2011). Extrudates produced during this thesis had protein and fat values of about 7% and 1.2%. Both values are slightly lower, however, this variation could possibly be due to a variation in grain species or between husked or non-husked rice grains.

The data are insufficient to reach conclusions about the effect of additional grains. Rather the data are a starting point for further work.

Chapter 4

Phase 3 - Introduction

Phases 1 and 2 used extrudates whose production (grain lot, screw configuration, power etc.) was beyond my control due to the owner of the machine having made configurations to the machine and grain changes without my knowledge, resulting in that valid comparisons between treatments were rare. Nonetheless, some conclusions were reached. The opportunity later arose to compare three grains each of which was extruded at two known nose temperatures. The aim of this experiment was to show the effect of nose temperature on physicochemical properties.

Experimental

The grains were used in Phase 3 were limited to brown rice, maize and wheat, which were the grains used in the previous phases, but not necessarily the same grain lots. The extrusion nose temperatures during the process were, controlled by the operator, one low and one high for each grain (Table 23).

Table 23 Experimental design of Phase 3

Grain	Low nose temp.	High nose temp.
Brown rice	70°C	92°C
Maize	80°C	123°C
Wheat	92°C	110°C

The physicochemical tests were moisture content (3 samples run for 3 replicates), bulk density (5), colour (5) and texture analysis (10).

Results and discussion

Figure 39 shows that extrudates at the lower temperature had about two percentage points of moisture more than the extrudates cooked at the higher temperature, yielding the percentage differences of 28, 22 and 27% for brown rice maize and wheat, respectively. Clearly more water is lost at the higher temperatures. At any ambient temperature these extrudates would be shelf stable. Table 24 reports the statistical analysis showing that nose temperature was much more important than grain source.

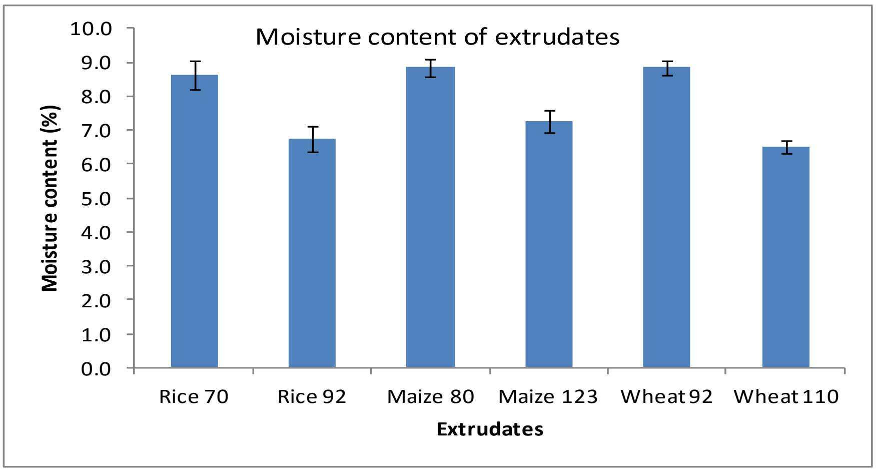


Figure 39 Moisture content of Phase 3 extrudates. Data are means of means of replicates ± SD.

Table 24 Moisture content of the extrudates in Phase 3 showing the mean values and the standard deviations. Statistical comparisons between-grains within-temperature treatment and within-grain between- temperature treatments are also shown. Please refer to Table 23 for the low and high nose temperatures.

	Moisture content (%)		
Grain	Low nose temp.	High nose temp.	P value within grain
Brown rice	8.61 ± 0.43	6.73 ± 0.38	0.005
Maize	8.84 ± 0.26	7.27 ± 0.34	0.003
Wheat	8.85 ± 0.22	6.50 ± 0.18	< 0.001
P value within temperature treatment	0.607	0.056	

Figure 40 shows that the bulk densities of wheat extrudates were higher than brown rice and maize extrudates, which is consistent with Phase 1 and Phase 2 results. In general, the bulk density of extrudates that were extruded at a lower temperature was higher than higher temperature equivalents. It was possible that as moisture was lost as steam the extrudates might expand in diameter, but this was not confirmed to the precision available (Table 25). Clearly the greater moisture content was responsible for the greater bulk density of low temperature extrudates.

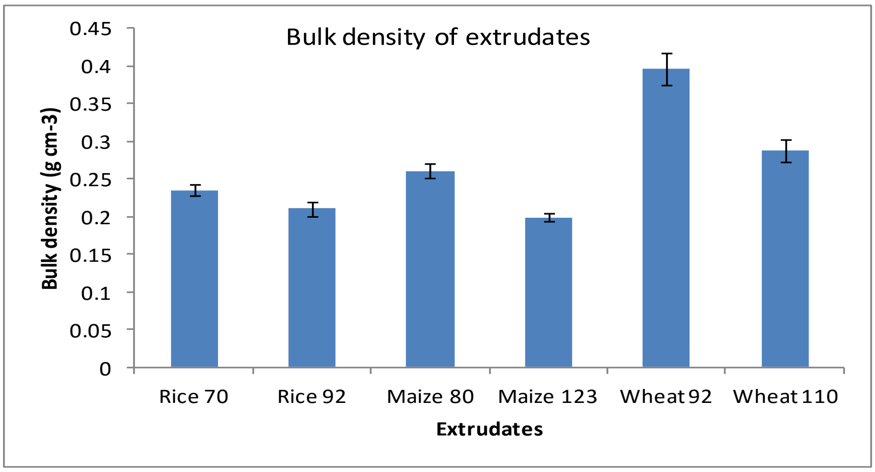


Figure 40 Bulk density of Phase 3 extrudates. Data are means of means of replicates ± SD.

Table 25 Diameters of the extrudates in Phase 3 showing the mean values and the standard deviations. Please refer to Table 23 for the low and high nose temperatures.

	Extrudate diameter (cm)	
Grain	Low nose temp.	High nose temp.
Brown rice	1.00 ± 0.02	1.00 ± 0.05
Maize	1.03 ± 0.05	1.17 ± 0.14
Wheat	0.86 ± 0.17	0.96 ± 0.05

A two-way analysis of variance showed that all the differences of interest were highly significant.

Table 26 Bulk density of the extrudates in Phase 3 showing the mean values and the standard deviations. Statistical comparisons between grains, and within grain-between treatments are also shown. Please refer to Table 23 for the low and high nose temperatures.

	Bulk density (g cm^{-3})		
Grain	Low nose temp.	High nose temp.	P value within grain
Brown rice	0.14 ± 0.04	0.13 ± 0.01	< 0.001
Maize	0.16 ± 0.02	0.10 ± 0.02	< 0.001
Wheat	0.33 ± 0.33	0.15 ± 0.01	< 0.001
P value within temperature treatment	< 0.001	< 0.001	

With the exception of brown rice, the compressive force was higher for the low nose temperature treatments (Figure 41), and again can probably be traced to higher moisture contents. These treatments were tougher. Wheat at 92°C was the most resistant to compression. However, in the 3-point bend test, wheat was not outstanding (Figure 43 and Figure 44). Again, the low nose temperature extrudates were more difficult to break. Table 27 shows a statistical analysis of these data.

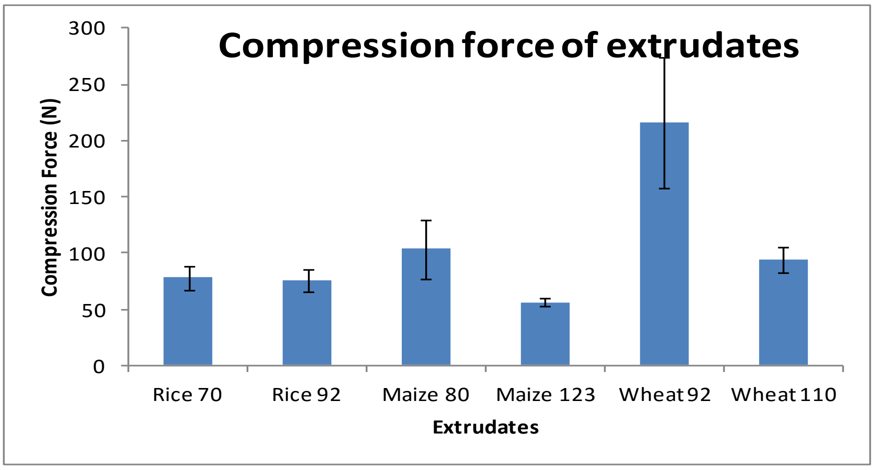


Figure 41 Compression force of Phase 3 extrudates. Data are means of means of replicates ± SD.

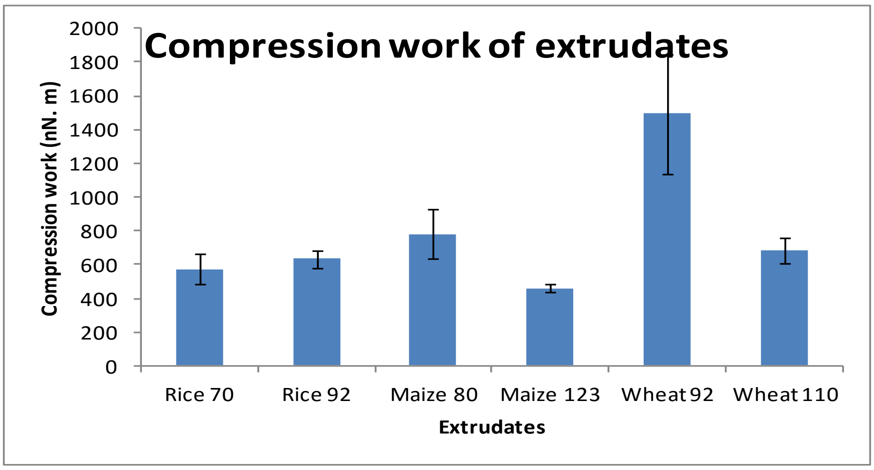


Figure 42 Compression work of Phase 3 extrudates. Data are means of means of replicates ± SD.

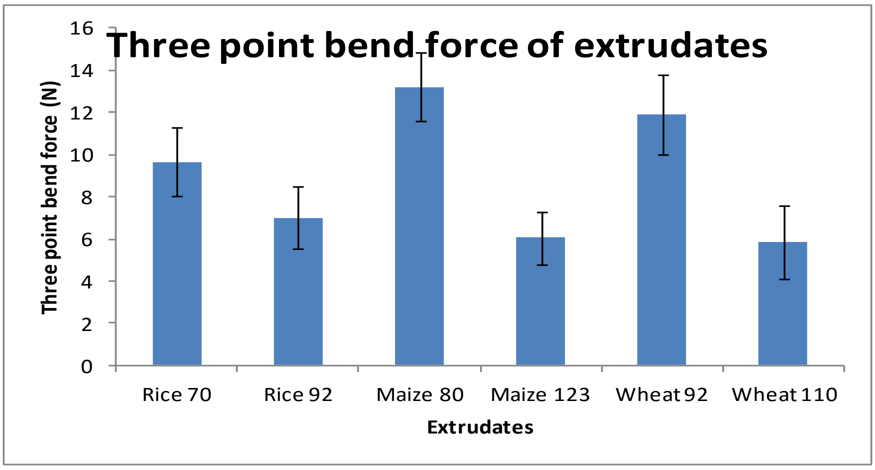


Figure 43 Three point bend force of Phase 3 extrudates. Data are means of means of replicates ± SD.

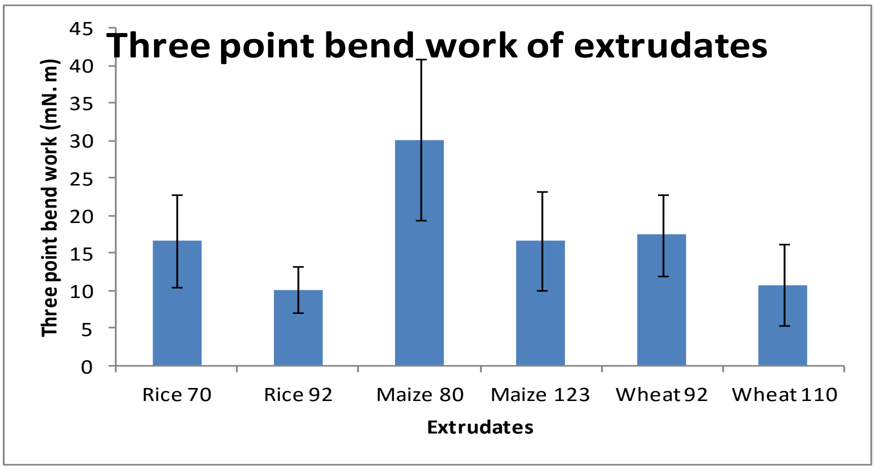


Figure 44 Three point bend work of Phase 3 extrudates. Data are means of means of replicates ± SD.

Table 27 shows that the only properties that were not affected by nose temperature changes were compression force and compression work and this only applied to brown rice grain. There were statistical differences for maize and wheat in all the texture analysis tests ($P = < 0.001$).

Table 27 Texture analysis of the extrudates in Phase 3 showing the mean values, the standard deviations and analysis of variance of nose temperature. Statistical comparisons within-grain between- temperature treatments are shown.

Grain	Temp.	Compression force (N)	Statistic effect of temperature	Compression work (mN. m)	Statistic effect of temperature	3-PB force (N)	Statistic effect of temperature	3-PB work (mN. m)	Statistic effect of temperature
		Mean ± SD	P	Mean ± SD	P	Mean ± SD	P	Mean ± SD	P
Brown rice	70°C	77.9 ± 10.9	0.660	575 ± 94	0.110	9.66 ± 1.60	0.001	16.68 ± 6.14	0.008
	92°C	75.8 ± 10.2		632 ± 54		7.00 ± 1.49		10.14 ± 3.10	
Maize	80°C	103.4 ± 26.0	<0.001	783 ± 142	<0.001	13.21 ± 1.62	<0.001	30.15 ± 10.69	0.003
	123°C	56.2 ± 3.9		461 ± 21		6.04 ± 1.28		16.59 ± 6.57	
Wheat	92°C	216.5 ± 58	<0.001	1494 ± 357	<0.001	11.9 ± 1.91	<0.001	17.43 ± 5.35	0.012
	110°C	94.0 ± 10.8		684 ± 71		5.84 ± 1.74		10.77 ± 5.36	

The colour characteristics of the extrudates in Phase 3 are very similar to the extrudates from Phase 1 and 2. This was no obvious pattern of colour variation due to nose temperature. (These measurements were collected from 5 samples run for 5 replicates.)

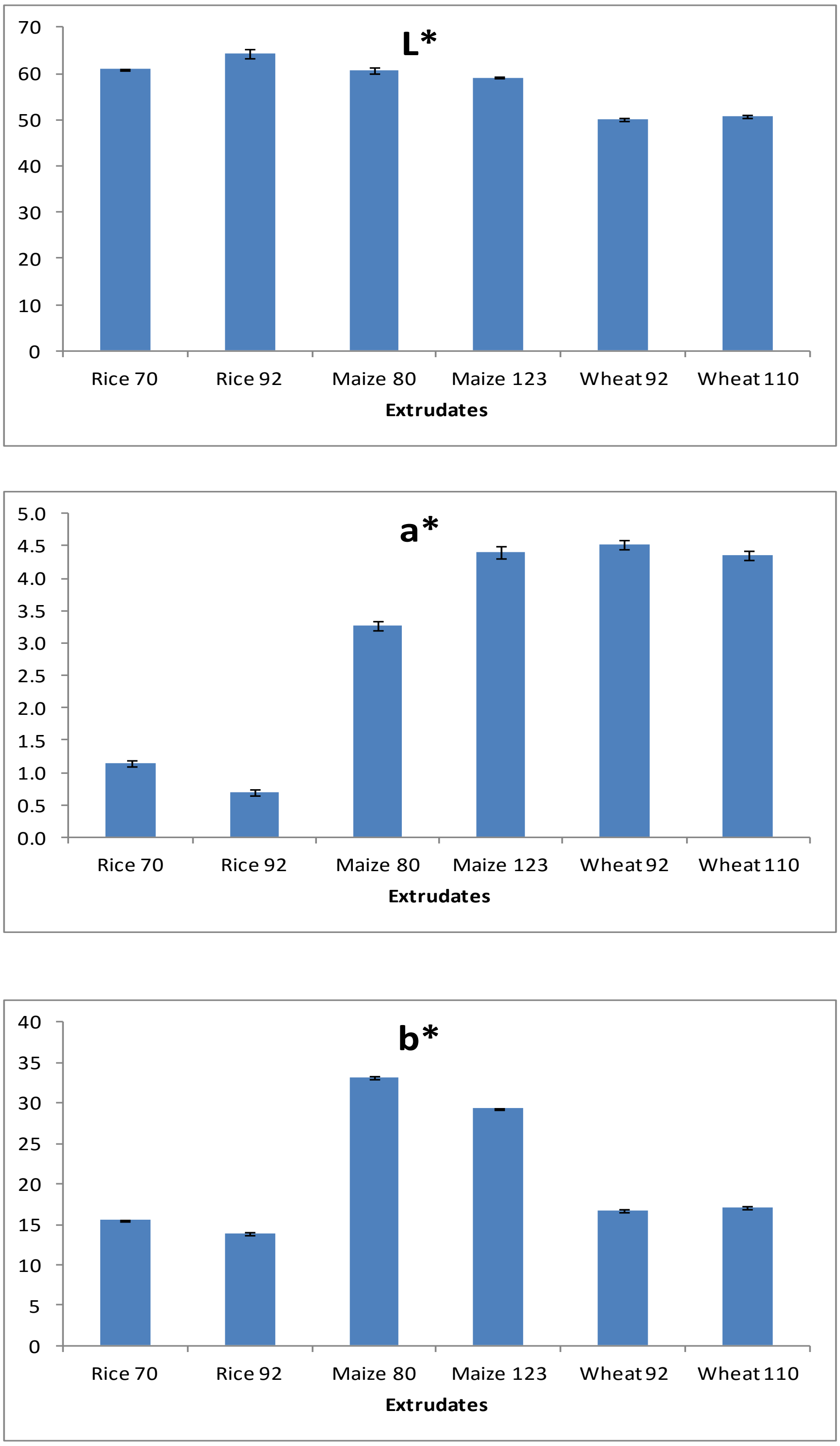


Figure 45 Colour characteristics of Phase 3 extrusions. Data are means of means of replicates within session ± SD.

Chapter 5

Concluding Discussion

In the beginning stages of this thesis there were many factors that were beyond control. These included changes made to the extruder, unknown origins and changes of the grains, availability of grains and also the availability of analysis machinery. Although most of these factors could not be altered or remedied there were occasions when methodology could be changed to accommodate, such as changing the protein determination method due to the unforeseen malfunction of the automated Kjeldahl VELP machine.

In this section the results from the different phases will be summarised. Results from the single phase extruder will be compared to those of a commercial standard running off three phase power. It will be discussed if, based on the research done and literature values, it could be possible for the single phase extruder to produce extrudates at a similar quality to that of a commercial extruder.

The following are the literature values compared with the experimental results.

Table 28 Nutrition values in grains based on literature

Grain	Moisture Content (%)	Ash Content (%)	Fat Content (%)	Protein Content (%)	Bulk density (g cm^{-3})
Brown rice	15.5	1.5	2.7	7.9	0.609
Maize	11.2	1.1	4.6	9.2	0.634
Wheat	10.3	1.6	2.0	11.6	0.490

Data extracted from (Ilo, Tomschik et al. 1996; Takuma Genkawa, Fumihiko Tanaka et al. 2008; Metzger, Morawicki et al. 2010)

Moisture content

The literature approximate percent moisture content for brown rice is 15.5% (Genkawa, T., Tanaka, F. et al. 2008), 11.2% for maize (Ilo, Tomschik et al. 1996) and wheat is 10.3% (Metzger, Morawicki et al. 2010), this value is close to the experimental values from this thesis, which were 8.1% from Phase 1 (Table 6) and 9.0% from Phase 2 (Table 19).

Ash content

The literature values for the ash content of cereal grains used in this thesis are brown rice 1.5%, maize 1.1% and wheat 1.6%, respectively (Metzger, Morawicki et al. 2010; Saleh, Zhang et al. 2013). The experimental results from Phase 1 and 2 were very close to the literature values, as shown on Table 6 and Table 19, they were brown rice 1.4%, maize 1.1% and wheat with an average of 1.55%.

Fat content

The literature value for the fat content of the grains used in Phase 1, 2 and 3 are 2.7% for rice, 4.6% for maize and 2.0% for wheat (Metzger, Morawicki et al. 2010; Saleh, Zhang et al. 2013). The fat contents of all the extrudates produced in this single phase extruder are ranging from 0.2% to 1.2%. Assuming the original grains used in this research where similar to that of the literature values then it appears some fat was lost during processing. This loss is most likely due to fat from the grain becoming coated on the extruder barrel and acting as a lubricant during extrusion.

Bulk density

In comparison the results obtained during my production indicated that wheat had the greater bulk density throughout the phases with the exception of session 1 in phase 1. The literature values show the opposite to be occurring. This discrepancy could be due to the differences in the pre-treatment of the grains before feeding or to use of a twin screw machine versus a single-screw machine. The bulk densities however show a similar values for rice and maize which is also indicated in my results. This perhaps indicating that both rice and maize act similarly during the expansion phase of extrusion. Again the literature values show a difference between the single-screw, single phase produced extrudates and the product produced giving these results. The literature values are higher than those obtained from these extrudates. Again this could be due to the pre-treatment of the grains, the type of extruder used or the method in which the bulk density was calculated (Saleh, Zhang et al. 2013).

Protein content

The literature protein content for brown rice is 7.9%, maize is 9.2% and 11.6% for wheat (Saleh, Zhang et al. 2013). Referring to Figure 38, the experimental protein content for the grains used in this thesis were 7.0% for brown rice and 9% for maize and just under 12.0% for wheat. These experimental values matched closely with the literature values.

For the chemical composition analysis results obtained in this thesis compared with the literature values mentioned above, they were all very close to the published literature values.

The protein gluten plays a major role in strength and elasticity of many food items that contain it. It is found primarily in wheat (Wieser 2007) which therefore indicates that the greater the amount of wheat in a product, the greater the gluten content.

In baked products gluten plays an important role in the structure building of the product. Gluten content affects the elastic of dough will be as well as the ability to capture gas produced during fermentation and baking. Gluten free products tend to suffer from being rather dense as gluten is replaced commonly with hydrocolloids. With the exception of xanthan, many hydrocolloids cannot provide the same structural abilities that gluten provides (Lazaridou and Duta, D. 2007)

The strength baked products is dependent on structural forming proteins. If the product does not contain any natural gluten and has not had any additional replacements added the final structure would be relatively weak and dense. The experiments carried out in this study have appeared to show this trend. The extrudates with higher protein levels have shown certain patterns in the triple bend results.

Summary of thesis

The initial phase of this thesis indicated that there was a significant correlation between the screw speed and the nose temperature of the extruder. Apart from this finding there was little other significant data to take from the experiments. Phase 2 of the thesis provided base data to indicate that the inclusion of two or more different grains could possibly have enormous effects of the final extrudate, however there was not enough evidence produced to confirm any findings and thus would need further study if significant data was to be produced. As with Phase 1, Phase 2 also showed little significant differences between the grains as well as between phases. Although the data for mixed grain extrudates is not enough to draw any clear cut conclusions there does appear to some sort of interaction occurring. In the case of bulk density the addition of amaranth appears hinder the bulk density of the extrudate. This may be due to the amaranth having an effect on the expansion of the maize. Experiments have shown that the addition of amaranth to the extrusion process can decrease expansion due to their high fat content (Ilo and Liu et al. 1999).

In Phase 3 more control was available over the extruder that is to say that the individual runs produced by the machine where consistent with variables being controlled. This produced results that could be more confidently analysed and this showed in the results. Phase three indicated that in most cases there was statistical evidence to suggest that the nose temperature had a significant effect on the extrudates.

I believe the proposed hypothesis, the versatility of this single phase extruder, can be accepted. When the results obtained were compared to those of commercial style extruders and those from other research, it has been found to be quite similar in several aspects. These include bulk density, protein content and fat content. In phase three of the experiment consistent results were obtained from an extruder that had a set configuration and no variation in mechanical and operating terms other than those requested meaning a more controlled experiment could take place. Clear patterns were beginning to emerge in regards to the effect of nose temperature and the texture or the extrudates; I believe with more research this extruder would be capable of producing constant products with a variety of grains. .

Limitations were discovered that were expected, as stated in the introduction, these consist of a lower production rate in comparison to commercial machinery, 7.8kg h^{-1} against over 1000kg h^{-1}, and the pre treatment of the raw materials. Large companies however are looking into small scale extruders with low production rates for various reasons. An example of this is NASA's desire to produce a small scale extruder capable of producing only 2.4kg per day for future long duration mission such as travelling to Mars (Penner, A. L. 2008).

The research done during this thesis has provided a good base data that can be built on in further research. Data produced from this research has shown that extrusion using a single phase power supply could be possible. Although no sensory experiments were carried out during this thesis, many of the results indicate well cooked products that could possibly be consumable. This research has shown that this single phase extruder can produce the simplest form of ready-to-eat snacks that are comparable in several aspects to those produced on larger and more complex machines which can be seen in the literature comparisons.

Appendix


millbank.FOOD
millbank@oxenton.com
ShrimpRice 75gm
Ingredients:- Rice, Dried Shrimp, Garlic, Onion, Chili, Salt, Citric Acid
Manufactured: 20.8.2014


millbank.FOOD
millbank@oxenton.com
ShrimpCorn 100gm
Ingredients:- Corn, Dried Shrimp, Garlic, Onion, Chili, Salt, Cumin, Coriander, Citric Acid
Manufactured: 20.8.2014


Date 20/12/13
Ingredient Product
Moisture content
Production Capacity
Power Consumption
Shaft Speed
Liner Nose Temp

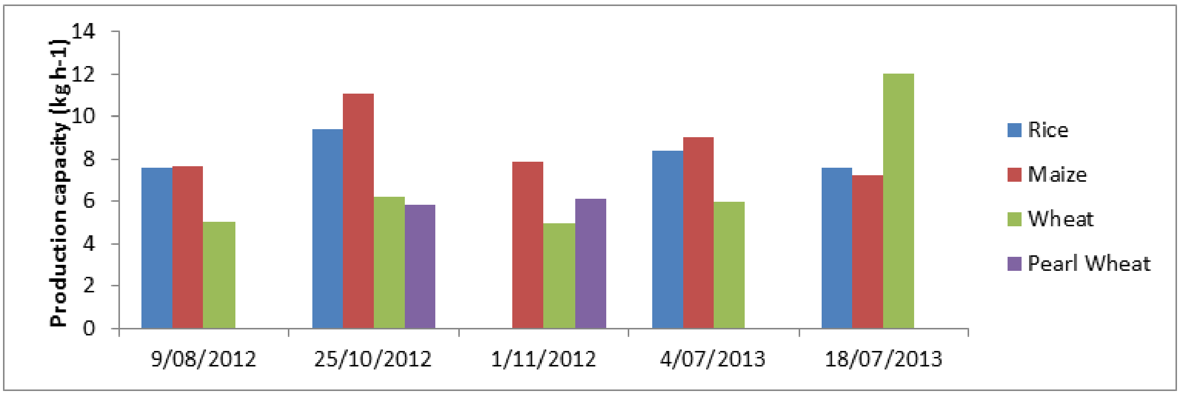

Wholegrain
Natural Foods
Sweet Cinnamon Rice 100gm
Manufactured: 5.9.2014
millbank@oxenton.com


Date 26.2.2014 Goji
Base Ingredient & %
Flavour Ingredient & %
Goji Berries
Star Anise
Sugar Pearls
Citric Acid
Shaft Speed
Liner Nose Temp

Figure 46 Ranges of extrudates produced, varied in shapes and colours

Appendix

Production capacity



One-way ANOVA production capacity : Rice, Maize, Wheat, Pearl Wheat

Source	DF	SS	MS	F	P
Factor	3	10.61	3.54	0.70	0.575
Error	9	45.43	5.05		
Total	12	56.03			

S = 2.247   R-Sq = 18.93%   R-Sq(adj) = 0.00%

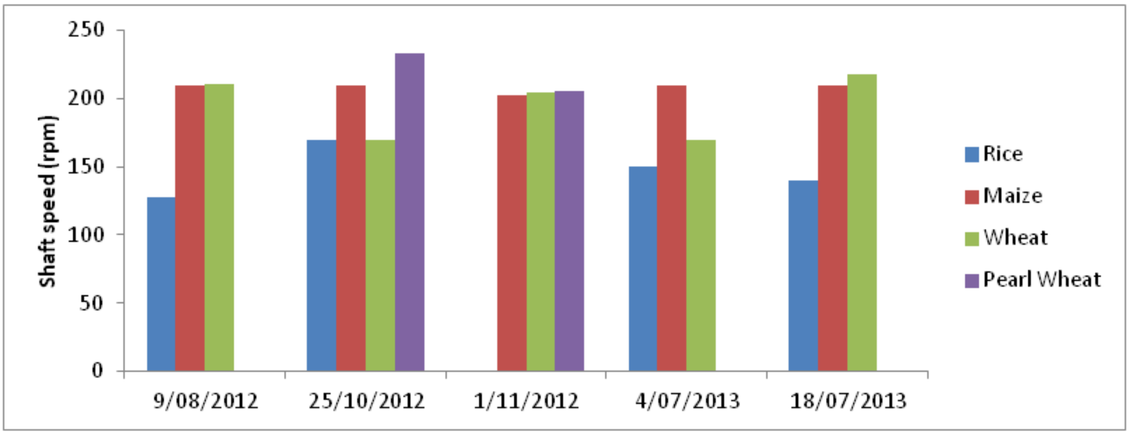
```
                                    Individual 95% CIs For Mean Based on Pooled StDev
Level         N   Mean  StDev    +---------+---------+---------+---------
Rice          3  8.197  1.060               (-----------*-----------)
Maize         4  8.470  1.778                  (---------*---------)
Wheat         4  7.045  3.350            (---------*---------)
Pearl Wheat   2  5.975  0.191    (-------------*-------------)
                                 +---------+---------+---------+---------
                                2.5       5.0       7.5      10.0
```

Current

One-way ANOVA current : Rice, Maize, Wheat, Pearl Wheat

```
Source  DF     SS    MS     F      P
Factor   3   4.49  1.50  1.49  0.282
Error    9   9.02  1.00
Total   12  13.51

S = 1.001   R-Sq = 33.22%   R-Sq(adj) = 10.96%


                              Individual 95% CIs For Mean Based on Pooled StDev
Level         N   Mean  StDev   +---------+---------+---------+---------
Rice          3  7.017  1.351                     (----------*----------)
Maize         4  5.800  0.529            (---------*---------)
Wheat         4  6.005  1.223              (---------*---------)
Pearl Wheat   2  5.205  0.219   (------------*-------------)
                                +---------+---------+---------+---------
                              3.6       4.8       6.0       7.2
```

Shaft speed



One-way ANOVA shaft speed : Rice, Maize, Wheat, Pearl Wheat

Source	DF	SS	MS	F	P
Factor	3	9119	3040	10.00	0.003
Error	9	2735	304		
Total	12	11854			

S = 17.43   R-Sq = 76.93%   R-Sq(adj) = 69.24%

```
                               Individual 95% CIs For Mean Based on
                               Pooled StDev
Level        N    Mean  StDev  -----+---------+---------+---------+----
Rice         3  146.00  21.63  (------*-----)
Maize        4  208.00   4.00                    (----*-----)
Wheat        4  200.75  21.28                  (----*-----)
Pearl Wheat  2  219.00  19.80                     (-------*-------)
                               -----+---------+---------+---------+----
                                  140       175       210       245
```

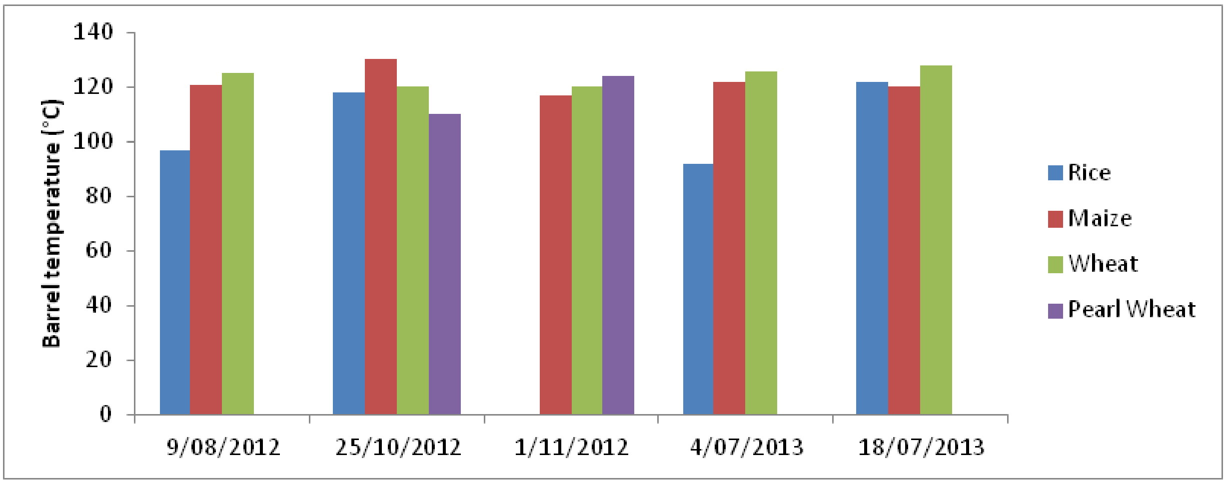
One-way ANOVA shaft speed : Maize, Wheat, Pearl Wheat

Source	DF	SS	MS	F	P
Factor	2	447	224	0.87	0.460
Error	7	1799	257		
Total	9	2246			

S = 16.03   R-Sq = 19.92%   R-Sq(adj) = 0.00%

```
                               Individual 95% CIs For Mean Based on
                               Pooled StDev
Level        N    Mean  StDev  ---------+---------+---------+---------+
Maize        4  208.00   4.00      (--------*--------)
Wheat        4  200.75  21.28  (---------*---------)
Pearl Wheat  2  219.00  19.80       (-------------*------------)
                               ---------+---------+---------+---------+
                                      200       220       240       260
```

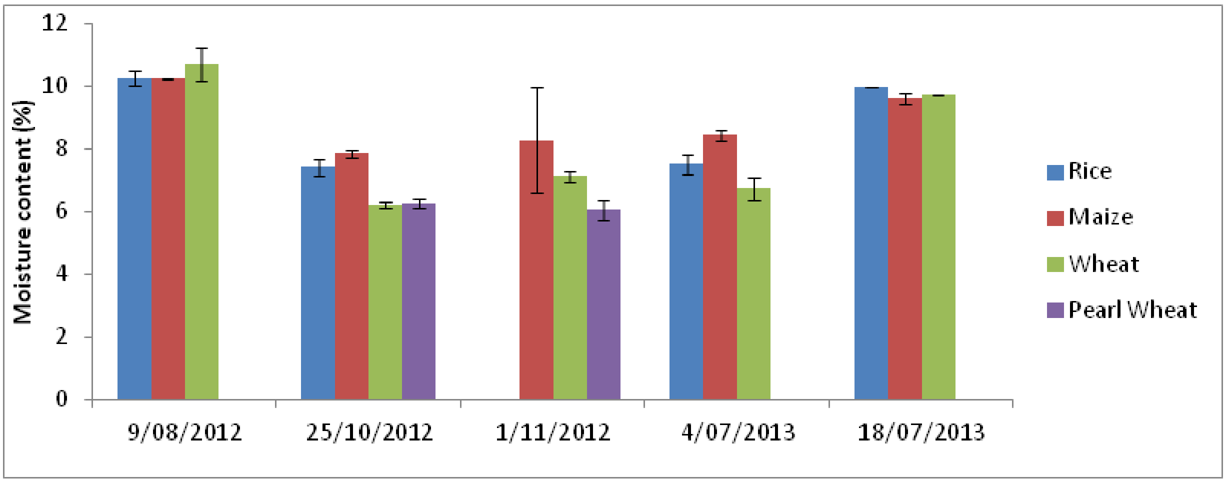
Barrel temperature



One-way ANOVA barrel temperature : Rice, Maize, Wheat, Pearl Wheat

```
Source  DF     SS    MS     F      P
Factor   3  247.7  82.6  1.24  0.351
Error    9  599.4  66.6
Total   12  847.1

S = 8.161   R-Sq = 29.24%   R-Sq(adj) = 5.65%


                               Individual 95% CIs For Mean Based on
                               Pooled StDev
Level        N    Mean  StDev   ---+---------+---------+---------+------
Rice         3  112.33  13.43   (------------*-------------)
Maize        4  122.00   5.60                (-----------*-----------)
Wheat        4  123.25   3.95                  (-----------*-----------)
Pearl Wheat  2  117.00   9.90      (---------------*----------------)
                                ---+---------+---------+---------+------
                               104.0     112.0     120.0     128.0
```

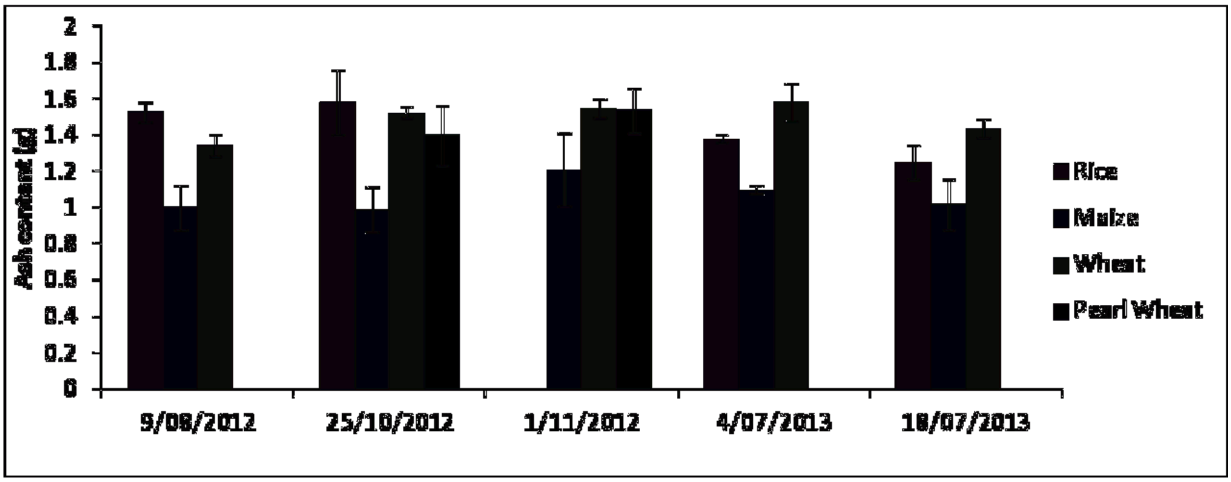
Moisture



One-way ANOVA moisture : Rice, Maize, Wheat, Pearl Wheat

```
Source  DF     SS    MS     F      P
Factor   3  13.42  4.47  1.81  0.216
Error    9  22.25  2.47
Total   12  35.67

S = 1.572   R-Sq = 37.62%   R-Sq(adj) = 16.83%


                              Individual 95% CIs For Mean Based on
                              Pooled StDev
Level        N   Mean  StDev  --+---------+---------+---------+-------
Rice         3  9.200  1.565                   (---------*---------)
Maize        4  8.987  1.122                   (--------*--------)
Wheat        4  8.422  2.125                (--------*--------)
Pearl Wheat  2  6.150  0.156  (------------*-----------)
                              --+---------+---------+---------+-------
                              4.0       6.0       8.0      10.0
```

Ash content



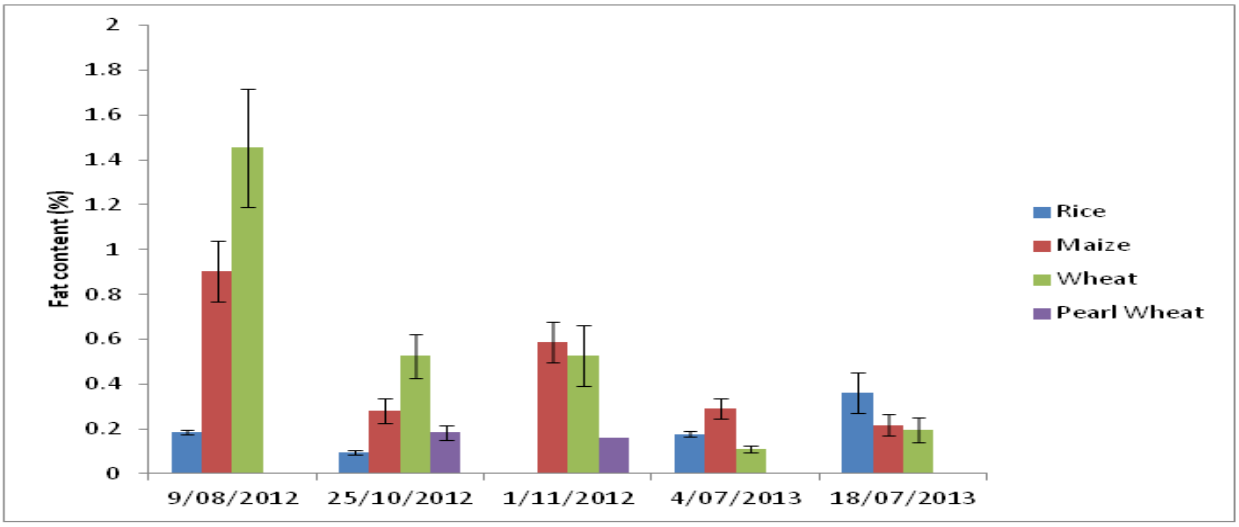
One-way ANOVA ash content: Rice, Maize, Wheat, Pearl Wheat

```
Source  DF      SS      MS      F      P
Factor   3  0.4560  0.1520  10.40  0.003
Error    9  0.1316  0.0146
Total   12  0.5876

S = 0.1209   R-Sq = 77.61%   R-Sq(adj) = 70.15%


                                Individual 95% CIs For Mean Based on
                                Pooled StDev
Level        N    Mean   StDev  ----+---------+---------+---------+-----
Rice         3  1.4527  0.1774                     (-------*-------)
Maize        4  1.0550  0.1041  (------*------)
Wheat        4  1.4635  0.0946                      (------*------)
Pearl Wheat  2  1.4670  0.0962                    (--------*---------)
                                ----+---------+---------+---------+-----
                                  1.00      1.20      1.40      1.60
```

One-way ANOVA ash content : Rice, Wheat, Pearl Wheat

```
Source  DF      SS      MS     F      P
Factor   2  0.0003  0.0002  0.01  0.991
Error    6  0.0991  0.0165
Total    8  0.0994

S = 0.1285   R-Sq = 0.31%   R-Sq(adj) = 0.00%


                                Individual 95% CIs For Mean Based on
                                Pooled StDev
Level        N    Mean   StDev  ------+---------+---------+---------+---
Rice         3  1.4527  0.1774    (--------------*---------------)
Wheat        4  1.4635  0.0946       (------------*-------------)
Pearl Wheat  2  1.4670  0.0962  (-----------------*------------------)
                                ------+---------+---------+---------+---
                                    1.32      1.44      1.56      1.68
```

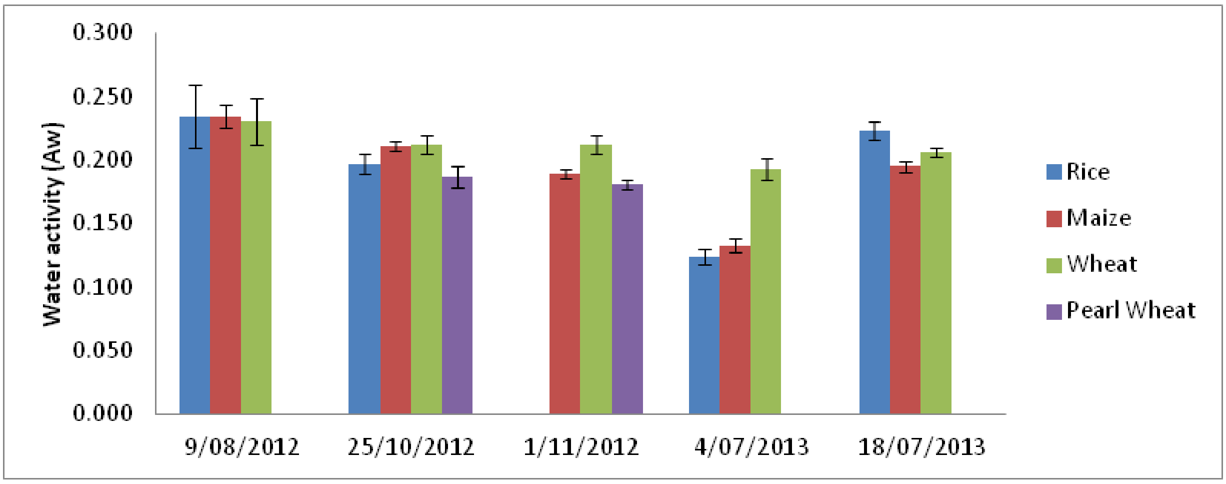
Fat



One-way ANOVA fat : Rice, Maize, Wheat, Pearl Wheat

```
Source  DF     SS     MS     F      P
Factor   3  0.532  0.177  1.31  0.329
Error    9  1.215  0.135
Total   12  1.747

S = 0.3674   R-Sq = 30.46%   R-Sq(adj) = 7.29%


Level        N    Mean   StDev
Rice         3  0.2133  0.1348
Maize        4  0.4975  0.3153
Wheat        4  0.6750  0.5416
Pearl Wheat  2  0.1715  0.0177

             Individual 95% CIs For Mean Based on Pooled StDev
Level           +---------+---------+---------+---------
Rice               (------------*------------)
Maize                       (----------*----------)
Wheat                           (-----------*---------)
Pearl Wheat     (-------------*--------------)
                +---------+---------+---------+---------
             -0.40      0.00      0.40      0.80
```

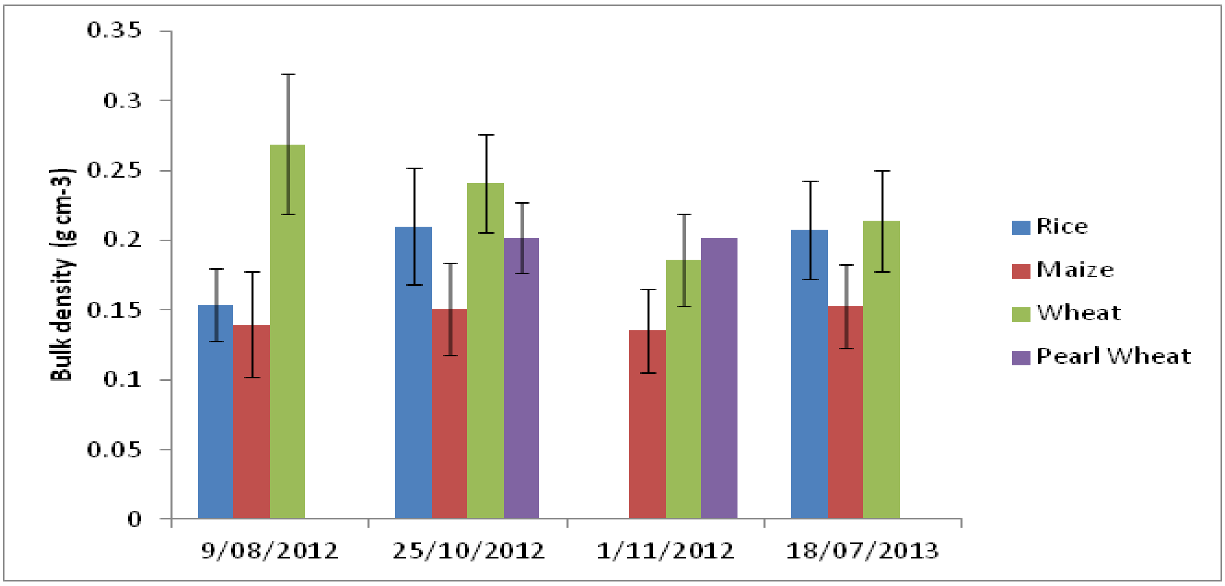
Water activity



One-way ANOVA water activity : Rice, Maize, Wheat, Pearl Wheat

```
Source  DF        SS        MS     F      P
Factor   3  0.001651  0.000550  2.14  0.165
Error    9  0.002309  0.000257
Total   12  0.003960

S = 0.01602   R-Sq = 41.69%   R-Sq(adj) = 22.25%


                                  Individual 95% CIs For Mean Based on
                                  Pooled StDev
Level        N     Mean    StDev  -------+---------+---------+---------+--
Rice         3  0.21810  0.01912                  (--------*---------)
Maize        4  0.20736  0.02030               (-------*-------)
Wheat        4  0.21500  0.01039                  (-------*-------)
Pearl Wheat  2  0.18400  0.00424  (-----------*----------)
                                  -------+---------+---------+---------+--
                                       0.175     0.200     0.225     0.250
```

Bulk density

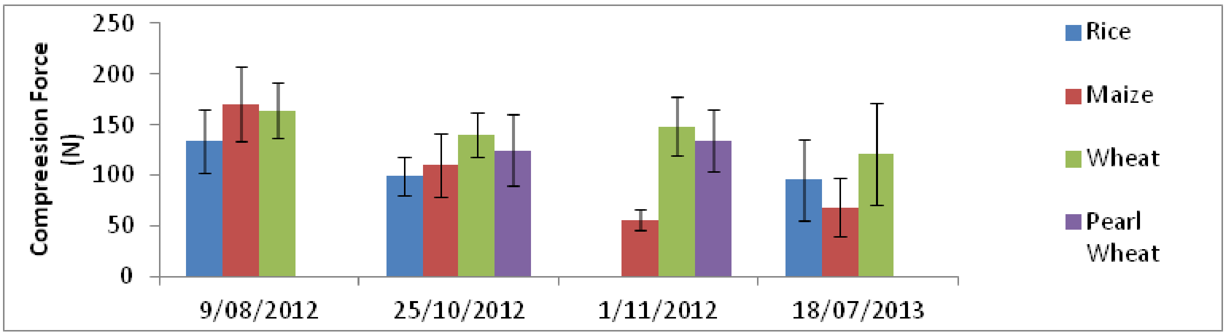


One-way ANOVA bulk density : Rice, Maize, Wheat, Pearl Wheat

```
Source  DF        SS        MS     F      P
Factor   3  0.014066  0.004689  7.00  0.010
Error    9  0.006028  0.000670
Total   12  0.020095

S = 0.02588   R-Sq = 70.00%   R-Sq(adj) = 60.00%


                                  Individual 95% CIs For Mean Based on
                                  Pooled StDev
Level         N     Mean    StDev  -+---------+---------+---------+--------
Rice          3  0.19070  0.03180            (--------*-------)
Maize         4  0.14488  0.00838  (-------*-------)
Wheat         4  0.22758  0.03557                       (------*------)
Pearl Wheat   2  0.20170  0.00000             (---------*----------)
                                   -+---------+---------+---------+--------
                                  0.120     0.160     0.200     0.240

Pooled StDev = 0.02588

Grouping Information Using Tukey Method

              N     Mean  Grouping
Wheat         4  0.22758  A
Pearl Wheat   2  0.20170  A B
Rice          3  0.19070  A B
Maize         4  0.14488    B

Means that do not share a letter are significantly different.


Tukey 95% Simultaneous Confidence Intervals
All Pairwise Comparisons

Individual confidence level = 98.78%
Rice subtracted from:
```

```
                Lower    Center    Upper
Maize        -0.10760  -0.04582  0.01595
Wheat        -0.02490   0.03688  0.09865
Pearl Wheat  -0.06284   0.01100  0.08484

                +---------+---------+---------+---------
Maize                (-------*--------)
Wheat                           (--------*--------)
Pearl Wheat               (----------*---------)
                +---------+---------+---------+---------
             -0.140    -0.070     0.000     0.070


Maize subtracted from:

                Lower   Center    Upper
Wheat         0.02550  0.08270  0.13990
Pearl Wheat  -0.01323  0.05682  0.12688

                +---------+---------+---------+---------
Wheat                                  (-------*-------)
Pearl Wheat                      (---------*---------)
                +---------+---------+---------+---------
             -0.140    -0.070     0.000     0.070


Wheat subtracted from:

                Lower    Center    Upper
Pearl Wheat  -0.09593  -0.02588  0.04418

                +---------+---------+---------+---------
Pearl Wheat           (---------*---------)
                +---------+---------+---------+---------
             -0.140    -0.070     0.000     0.070
```

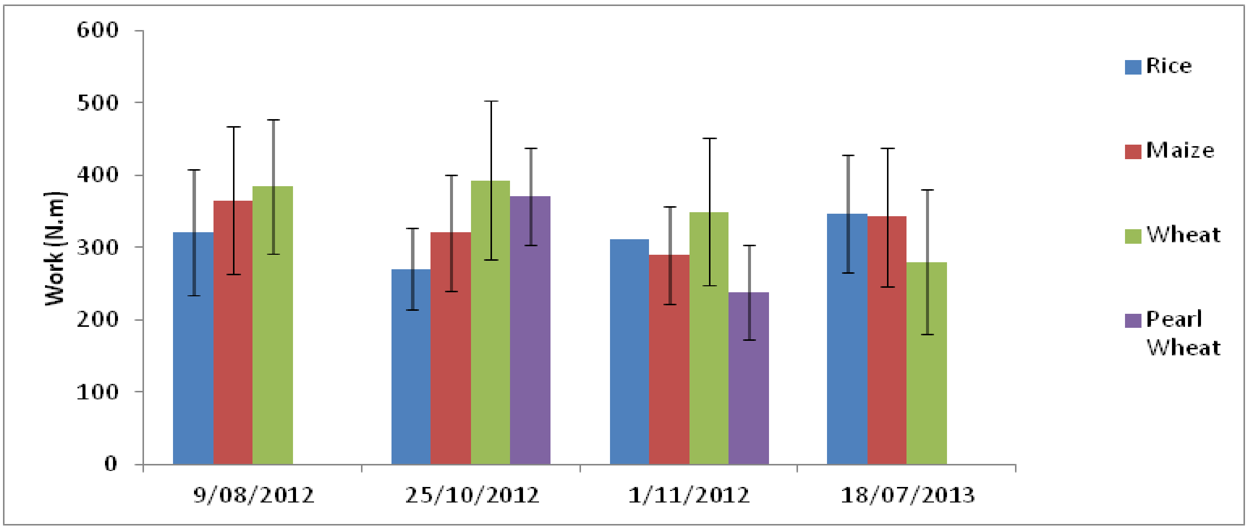
Compression force



One-way ANOVA compression force : Rice, Maize, Wheat, Pearl Wheat

```
Source  DF     SS    MS     F      P
Factor   3   4088  1363  1.23  0.355
Error    9   9988  1110
Total   12  14077

S = 33.31   R-Sq = 29.04%   R-Sq(adj) = 5.39%


                               Individual 95% CIs For Mean Based on
                               Pooled StDev
Level        N    Mean  StDev  ---------+---------+---------+---------+
Rice         3  109.64  21.40   (--------------*-------------)
Maize        4  101.15  51.81  (------------*-----------)
Wheat        4  143.28  17.99                (------------*-----------)
Pearl Wheat  2  129.50   6.86      (-----------------*-----------------)
                               ---------+---------+---------+---------+
                                       90       120       150       180
```

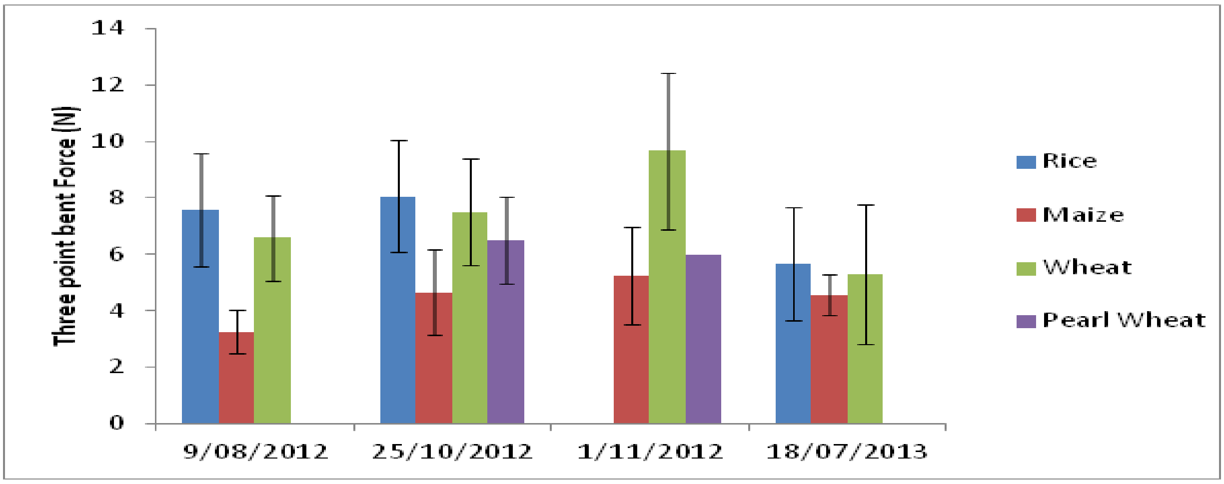
Compression work



One-way ANOVA compression work : Rice, Maize, Wheat, Pearl Wheat

```
Source  DF     SS    MS     F      P
Factor   3   4092  1364  0.54  0.669
Error    9  22919  2547
Total   12  27011

S = 50.46   R-Sq = 15.15%   R-Sq(adj) = 0.00%


                              Individual 95% CIs For Mean Based on
                              Pooled StDev
Level        N    Mean  StDev  -----+---------+---------+---------+----
Rice         3  313.22  39.18      (-------------*-------------)
Maize        4  329.85  32.29            (-----------*-----------)
Wheat        4  352.35  51.37                (-----------*------------)
Pearl Wheat  2  304.90  93.84  (---------------*----------------)
                               -----+---------+---------+---------+----
                                  250       300       350       400
```

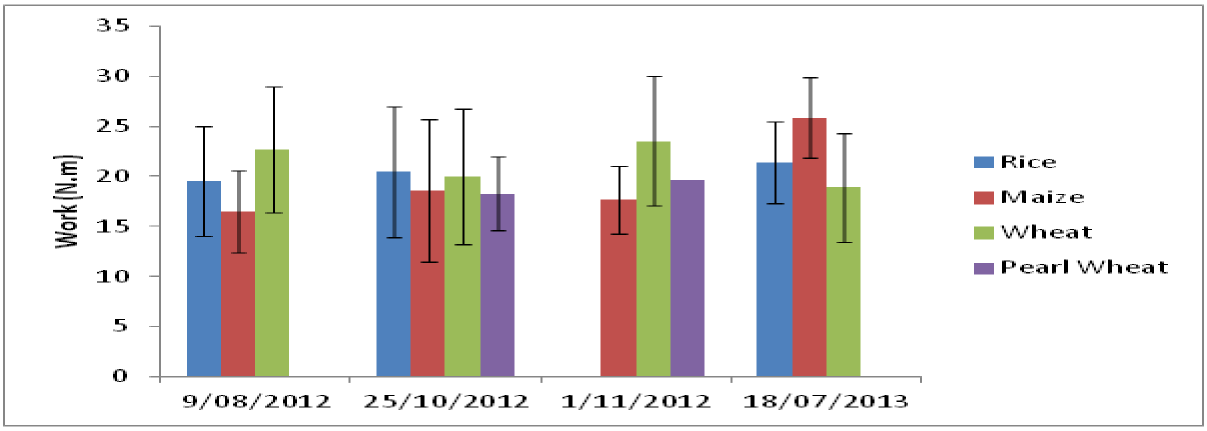
Three point bend force



One-way ANOVA three point bend force : Rice, Maize, Wheat, Pearl Wheat

```
Source  DF     SS    MS     F      P
Factor   3  19.55  6.52  3.78  0.053
Error    9  15.53  1.73
Total   12  35.08

S = 1.313   R-Sq = 55.74%   R-Sq(adj) = 40.99%


                              Individual 95% CIs For Mean Based on Pooled StDev
Level         N   Mean  StDev    +---------+---------+---------+---------
Rice          3  7.105  1.267                    (-----------*-----------)
Maize         4  4.428  0.841    (---------*--------)
Wheat         4  7.264  1.832                       (--------*---------)
Pearl Wheat   2  6.248  0.354            (--------------*--------------)
                                 +---------+---------+---------+---------
                               3.0       4.5       6.0       7.5
```

Three point bend work



One-way ANOVA three point bend work : Rice, Maize, Wheat, Pearl Wheat

```
Source  DF     SS    MS     F      P
Factor   3   8.75  2.92  0.37  0.776
Error    9  70.90  7.88
Total   12  79.65

S = 2.807   R-Sq = 10.99%   R-Sq(adj) = 0.00%


Level        N    Mean  StDev
Rice         3  20.459  0.941
Maize        4  19.680  4.229
Wheat        4  21.262  2.196
Pearl Wheat  2  18.980  1.003

             Individual 95% CIs For Mean Based on Pooled StDev
Level         --+---------+---------+---------+-------
Rice                   (--------------*-------------)
Maize                (-------------*-----------)
Wheat                      (-------------*------------)
Pearl Wheat   (-----------------*-----------------)
              --+---------+---------+---------+-------
             15.0      17.5      20.0      22.5
```

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