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Feed Structure: Effects on physical quality of the feed, chemical status of the feed and nutritional consequence

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ABSTRACT

Two experiments were conducted to study effects of grinding and pelleting on feed structure using either wheat or maize as a base ingredients. In experiment 1, four diets were formulated to contain either completely ground base ingredients using 3 mm and 6 mm screen size in hammer mill or base ingredients were added as whole grain in ration of 30% whole grain 70% ground material. In addition base ingredients were mixed with mineral and vitamin premix to make complete diets. Smaller particles improved pellet durability but replacement of ground ingredients with whole ingredinets increased hardness. Coarse structure of the diets reduced energy consumption when compared with fine structured diets.

In experiment 2, pure wheat and barley were used as ingredients and were ground using either hammer mill fitted with 3 mm sieve or roller mill using 1.5 mm gap between rolls. In addition, a combination of the hammer mill fitted with 3 mm screen and roller mill with the 1.5 mm gap between rolls as a singular method was tested. Higher pellet durability and lower energy consumption was observed for wheat diets when compared to maize diets. Combination of the hammer mill + roller mill showed higher pellet durability for both cereal sources when compared with either hammer mill or roller mill alone.

Larger proportion of the particles smaller than 1.0 mm were found when diets were ground on a hammer mill fitted with 3 mm screen in comparison to hammer mill fitted with 6 mm screen (experiment 1) or roller mill with 1.5 mm roller gap (experiment 2). Roller mill had larger proportion of the particles over 1.6 mm in comparison to either combination of the hammer mill and roller mill or hammer mill alone (experiment 2).

Keywords: durability, hardness, hammer mill, roller mill, pelleting.

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Ljubisa Rakic

1. INTRODUCTION

Feed milling has been dramatically developed in recent years due to increase in animal`s productivity. Different cereals such as maize, wheat, barley, and oats are used in different amounts during feed formulation depending on their nutritive values and processing characteristics. Their nutritive value is significantly affected by the processing condition which leads to changes in chemical composition and physical behaviour of these materials (Tilden, 1995).

Feed processing includes the physical, chemical and/or thermal treatment of a feed prior to consumption by animals. The quality of the raw material used in feed manufacturing, is among the key factors required to produce highly quality feed. This is because, the nutritive value of the feed depends on the chemical composition of the feed ingredients (i.e. maize) used. Nutritive value may be broadly defined as the ability of a feed to provide the nutrients required by an animal for maintenance, growth and reproduction (Corley *et al.*, 1997). It is an indication of the contribution of a feed to the nutrient content of the diet.

Pellets of high physical quality must have properties which give a high nutritional quality for example in terms of higher feed intake and perhaps, improved nutritional value (Skoch *et al.*, 1981a; Skoch *et al.,* 1983). Raw ingredients are ground in order to reduce particle size. Particle size of raw ingredients affects physical pellet quality (Svihus, 2009a). A fine grinding increases the surface area of particles, and thus contributes to an improved binding ability between particles, and thus improves pellet durability. Coarser grinding on the other hand may reduce the amount of fines in the pelleted product and thus potentially reduce transport loss and dust problems in the feed mill and on the farm (Reece *et al.,* 1986). In addition, feeding whole grains or larger particle sizes may improve the health of the bird as well as strongly influence gizzard size and function (Amerah *et al.*, 2008). Nir *et al.* (1995) found that when 1 day old chicks were fed coarse and medium corn particles, gizzard weight increased by 26 to 41% when compared with chicks fed fine particles. Digestion of larger particle sizes is slower within the gizzard and small intestine and increased exposure time of nutrients to digestive enzymes, which in turn may improve energy and nutrient utilization (Nir, 1994; Nir *et al.,* 1995). In pig, pelleted feed compared with mash, resulted in a decreased feed intake of 2%, increased weight gain of about 7% and improved feed utilisation of around 8% (Thomas *et al.*, 1998). Wondra *et al.* (1995) found that pelleting and reduction of the particle size improved growth performance of pigs, but in same time frequency of ulcers was increased.

Animal performance may be increased by thermo-mechanical treatments such us for example steam-pelleting. Processing parameters, ingredient source and level of moisture among other factors influence pellet quality and chemical changes during process the most. Pelleting process have limited possibility to chemically modify starches and possibly other feed components (Skoch *et al*., 1981; Perez and Oliva-Teles, 2002; Zimonja and Svihus, 2009). However, increase in operation temperature and moisture content, may increase level of the starch gelatinisation during pelleting (Skoch *et al*., 1981). Choice of the equipment and screen size during grinding also has strong influence on the chemical changes of the feed components during feed processing (Svihus *et al*., 2004; Svihus *et al*., 2004a).

Two experiments have been conducted to study effects of feed structure (using either hammer mill or roller mil as tools for particle size reduction) on physical pellet quality. In addition, effects of feed structure on chemical status of the main feed components (primarily starch) with aspects of nutritional consequences of the feed quality are described and discussed in this study.

2. LITERATURE REVIEW

Most cereals are processed before being fed to animals (Maier and Gardecki, 1993). Different animal species require different physical properties for their respective feeds. This means, different quality standards are used during feed manufacturing which involves several technological processes such as physical, chemical and thermal processes (Table 1) (Skoch *et al.*, 1983; Thomas *et al.*, 1997; Thomas and van der Poel, 2001).

Table 1. *Overview of common treatment processes for concentrate feeds (Svihus, 2008)*

Mechanical treatment	Thermal treatment	Thermal/mechanical treatment	Chemical treatment
Grinding/rolling	**Drying**	**Pelleting**	Extraction
Squeezing	Boiling	**Expanding**	Non-enzymic browning
Homogenisation	Toasting	**Extrusion**	Formaline treatment
	Micronisation		Enzymatic hydrolysis
	Microwaves		Acid hydrolysis
	Freeze drying		Alkali hydrolysis
	Conditioning		

In general, processing may involve a simple process like a blending in the form of mash or processing can be much more complicated, such as pelleting, crumbling or when an extruder or expander is used (Thomas and Poel van der, 1996; Satoh *et al.*, 1998) (Figure 1).

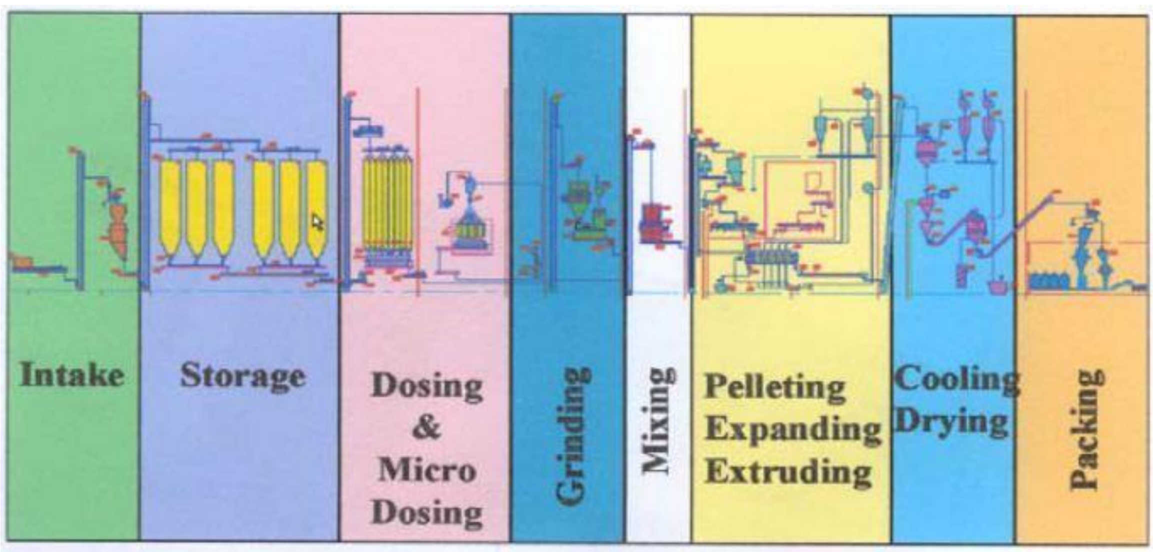

Figure 1. *A Typical Feed Plant.*

Often, they are applied in order to achieve certain specific goals such as gelatinisation of starch, denaturation of protein, inactivation anti-nutritional factors (endogens enzymes, trypsin inhibitors, etc.), drying/cooling and shaping. These chemical changes have a main task to improve nutritional value and increase digestibility of feeds.

2.1. Grinding

Grinding is size reduction the raw ingredients by different of various mill designs, what has consequence reduction particle size, decrease segregation, improve digestion and to facilitate further processes like pelleting or extrusion.

According to Svihus (2009a) causes for grinding can be divided into:

- increasing the surface and thus improve digestion,
- increasing surface and thus improve the binding ability between particles,
- improving mixing of ingredients,
- elimination of germination ability,
- increasing particle homogeneity.

Fineness of grinding depends on factors as a type of grain, moisture content, screen size and flow rate. The most commonly used equipment in grinding process in feed technology is hammer mill and roller mill.

The hammer mill consist the steel hammers or knives and they are fixed to a rotating shaft in chamber. Around the rotor is metal screen which size (hole) depends on the requested particle size, allowing only the right size pass through the screen (Figure 2). The closer distance between the hammers and the screen are the finer grinding of particles one will achieve. The hammers are usually attached to the axis in several rows, 4 to 8 rows are commonly (Svihus, 2009a).

The roller mill consists of a framework that houses the rolls. The rolls are fixed in the frame and they are placed in opposing position and one roll always going faster than other (Figure 3). Roller mills have two or more pair of rolls which crush the material as it passes between the counter-rotating rolls. Roller mills are not as commonly used as hammer mills, but advantages is to reduce energy consumption, reduce noise and uniformity of particle size.

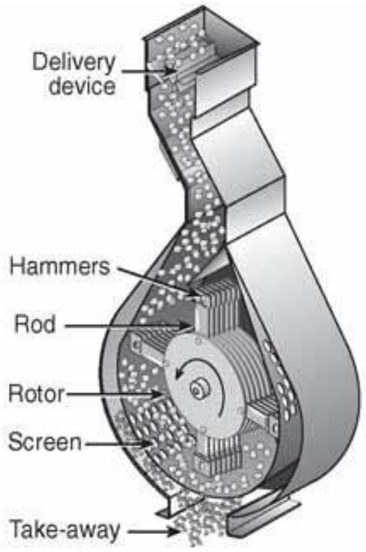

Figure 2. Hammer mill (Svihus, 2009a)

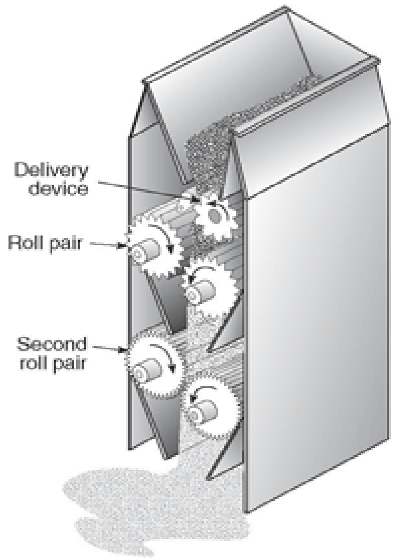

Figure 3. Roller mill (Svihus, 2009a)

2.2. Conditioning

Conditioning is a process where steam is added while the mixed feed ingredients are under constant agitation. The ultimate purpose of conditioning is to pre-heat and moisten the feed such that the pelleting process becomes more lenient. Conditioning can be defined as the process of converting the mixed mash with the use of heat, water, pressure and time to a physical state that facilitates compaction of the feed mash (Skoch *et al.,* 1981).

Conditioning increases production capacity and reduces power consumption during pelleting, and simultaneously affects physical, nutritional and hygienic quality of the produced feed (Skoch *et al.,* 1981a; Moritz *et al.,* 2002).

The steam is added during conditioning in order to assure a complete and homogenous mixing of the water and heat in the steam with the feed ingredients. Retention time in the conditioner is usually less than 20 seconds, though it may be increased to over 60 seconds depending on feeder rate and/or paddle angle. Normally, during conditioning, moisture content of feed mash is increased approximately 4-5 % and feed temperature is heightened to the range of 70-120 °C for a duration of normally 20-30 sec. Higher moisture content achieve during conditioning have lubricating effect, decreasing friction in the die channel, decreasing the specific energy consumption, but also reduce pellet durability.

Usually, a temperature of around 75 °C is achieved during conditioning. During condensation of the steam, a thin film of water is created around the particles, which, together with the temperature increase, facilitates binding between particles (Thomas and Poel van der, 1996). To obtain a specific temperature during conditioning, the rule of thumb is used (0.7 % of water in the form of steam must be added for each 10 °C increase in mash temperature). As temperature reaches the desired temperature, the heat and water affects non-covalent bonds in molecules in the feed mash.

The conditioner usually consists of a cylindrical chamber with a rotating shaft running along the centre where paddles (or picks) which agitate the feed and move it in one direction, are attached (Picture 1).

***Picture 1**. Double shift conditioner*

The increase in conditioning time, increases starch gelatinization, protein denaturation, pathogen reduction, production rate and improved pellet quality (Olkku and Rha, 1978; Briggs *et al.*, 1999; Zimonja and Svihus 2009). Though, other nutrients are lost i.e. vitamins due to high temperature and therefore nutritional loss occurs.

The use of differential scanning calorimeters has shown that maximum 3.5 % of the starch is gelatinised after conditioning of diets based on wheat, while a slightly higher extent of gelatinisation is obtained during conditioning of diets based on oats (Skoch *et al.*, 1983; Yu and Christie 2001). Although, data for denaturation of proteins and solubilisation of fibres are not available, it is reasonable to believe that such non-covalent changes to some extent will occur during conditioning. Thus, the effect of conditioning is that some molecules in the feed mash becomes solubilised and thus contribute to a more sticky feed mash and more liquid flow behaviour of the feed. These altered chemical bonds and the resulting changes in flow properties and stickiness will contribute to binding properties of the feed during the pelleting process. Water may sometimes also be added in the conditioning process since it has been shown that increased water content alone may contribute to a better physical quality of the pellets (Gilpin *et al.*, 2002). Applying too much heat or water, however, will impair production capacity and pellet quality and may lead to plugging of the pellet press (Winowiski, 1985).

Proper conditioning of feeds before pelleting improves pellet durability and reduces amount of fines in the finished product as binding ability of components is assumed to be optimized.
In addition, approximately 40-60% of energy consumption in a feed mill goes on pelleting. Steam addition to the feed mash lowers friction through the die of the pelleting mill or extruder saving energy (Hasting and Higgs, 1978). The effect steam has on the pellet is connected to the feed through liquid-necking (Thomas and van der Poel, 1996), where air, water and the mash are the binding property together.

2.3. Pelleting

The pelleting process is a process where a ground mix of feed ingredients is being forced through a thick metal plate containing cylindrical holes, a so-called die (Figure 5). A majority of pellet presses operated in the feed manufacturing are of the ring design. Different designs exist in which usually two or three rollers are used (Figure 4). In the most designs the die revolves around the fixed rollers. The feed is forced through the die due to the pressure caused by rolls which roll along the inner surface of the die. The die can either be ring-formed or flat, and the thickness of the plate is usually between 45 and 70 mm, while the diameter of the holes may vary between 1 and 20 mm. As feed is forced through the holes, the resulting pressure combined with the temperature increase as a consequence of friction between the feed and the metal and between different metal parts, will result in chemical changes that cause the feed particles to be glued together.

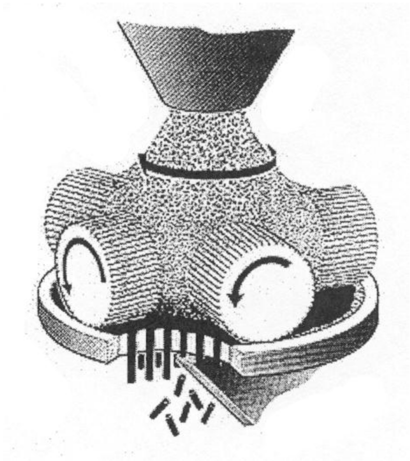

Figure 4. *Pellet rollers (Svihus, 2009)*

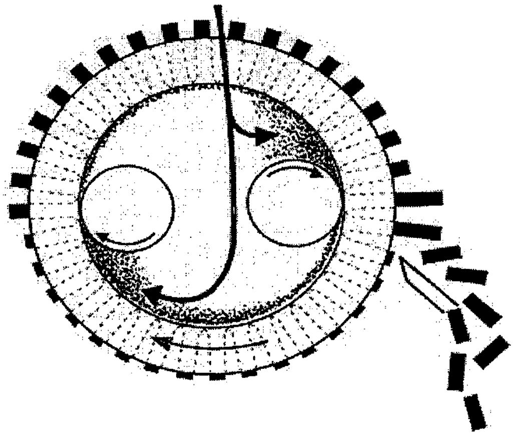

Figure 5. Pellet die(Svihus, 2009)

Pelleting is not the sum of conditioning, pelleting and cooling steps, but should be considered as an integral system which performance is dependent on interrelations between the three unit operations: conditioning, pelleting and cooling (Thomas and van der Poel, 1996).

The process improves the following performance (Behnke, 1994):

1. Decreased feed wastage,
2. Reduced selective feeding,
3. Decreased ingredient segregation,
4. Destruction of pathogenic organisms,
5. Thermal modification of starch and protein,
6. Improved palatability.

2.4. Extrusion

According to Sørensen (2006), extrusion is stronger conditioning that ensures complete gelatinization allowing more moisture and heat into the system compared to pelleting. Extrusion is a process by which moistened, expansible, starchy and /or pertinacious materials are plasticized in a tube by a combination of moisture, heat and mechanical shear. This results in an elevated product temperature and pressure within the tube, gelatinization of starch components, denaturisation of proteins, stretching or restructuring of tactile components and the exothermic expansion of the extruded material within seconds.

This process is mainly used for production of fish or pet food. Normally, when the mash enters the extruder it is driven towards the die by one or two screws. After the mash has gone through the die in the extruder, the pellet is porous and by vacuum coating addition of fat directly into the pores of the pellet is possible (Jozin, 2008). This can be mentioned as one of the positive effect of the extrusion process since it allows addition of fat and vitamins in the pellets and therefore increasing nutritional value of the feed produced.

Extruder barrel (Figure 6) can be divided on tree different zones (Rokey, 2000):

- Feeding zone (moistening and preheating of feed mash),
- Kneading zone (transition of the fed mash to a plasticized dough-like mass) and
- Cooking zone.

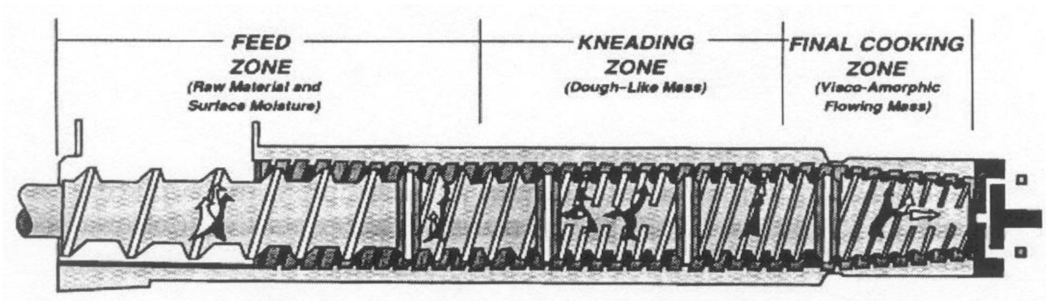

***Figure 6**. The figure is showing three principal different regions on the screw (Rokey, 2000)*

The advantages of extrusion process compared to pelleting is an increase of temperature (90°C -160°C), increased fat addition (30% or more), increased gelatinisation of starch (70% to 95%), low dust quantities, a better sterilization of the feed (high temperatures ≥90°C), and an improved pellet quality. Disadvantages extrusion process is big energy consumption (compared with other processes) and more expensive (compared to pelleting for example). Other negative effects include reduced the protein degradation and loss of heat labile components such as vitamins and enzymes.

However, moderate heat treatment may improve the nutritive value of ingredients, especially ingredients of vegetable origin. Extrusion process also has a pre-conditioner, which is a chamber either atmospheric or pressurized, where feed ingredients are uniformly moistened and heated by contact with water or live steam before entering in extruder. The purpose of pre-conditioning is to add moisture and heat to the feed mash in order to soften the particle and start gelatinisation of starch and denaturation of protein (Strahm, 2000).

2.5. Effect of processing

Effect(s) of processing depends on chemical composition of the raw material used, temperature applied, steam applied, and retention time. Many processes involve increase of temperature and addition of water (usually in the form of steam). This results in physical and chemical changes of the feed ingredients such as particle size and molecular structure of feed components, which may both increase and decrease the nutritional value of the feed (Dellavalle *et al.,* 1994; Medel *et al.,* 2004).

Normally, processes are used to reach some specific objectives like reduction of dustiness, improvement of handling, conveying or nutritional safety, but one of the main issues is to improve the nutritional value of the feeds (Skoch *et al.,* 1983; Ziggers, 2001). The consequences of these processes on the average daily gain (ADG) and the feed conversion ratio (FCR) are known, and it is widely accepted, for example both pelleting and particle size reduction generally improve FCR and pelleting may increase ADG (Wondra *et al.*, 1995).

During processing the reduction of particle size improve digestibility of carbohydrates and proteins in pig diets (Wondra *et al.*, 1995). This effect may be partly explained by the feedstuff fragmentation which increasing the surface area exposed for enzymatic attacks. For example, starch is more sensitive to hydrolysis when particle size is decreased (Champ and Colonna, 1993). In additional, availability and digestibility of wheat protein is improved when the particle size is decreased due to the disruption of aleurone cells (Saunders *et al.,* 1969) and therefore liberation of its protein contents.

Conversely, higher shearing forces and hydrothermal pressures applied during processing result in much higher temperature, though for a very short period of time, especially during the passage in the die. This affects on protein utilisation (Ludovic *et al.*, 2004). However, on the other hand it positively disrupts cell walls and structures of high fibre content material

(Saunders *et al.,* 1969), and influence the solubility and degradability of fibre components (Björck *et al.,* 1984).

Experiments have shown that, starch is to a small extent gelatinised during pelleting. The extent of gelatinisation depends upon the starch source. For example, starch from oats is easier to gelatinise than wheat maize and barley (Tester and Karkalas, 1996; Hoover *et al.*, 2003). However, even within cereal source, extent of gelatinisation varies. The extrusion process to a large extent results in a total gelatinisation of the starch due to higher water content, heat and frictional forces. Though, this is an advantage when the extrusion process is used for carnivorous animals i.e. salmon fish.

For both starch and proteins, the breakage of the tri-dimensional structure (denaturation of proteins and gelatinisation of starch) increases nutrients availability (Goelemal *et al.*, 1999). This is because the protein and starch molecules become more interspersed in water and therefore easier broken down by enzymes. Though, for proteins the effect may be small under practical conditions due to the fact that most proteins are quite easily broken down even when consumed in the native form (Gressley and Armentano, 2007). A larger challenge is the formations of new covalent bonds during processing which may reduce protein digestibility.

2.6. Chemical changes during feed processing

The two most important feed components that are modified during processing of feeds are starch and proteins. Both components are characterized by being very large molecules with a sophisticated three-dimensional structure held together by a large amount of covalent bonds as shown in figure 7 and 8 below. These molecules are also characterized by not having one common structure, but a huge number of different possible configurations. This is particularly true for proteins, because of the variety of amino acids that they can be composed of.

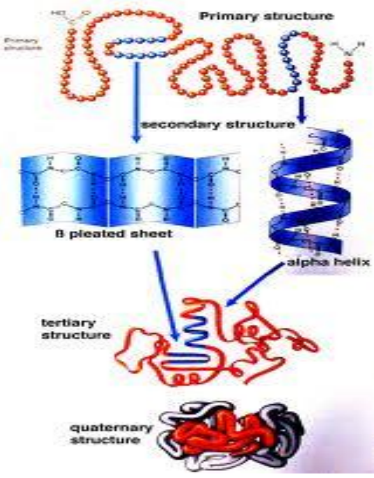

Figure 7. *Three-dimensional structure of the protein*

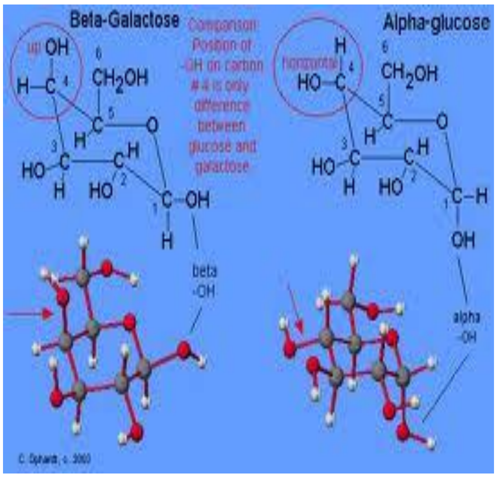

Figure 8. *Three-dimensional structure of a starch*

Protein denaturation occurs during pelleting, extrusion and sometimes even during pre-treatment of the raw material (Jasim *et al.*, 2008). According to Svihus *et al.* (2004), pelleting improve efficiency animal feeding and convenience during feed handling, to mention but few. The improvement in the performance of animals consuming pellets is attributed to the combined effect of moisture, heat, and pressure in making starch gelatinization and protein denaturation.

2.7. Protein structure and protein denaturation

Protein is among the most abundant nutrient in pelleted feeds due to the changes which occur in proteins during the pelleting process (Ludovic *et al.*, 2004). Proteins, as naturally occurring polymers found in all living cells, are composed of amino acids linked together by peptide bonds (Hoseney, 1994).

These amino acids are absorbed and assembled into body proteins which are used in the construction of body tissue (muscles, nerves, skin and feathers). Dietary crude protein levels do not indicate the quality of the proteins in a feed, protein quality is based on the presence and balance of essential amino acids in the feed ingredients. The nutritional value of protein depends of level and availability essential amino acids (Table 2) and digestibility of the protein.

Table 2. *Composition(%) (amino acids) of the feed ingrdients(Mydland, 2010).*

Item	Corn	Barley	Wheat	SBM[a]	CM[b]
Dry matter	83.30	86.50	84.50	87.40	89.10
Crude protein	7.50	8.50	10.80	43.30	31.40
Ash	1.02	1.54	1.99	6.10	6.40
Indispensable amino acids					
Arginine	0.40	0.45	0.57	3.55	2.19
Histidine	0.24	0.20	0.27	1.30	0.98
Isoleucine	0.29	0.29	0.37	2.13	1.32
Leucine	1.07	0.58	0.74	3.74	2.48
Lysine	0.24	0.35	0.35	3.05	2.05
Methionine	0.18	0.15	0.21	0.68	0.70
Phenylalanine	0.43	0.40	0.49	2.47	1.44
Threonine	0.30	0.29	0.33	1.91	1.55
Tryptophan	0.07	0.09	0.12	0.65	0.47
Valine	0.40	0.46	0.52	2.30	1.80
Dispensable amino acids					
Alanine	0.64	0.38	0.42	2.12	1.59
Aspartate	0.52	0.56	0.58	5.43	2.57
Cysteine	0.19	0.20	0.30	0.73	0.85
Glycine	0.33	0.39	0.49	2.04	1.82
Glutamate	1.57	1.72	2.92	8.66	5.82
Proline	0.72	0.81	1.04	2.55	2.14
Serine	0.39	0.32	0.44	2.36	1.52
Tyrosine	0.28	0.22	0.27	1.75	1.02

All amino acids have a carboxyl and amino group. A sequence of amino acids linked together with peptide bonds is called primary structure of polypeptide chain.

The secondary structure is conformation of the polypeptide chain due to different angles of the peptide bonds caused by the polar characters and formation of hydrogen bonds between side chains of the amino acids. The conformation of polypeptide chain can be regular, forming £-helix or β-pleated sheet.

Polypeptide linkages between these three conformations are described as turns and loops and they are changing direction of polypeptide chain, thus making side groups of amino acids interacting trough hydrogen bonds, salt bridges, disulphide bonds, and hydrophobic interactions (Mathews and van Holde, 1996**)**. This structure is known as tertiary structure of the protein.

The quaternary structure is described as aggregates, which contain two or more polypeptide chains bonded with same bonds as in tertiary structure (Mathews and van Holde, 1996).

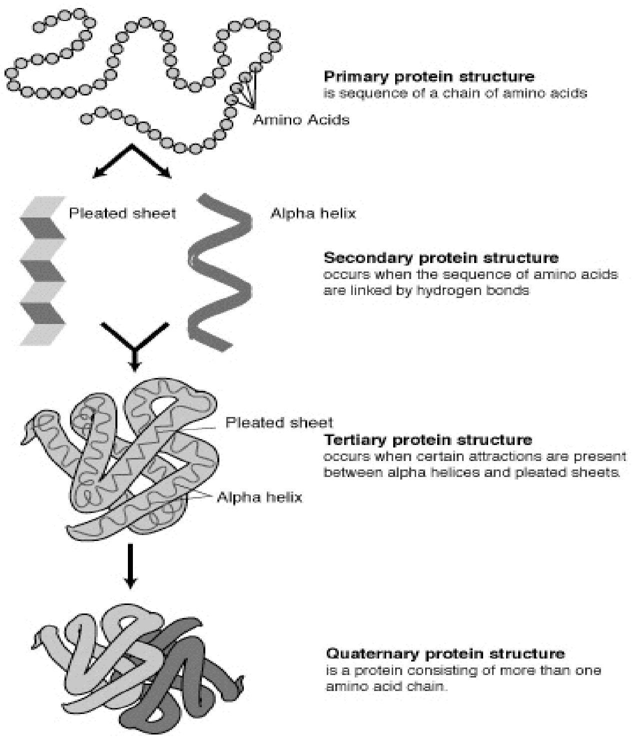

Figure 9. *Protein structure: primary, secondary, tertiary and quaternary.*

Normally, proteins are known to respond easily to heat when water is present, this changing their tri-dimensional structure and thus their physical behaviour.

Process with the breakdown of the three-dimensional structure of the proteins (the secondary, tertiary and quarterly structures), without breaking the primary structure is called denaturation of the protein (Figure 10).

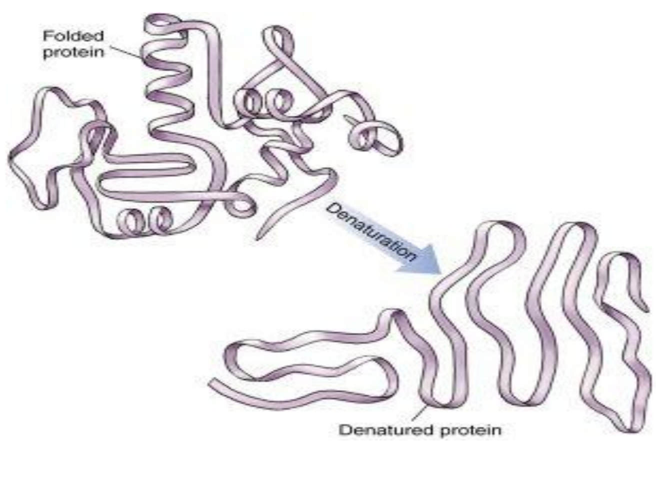

Figure 10. *Protein denaturation*

Heat processing significantly affects the digestibility of a protein due to the changes which occur in covalent bond. A moderate heat is enough for the protein denaturation to occur due to the modification of tertiary structure. During denaturation process, the physical and chemical properties of protein are changing (Leontine, 2000; Zhi-Sheng *et al.*, 2004).

In many proteins (unlike egg whites), denaturation is reversible (the proteins can regain their native state when the denaturing influence is removed) (Campbell *et al.*, 2008). This process can be called renaturation (Figure 11).

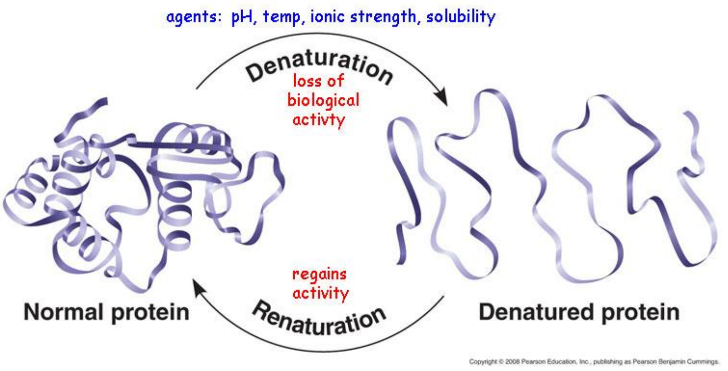

Figure 11. *Renaturation of the protein*

Proteins from different origins require different temperatures for denaturation. The denaturation temperatures is usually around 100°C (depend of the water content) but some ingredients have a higher/lower denaturation temperature, like sunflower between 120-190°C or wheat gluten protein are starting denaturation at room temperature and moisture content of 16%.

2.8. Negative effect of the high temperature

2.8.1. Degradation

Under severe and/or prolonged heating, protein denaturation may by followed by association and disassociation reactions, which ultimately may result in destruction of primary structure, often referred to as a degradation of the protein (Finley, 1989).

Degradation of proteins, reduce utilization of the protein and nutritional quality. Table 3 shows the influence mild heat treatment on change of the protein and a more extreme form of heating cause destruction of the primary structure.

Table 3. *Effect of heat treatment on denaturation and degradation of protein (Finley, 1989)*

Temperature, °C	Effect of heating
≤ 50	Increase hydration, some loss of crystalline structure
70-80	Disulfide splitting, loss of tertiary structure
80-90	Loss of secondary structure disulfides
90-100	Intermolecular disulfides formed
100-150	Lysine and serine loss, isopeptide formation
150-200	Peptidization and more isopeptide formation
200-250	Pyrolysis of all amino acid residues

2.8.2. Maillard reaction

The essential amino acids such as lysine, methionine, cysteine and tryptophan are very sensitive to destroy. The Maillard reaction is reactions between reducing sugars (fructose, glucose and pentose) and free amino groups from amino acids, lysine in particular.

During feed manufacturing processes (extrusion), Maillard reactions are favoured by increasing temperature (≥ 180°C) and low moisture content with low moisture (≤ 15%). It can be assumed that available lysine would be higher with increased screw speed or decreased retention time in the barrel.

Due to the formation of Maillard products, the utilization of protein and perhaps carbohydrates may be reduced. Nutritional quality is loss due to destruction in essential amino acids and decreased digestibility.

The products of Maillard reactions are inaccessible for digestibility (enzymatic degradation). Digestive enzymes are unable to hydrolyse amino acid linkages caused by these reactions and thus excretion of peptide fragments occurs in the faeces.

2.9. Starch structure and starch gelatinisation

Starch is a carbohydrate, consisting of a large number of glucose units linked together by glycoside bonds.

The starch granules are made up by essential linear polysaccharide-amylose and a highly branched polysaccharide-amylopectin. Branched amylopectin molecules give viscosity, amylose molecules contribute to gel formation. This is because the linear chains can orient parallel to each other, moving close enough together to bond.

The ration between amylose and amylopectin is different between starches but a typical value for a starch is 25 % amylose and 75 % amylopectin.

Amylose is a linear molecule, composed of (1-4) linked £-D-glucose units (Figure 12). The level of amylose and molecular weight vary between different starch types.

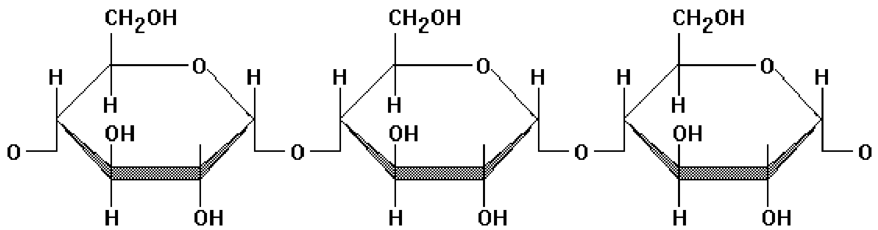

***Figure 12**. Amylose - (1-4) linked £-D-glucose units*

Amylopectin is larger molecule then amylose, made up by £-D-glucose units linked mainly by £-(1-4) linkages (as amylose) but with a greater proportion of £-(1-6) linkages, which gives a large highly branched structure (Figure 13). Amylopectin has a greater molecular weight then amylose.

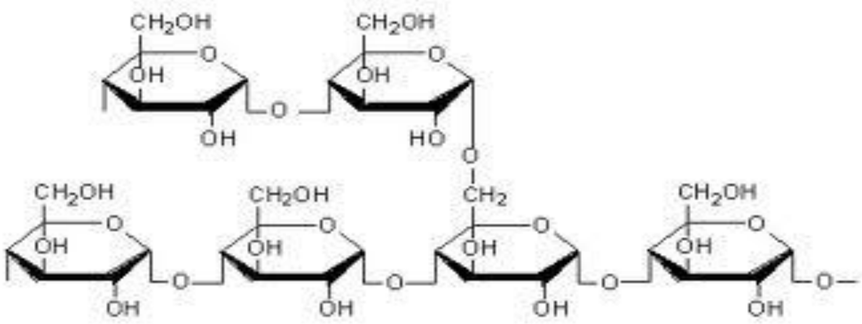

Figure 13. *Branched structure of Amylopectin units- linked by £-(1-4) linkages with£-(1-6) Linkages*

Concentration of starch in cereal grains is different but usually is between 60-75% (Table 4).

Table 4*. The average content of starch in grains (Riaz, 2007).*

Ingredient	Starch [%DM]
Maize	73
Wheat	65
Barley	60
Oats	45
Rice	75

Starch is one of the main binders in feed and is therefore important for the physical quality of the feed. However, native starch does not have any gluing properties. Starch need to be gelatinised before it can act as a binder.

Thermo mechanical processes lead to modification of starch by mechanisms like swelling, gelatinisation and retrogradiation (Zimonja and Svihus, 2009).

With increasing heat starch granules will start to swell. Swelling is caused by water absorption into the granule and this cause disruption of the hydrogen bonds between the amylose and amylopectin in the starch, which in next tour weakness the granule. If heat is more added, more granules will absorb water. Amorphous regions that are made up by amylose absorb water first and become more swollen. This will cause friction between crystalline parts of granules, dominated by amylopectin, resulting in destruction of the starch wall. Amylose will start to leach from the broken granule, while amylopectin will leach after some time. Gelatinisation is not reversible since it causes total disorganisation of the structure.

Starch gelatinisation is a process that breaks down the intermolecular bonds of starch molecules in the presence of water and temperature and allowing the hydrogen bonding sites (the hydroxyl hydrogen and oxygen) to engage more water (Figure 14).

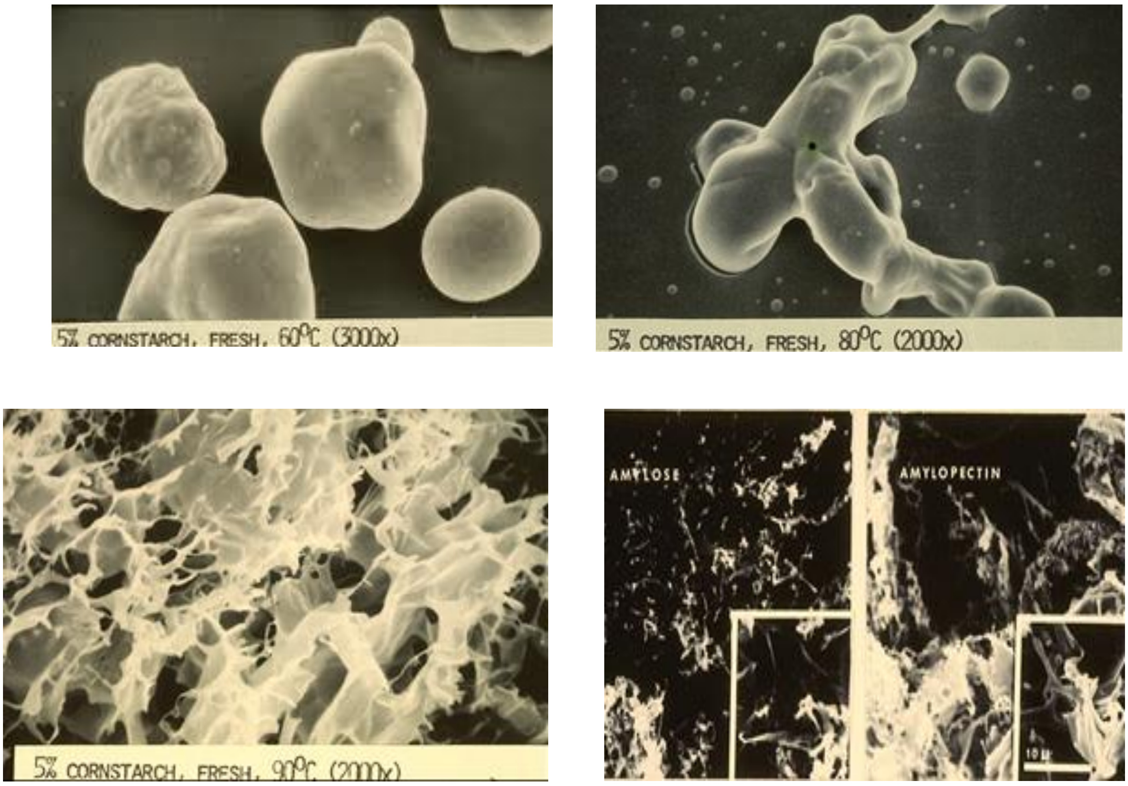

Figure 14. *Steps of the starch gelatinization in maize (Keeling et al., 1988)*

This penetration of water increases randomness in the general structure and decreases the number and the size of the crystalline region. The crystalline region does not allow water entry.

As heat and water is applied in the pelleting process, some starch granules dissolved and form an amorphous water-starch suspension and the starch gelatinise. The significance of starch gelatinisation is also dependent on the extent to which starch gelatinisation occurs during the pelleting process. A number of investigations (Skoch *et al.*, 1981; Xue *et al.*, 1996; Perez and

Oliva-Teles, 2002; Svihus *et al.*, 2005) have shown that only a limited extent of starch gelatinisation occurs during a regular pelleting process.

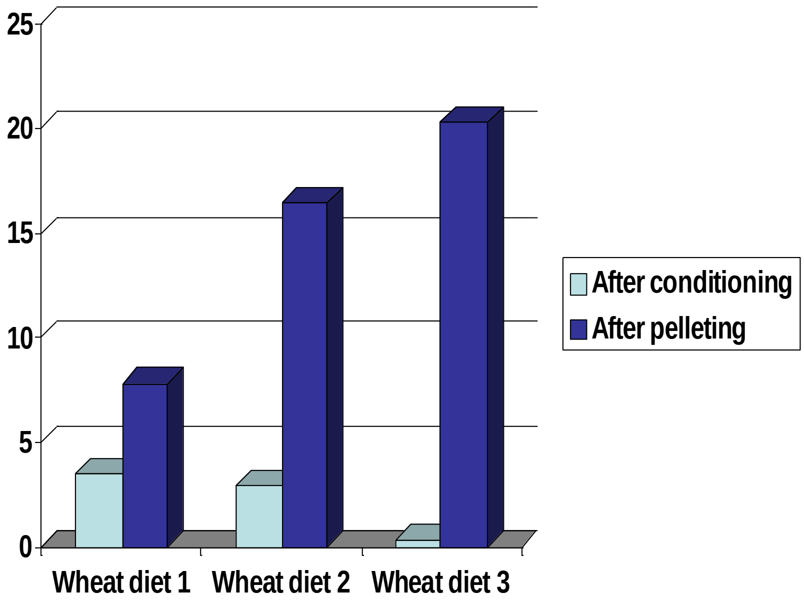

Figure 15. *Extent of starch gelatinisation after conditioning and pelleting (Svihus, 2009).*

Usually, only a small percentage of the starch is gelatinised in the conditioner (Katleen and Elke, 2010). Despite the fact that only a small extent of starch gelatinisation takes place in the conditioner, this does not mean that conditioning is not important for the subsequent gelatinisation in the pellet press (Figure 15). Research shows that conditioning doubles the extent of gelatinisation in the pellet press due to the presence of moisture. This has to do with the importance of water for gelatinisation to take place. In addition of having binding properties, gelatinized starch is also more rapidly digested because internal bonds in the starch molecule are more accessible for amylase scission when being dispersed in water. The extent of gelatinisation depends on the starch source, temperature (45-90°C) and moisture level (30-35% for a certain time of heating).

Normally, less than 20 % of the starch is usually gelatinised when is pelleting process used compare with extrusion process where is gelatinisation much higher (Figure 16). This doesn't apply for oats which consists of a starch with very small starch granules that easily gelatinised and present of gelatinisation is around 29% (Zimonja *et al*., 2007). Also in expander-pelleting treatment gelatinisation is not completed. Zimonja *et al.* (2007) has reported 21% and 36% of gelatinisation for expander wheat-barley mixtures, while Van der Poel *et al.* (1997) found gelatinisation degree to increase from 41.5% to 51.8% when feed where expanded and pelleted. Extruded process have higher percentage of gelatinisation and improve starch digestibility, example maize at temperature 137°C and moisture of approximately 30% the rate of the gelatinisation is 89.3% (Hongtrakule *et al.*, 1998).

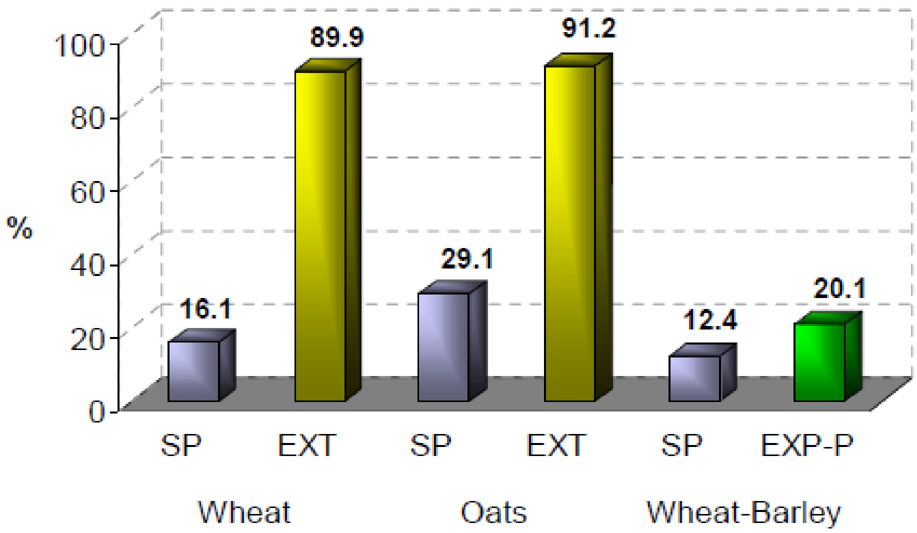

Figure 16. *Effect of the feed processes (pelleting and extrusion) on gelatinisation (Zimonja 2009)*

Resistant starch is a starch resistant to enzymatic (α-amylase) digestion, defined as starch that is not degraded and absorbed in the small intestine.

Resistant starch (RS) can be divided into different types (Svihus, 2003):

- Resistant starch 1 **(RS_1)** is starch that is physically inaccessible e.g. due to insufficient grinding,
- Resistant starch 2 **(RS_2)** is defined as starch resistant to digestion due to the structure of the native starch granules,
- Resistant starch 3 **(RS_3)** is defined as starch that has been retrograded during processing,
- Resistant starch 4 **(RS_4)** has been defined as chemically modified starches that are resistant to digestion.

Retrogragiation of starch is re-crystallisation of starch molecules after gelatinisation, where hydrogen bonds between amylose and amylopectin are re-established (Hoseney, 1994). This process take a place after cooling when pellets still have higher amount of water in the structure. Retrogradiation will make the starch less sensitive for enzymatic degradation of animals. Retrogradiation is not desirable in feed production since it may push water from the gel structure and precipitate starch (Weurding, 2002**).** This could lead to cracks in the pellets and increase dust formation when feed is transported. Retrogradiation of starch can be reduced if the pellets are dried at low level of water before the feed is cooled (Weurding, 2002).

2.10. Physical Quality of Pellets – Hardness / Durability

The physical quality of feed pellets is important for a many of reasons. Transportation and handling in both the factory and one the farm require pellets of certain integrity without fines produced by attrition stresses. If is fines present feed intake by livestock may be reduced, and utilization of nutrients may be reduced.

Pellets of high physical quality must have properties, which give a high nutritional quality for example in terms of high feed intake and perhaps improve nutritional value (Skoch *et al.*, 1983).

The two main physical indicators of the pellet quality are:

- Hardness – measured by pellet resistance to breaking when submitted to external pressure (force needed to fragment a pellet)
- Durability – measured by the level of fines returned from a batch of feed pellets under standardized conditions (Thomas and van der Poel, 1996).

According to Reimer, (1992) pellet quality is proportionally dependent on the following factors (Figure 17):

- Diet formulation 40% ,
- Particle size 20% ,
- Conditioning 20% ,
- Die specification 15% ,
- Cooling/drying 5%.

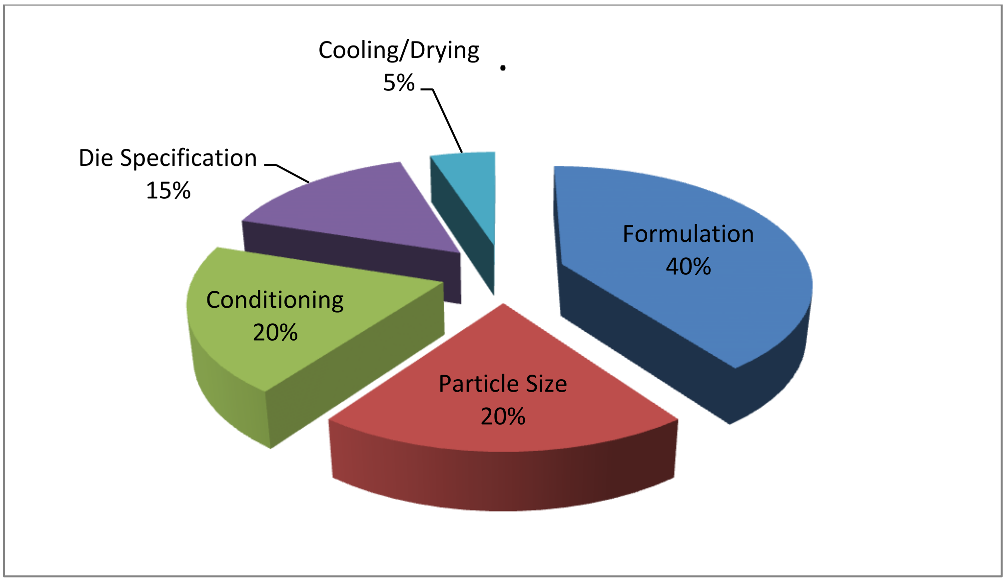

Figure 17. *Factors affecting of the pellet durability (%)*

Hardness is determined by using equipment which measures the force needed to fragment a pellet. The most common device for measure pellet hardness is Kahl tester (Figure 18) and a device for measure pellet durability is Holmen tester and Ligno tester.

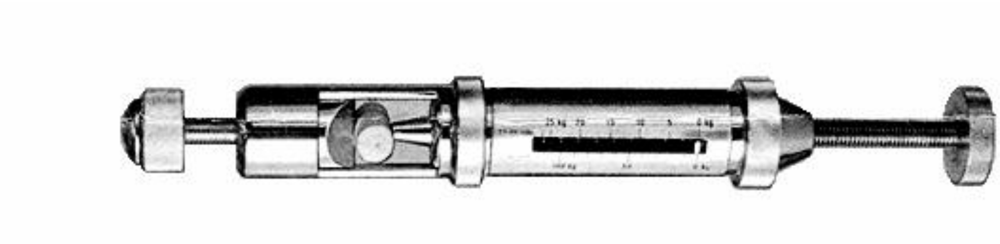

Figure 18. *Kahl pellet hardness tester*

Composition properties, such as starch, protein, fat, fibre and sugar content are important factors on determining the hardness and durability on the final feed compound.

Starch has function as an adhesive or binding agent in feed production. Starch used for this purposes have undergone a heat or chemical treatment in which the properties of the native starch are changed to provide good binding properties. The presence of water and heat is most common way to affect functional properties of the starch.

After gelatinisation, amylose immediately forms double helix, which may aggregate to each other and create semi-crystalline regions. Pellet binding occurs probably by amylopectin due to the double helix formed at the non-reducing ends of this very large branched molecule that may aggregate with compatible starch or fibre surface on the different particles present during and after gelatinisation (Moran, 1989). If the pre-gelatinised starch included in diets (and hot conditioner) that have influence on the pellet quality (lead to harder and more durable pellets). Sugars may act as a binder and in the form of molasses positively affect pellet hardness and durability.

Protein can act as a binding agent and during denaturation processing may positively affect the hardness and durability of the feed pellets (Thomas *et al.,* 1998). Also will affect mechanical stability of protein may affect on pellet quality, involve covalent binding, electrostatic interactions, hydrogen bonds and entropic factors. The changes are the result of changes in the combination of all of these factors.

Soluble fibre with a high viscosity may act as filler in the feed; the viscous material embeds the more coarse particles, which will reduce porosity in the feed. Subsequently, the structural integrity of the feed is higher, resulting in higher durability and hardness of the pellets.

The insoluble fibre is beneficial in the pelleting process since they can implicate and fold between different particles or strands of fibre. On the other hand, due to their stiffness and elasticity, they may impair problems to the pellet press. Large fibre strands within the pellet are possible weak spots, which facilitate breaking of the pellet, thus decreasing their quality.

Fats added in the diet are known for its adverse effect on pellet hardness and durability (Thomas *et al.,* 1998). Fat acts as lubricant between particles, feed mash and die, which resulting a lowed pressure in the pellet press. This resulting reducing energy consumption, but is has negative effect on the physical quality of pellets. Also, gelatinisation of starch can be inhibited in the present of lipid or delayed to higher temperatures (Eliasson, *et al.*, 1981).

When pellet hardness or durability is low, pellet binders such us bentonite, carboxymethylcellulose (CMC; modified cellulose) and lignosulphonates used to improve pellet quality. They reduce void of spaces leading to further compact and durable pellet.

3. MATERIAL AND METHODS

Two experiments were conducted at Centre for Feed Technology - FôrTek, Norwegian University of Life Science (UMB), Ås, Norway.

3.1. Experiment 1

Four different feeds were composed and processed using wheat and maize as base ingredients in the experiment 1 (table 5). Four different diets were formulated to contain either completely ground base ingredients using 3 mm and 6 mm screen size in hammer mill (Model E-221115, Munch-Edelstahl, Wuppertal, Germany, licensed by Bliss, USA, 18 kW, 3000 RPM) or base ingredients were added as whole grain in ration of 30% whole grain 70% ground material.

Table 5. *Feed composition with different feed ingredients (grounded and whole)*

Ingredients	Feed 1 (%) HM 3 mm	Feed 2 (%) HM 6 mm	Feed 3 (%) HM 3 mm	Feed 4 (%) HM 6 mm
Wheat	30	30	30	30
Maize	50	50	20	20
Whole wheat	0	0	30	0
Whole maize	0	0	0	30
Soybean meal	12	12	12	12
Soy oil	5	5	5	5
Mono-Calcium P	1.5	1.5	1.5	1.5
Ground limestone	1.5	1.5	1.5	1.5

Ingredients were mixed in twin shaft paddle mixer (Model 1992 OB-1078, licensed by Forberg Int.) around 180 seconds.

Each diet was heated at 75°C in a continuous flow conditioner (Münch-Edelstahl, Wuppertal, Germany) at the steam pressure regulated down to 2.5 bar by steam regulating valve (Gestra 1,1 – 10 bar, AG type 5801, F-340, Bremen, Germany) prior pelleting process. Approximate residence time in the steam conditioner was 30 seconds. Conditioned mash was thereafter pelleted in a pellet press (Münch-Edelstahl, Wuppertal, Germany, RMP 350.100, 2000 kg/h capacity, 2x17.5 kW). The pellet press had two rolls with fixed distance to a die (approximately 0.25 mm). Diameter of die holes was 3.5 mm while the thickness of the die was 50 mm. Temperature was controlled during processing by laser gun (Raytek, Raynger, ST, USA).

Feed sample were collected in an isolated box to measure the post-pelleting temperature using the Electronic Thermometer **(**Anritsa HA-250, Co.LTD, Japan). An average of 10 kg of each sample was collected immediately after the pelleting in a portable fan cooler (Cooler, FôrTek, Norway, 40 kg) and cooled for 10 minutes. After cooling approximately 2.5 kg sample of the each feed was collected to measure pellet durability and pellet hardness.

3.2. Experiment 2

Six different feeds were processed using pure wheat and barley as base ingredients. The ingredients have been ground using either a hammer mill (Model E-221115, Munch-Edelstahl, Wuppertal, Germany, licensed by Bliss, USA, 18 kW, 3000 RPM) with the sieve size of 3 mm or roller mill (Model DP 900-12, 1.5 t/h, motors 13 Kw**,** Roskamp, Indiana, USA) with 1.5 mm gap between two rollers. In addition, a combination of the hammer mill fitted with 3 mm screen and roller mill with the 1.5 mm gap between rolls as a singular method was tested. Ingredients were mixed in twin shaft mixer (Model 1992 OB-1078, licensed by Forberg Int.) for approximately 180 seconds.

All six diets were heated at 75°C in a continuous flow conditioner (Münch-Edelstahl, Wuppertal, Germany) at steam pressure regulated down to 2.5 bar by steam regulating valve (Gestra 1,1 – 10 bar, AG type 5801, F-340, Bremen, Germany) prior pelleting. Mash was pelleted in a Pellet press (Münch-Edelstahl, Wuppertal, Germany, RMP 350.100, 5000 kg/h capacity, 2x17.5 kW). The pellet press had two rolls with fixed distance to a die (approximately 0.25mm). Diameter of die holes was 3 mm while the thickness of the die was

42 mm. Laser gun (Raytek, Raynger, ST, USA) was used to control temperature during pelleting process.

Feed sample were collected in an isolated box to measure the post-pelleting temperature using the Electronic Thermometer **(**Anritsa HA-250, Co.LTD, Japan). An average of 10 kg of each feed was collected immediately after the pelleting process in a portable fan cooler (Cooler, FôrTek, Norway, 40 kg) and cooled for 10 minutes. After cooling approximately 2.5 kg sample of the each feed was collected to measure pellet durability and pellet hardness.

3.3. Analytical measurements

Pellet Durability was measured by using Holmen Pellet Tester (Holmen Chemical Ltd., Borregaard Group, Norsolk, UK), where the feed samples of 100 grams were pneumatically conveyed in a closed circuit for 60 seconds. PDI was recorded as the proportion of the feed not passing through the 2 mm sieve after treatment in the Holmen Tester. Each sample was treated two times.

Hardness analyses defined as the maximum force needed to crush a pellet were performed by Kahl cylinder tester. A pellet is placed between two steel parts and pressure is applied on the pellet in the form of a coil spring by screwing down hand. Methods have been described in detail by Thomas and Van der Poel (1996).

Wet sieving was performed by sieving 100g of the feed through a series of sieves (0.2 mm, 0.5 mm, 1.0 mm, 1.6 mm, 2 mm, 2.8 mm and 3.6 mm, 4 mm, 5.6 mm) under excess water. Previously the pellets were soaked in the water for two hours. Sieving time was nine minutes and vortexing amplitude was 1.5 mm. Particle size distribution was calculated by the proportion of the dry matter left on each sieves after the overnight drying at the temperature of 104° C.

Dry sieving also was performed by sieving 100g of the feed through a same series of sieves (as in wet sieving) without water.

4. RESULTS

4.1. *Experiment 1*

4.1.1. *Grinding/Pelleting parameters*

The process parameters collected during grinding and pelleting process are shown in table 6.

Table 6. *Hammer mill and pellet press parameters*

		Feed 1 (3mm)	Feed 2 (6mm)	Feed 3 (3mm) whole wheat	Feed 4 (6mm)whole maize
PELETTING TEST					
Grinding					
Screen size	**mm**	3.0	6.0	3.0	6.0
Density	**g/l**	550.0	498.0	573.0	557.0
Die diameter	**mm**	3.5	3.5	3.5	3.5
Die length	**mm**	50.0	50.0	50.0	50.0
Pelleting Process					
Production Capacity	**kg/h**	600	600	600	600
Cond. Temp	**ºC**	75	75	75	75
Feeder	**%**	33	33	33	33
Steam working pressure	**bar**	2.5	2.5	2.5	2.5
Motor load	**%**	23	24	23	27
Amperes Motor 1	**amp**	14.5	14	14	14.5
Amperes Motor 2	**amp**	13.5	13.5	13.0	14.0
Total Ampers motor	**amp**	28	27.5	27	28.5
Energy Consumption pellet press	**kW**	8.61	8.46	8.30	8.76
Spec.Energy consumption pellet press	**kW/t**	14.4	14.1	13.8	14.6

Slight increase in motor load values was observed for feed 4 compared with the rest of the experimental feeds. No clear numerical difference was observed in energy consumption during pelleting process between finely ground feed and feed that contained whole grain.

4.1.2. Particle size distribution – dry sieving

The effect of grinding by use of either 3 mm or 6 mm screen size on particle size distribution of maize and wheat is shown in table 7 and figure 19.

Table 7. *The effect of 3 mm and 6 mm Hammer mill screen on particle size distribution of maize and wheat*

Sieve size (mm)	Maize 3mm	Wheat 3mm	Maize 6mm	Wheat 6mm
<0.2	34.08	37.51	24.04	22.22
0.5	15.36	10.19	23.14	7.64
1.0	45.27	46.79	35.92	45.25
1.6	2.30	3.72	7.10	11.95
2.0	1.02	0 88	5.12	9.50
2.8	1.41	0 25	2.08	2.12
3.6	0.0	0.11	0.85	0.16
4.0	0.57	0.10	0.69	0.04
5.6	0.03	0.01	0.50	0.07

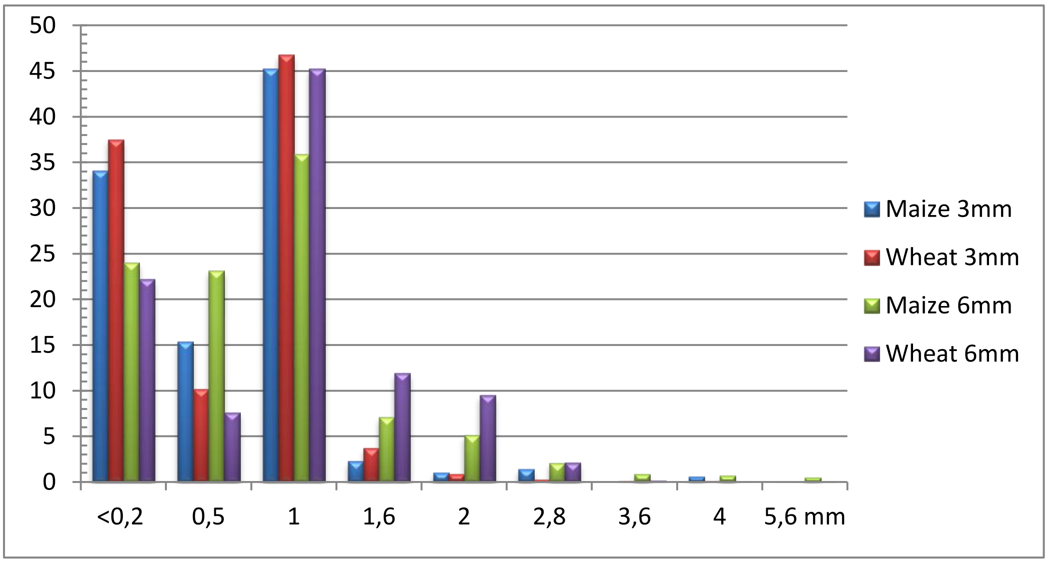

Figure 19. *The effect of 3 mm and 6 mm screen size on particle size distribution of maize and wheat*

As expected, the distribution of the small particles in collector (<0.2mm) were higher for the maize and wheat ground by using the 3 mm screen compared to 6 mm screen. If we compared wheat and maize ground on HM 3 mm, no obvious numerical difference could be observed in particle size distribution for sieves <0.2 mm, 0.5 mm, 1.0 mm and 1.6 mm. However, ingredients ground on HM 6 mm have shown clear numerical difference in distribution of the small particles (0.5mm, 1.0mm and 1.6mm). Maize shown higher proportion of particles bellow 1.0 mm than wheat, but wheat has shown greater proportion of the particles over 1.0 mm and 1.6 mm (Table 7).

4.1.3. Particle size distribution - Wet sieving

Particle size distribution of the pelleted feeds is shown in table 8 and figure 20.

***Table 8**. Particle size distribution by wet sieving for feeds (1 to 4) in the experiment 1*

Sieve size (mm)	Feed 1, HM 3	Feed 2, HM 6	Feed 3, HM3 whole wheat	Feed 4, HM 6 whole maize
<0.2	36.31	26.58	17.84	15.05
0.5	10.28	8.62	6.11	6.06
1.0	49.16	48.08	39.97	33.34
1.6	2.68	16.77	3.06	8.07
2.0	0.48	5.63	2.95	7.03
2.8	0.46	1.78	20.08	3.02
3.6	0.15	0.24	9.71	1.08
4.0	0.1	0.33	0.41	1.97
5.6	0.08	0.24	0.10	24.38

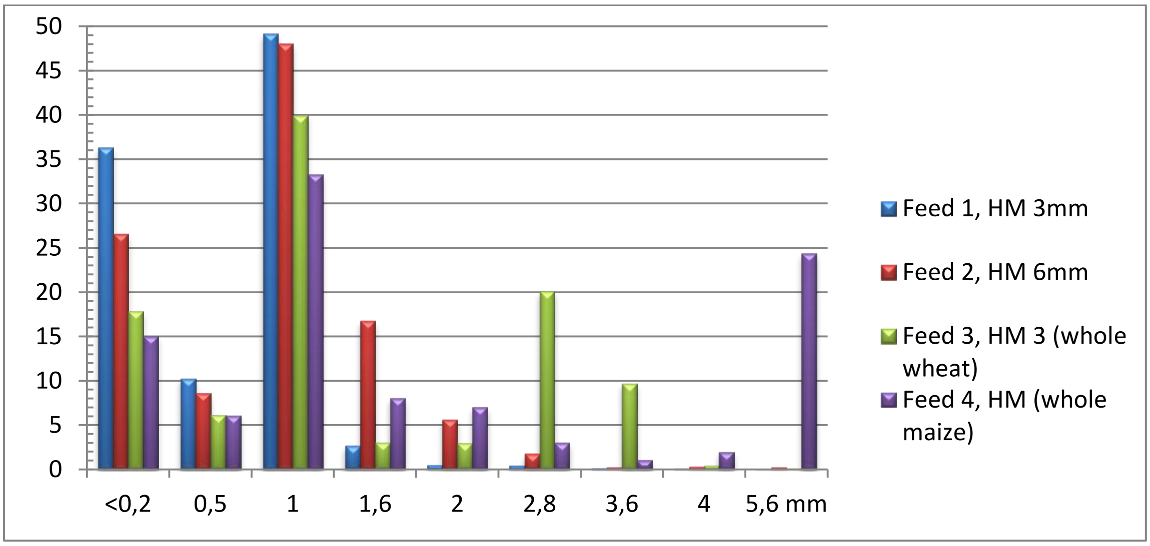

Figure 20. *Particle size distribution by wet sieving for feeds in experiment 1*

Feed 1 and feed 2 contained larger amount of small particles (<0.2mm, 0.5mm, and 1.0mm) when compared to feed 3 and feed 4. Feed 3 contained larger amounts of the particles bigger than 2.8 mm and 3.6 mm when compared to feed 1 and 2. Sieving results showed that feed 4 contain larger amount of coarse particles (4.0 mm and 5.6 mm) compared to feed 1, 2, and 3 (Figure 20).

4.1.4. Pellet Durability Index (PDI) and Hardness

Figure 21 show the relation between the feed structure and durability.

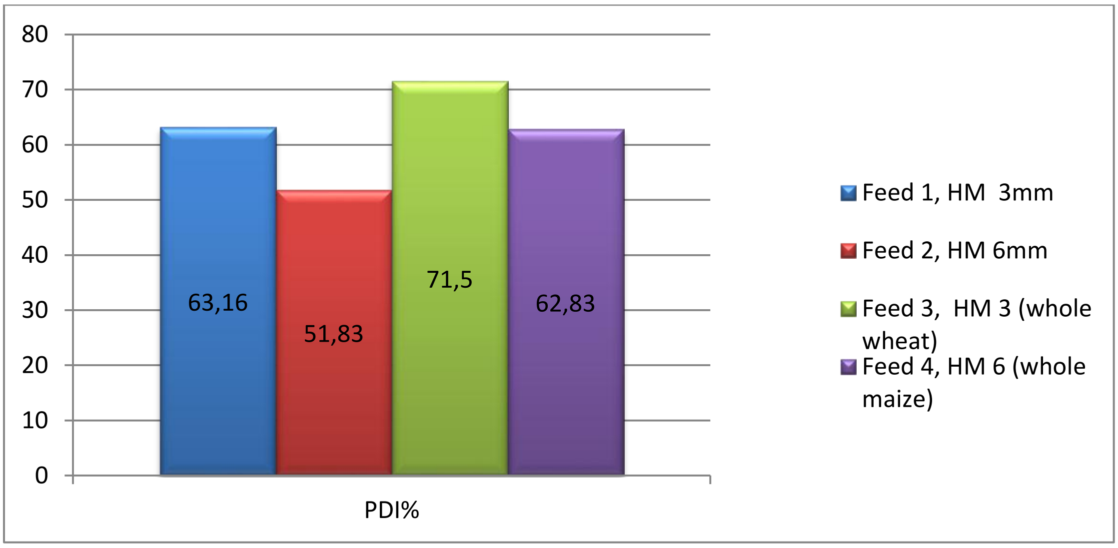

Figure 21. *Holmen Durability index for feeds based on fine and coarseness grinded ingredients.*

By comparison of the feeds ground on HM 3 mm (feed 1 and 3) and HM 6 mm (feed 2 and 4) we can see that the pellet durability was higher for HM 3mm feeds. Feed 2 is shown a lower durability then feed 4, even though the feed 4 has contained the high level of whole maize. The similar result was observed for feed 1 and feed 3 which contained the whole wheat. Also, the PDI was higher for feed 3 in comparison to finely ground feed 1 (Figure 21).

Pellet hardness measured by Kahl cylinder tester is shown in figure 22.

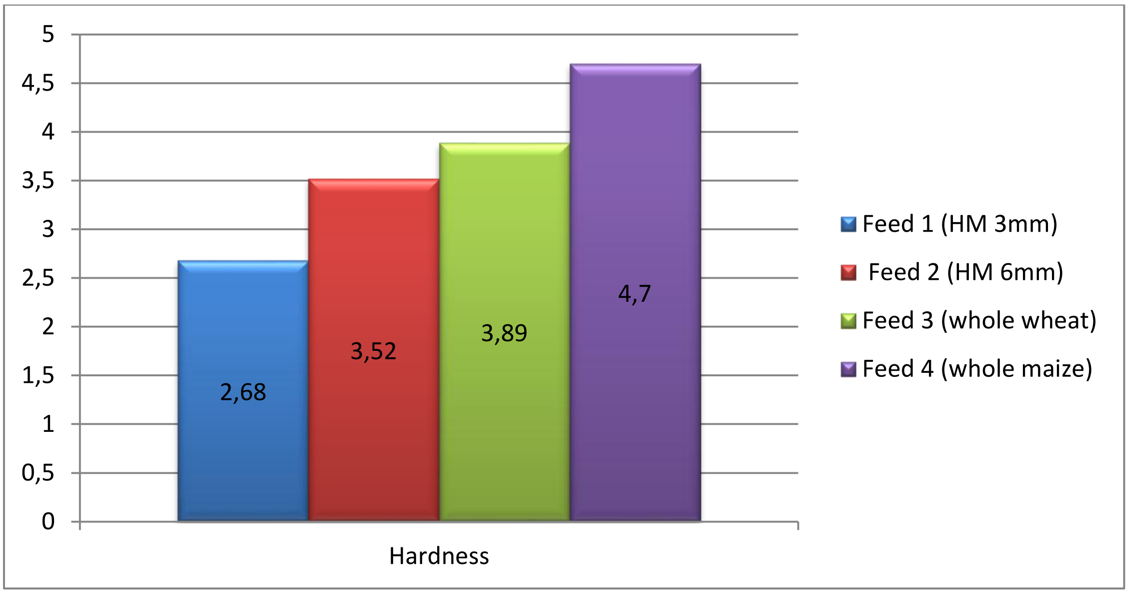

Figure 22. *Hardness test for feeds based on fine and coarseness grinded ingredients*

The relation between pellet hardness and feed structure followed the same trend as pellet durability (Figure 22). Addition of the whole grains (feed 3 and 4) resulted in harder pellets in comparison to feed 1 and feed 3. The highest hardness value was obtained for the feed 4 who contain whole maize.

4.2. *Experiment 2*

4.2.1. *Grinding/Pelleting parameters*

Energy consumption and specific energy consumption for the wheat and barley based diets are shown in figure 23.

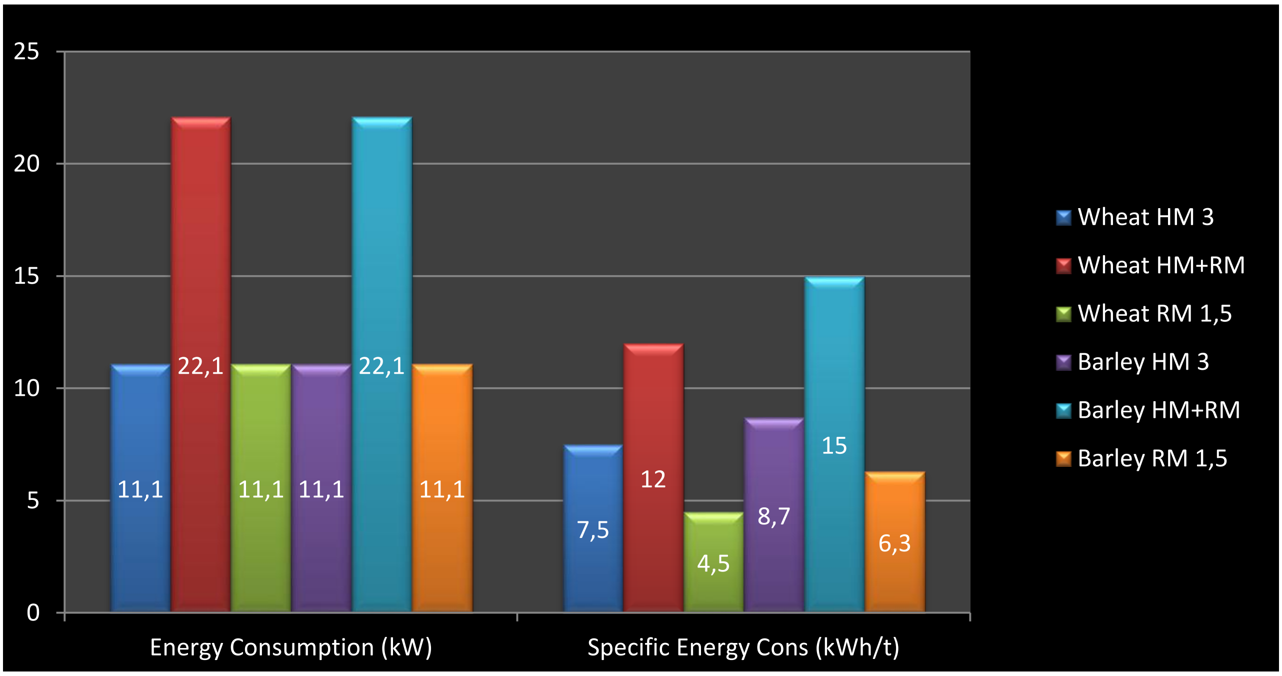

Figure 23. *Grinding energy consumption and specific energy consumption*

When compared wheat to barley diets, the energy consumption was equal. Specific energy consumption was higher for barley diets when compared to wheat diets (Figure 23). As expected the energy consumption during the double grinding technique (RM+HM) was numerically higher when compared to separate grinding (HM or RM).

Table 9. *Pelleting parameters in experiment 2*

		Diet 1w	Diet 2w	Diet 3w	Diet 4b	Diet 5b	Diet 6b
Grinding		**HM 3mm**	**HM+RM**	**RM 1. 5mm**	**HM 3mm**	**HM+RM**	**RM 1.5mm**
Conditioner temperature		76.0	75.0		75.0	75.0	75.0
PELLETING							
Die diameter	**mm**	3.0	3.0	-	3.0	3.0	3.0
Die length	**mm**	42.0	42.0	-	42.0	42.0	42.0
Capacity	**kg/h**	500	500	-	500	500	500
Motor load - p.press	**%**	25	36	-	35	34	30
Amperes Motor 1	**amp**	17.5	18	-	17	16.5	17
Amperes Motor 2	**amp**	16.5	17.0	-	16.0	15.5	16.0
Total Ampers motor	**amp**	34.00	35.00	-	33.00	32.00	33.00
Energy Consumption, P.Press	**kW**	20.91	21.53	-	20.30	19.68	20.30
Specific Energy Cons. P.Press	**kWh/t**	41.82	43.05	**-**	40.59	39.36	40.59

4.2.2. Particle size distribution – dry sieving

Particle size distribution of dry-sieved wheat and barley feeds ground through a hammer mill, roller mill or both of them is shown in table 10 and figure 24. The percentage of coarser particles after grounding through roller mill is higher compared to hammer mill. A greater proportion of larger particles (> 2 mm and > 1.6 mm) in the diet ground by RM in comparison to HM were observed (Table 10).

Table 10. *Particle size distribution by dry sieving for wheat and barley*

	Wheat	**Dry sieving**		**Barley**	**Dry sieving**	
mm	**Feed 1, Wheat *HM 3mm***	**Feed 2, Wheat *RM+HM***	**Feed 3, Wheat *RM 1.5mm***	**Feed 4, Barley *HM 3mm***	**Feed 5, Barley *RM+HM***	**Feed 6, Barley *RM 1.5mm***
2,8	0.03	0.03	13.34	0.01	0.01	19.42
2	1.05	1.12	62.04	0.97	0.94	56.50
1,6	6.02	8.35	16.92	5.12	8.01	15.46
1	25.88	29.56	4.64	27.24	33.78	5.29
0,5	31.64	30.63	1.72	39.85	32.97	1.92
0,2	20.58	19.78	0.64	20.47	17.25	0.72
< 0,2	14.52	10.51	0.73	6.75	6.09	0.32

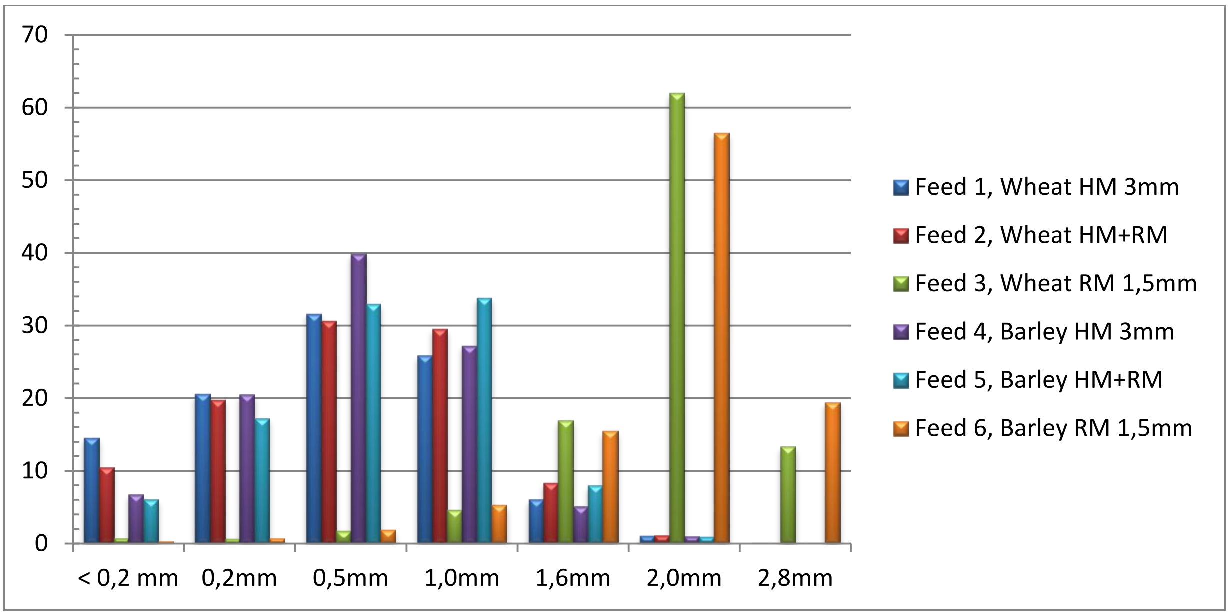

Figure 24. *Particle size distribution by dry sieving for wheat and barley*

The results of the ground material in combination with roller mill and hammer mill shows that the percentage of fine particles is lower when compared to hammer mill ground ingredients only. In case of the pre-ground wheat and barley through roller mill, the particles entered to hammer mill were smaller and produced less fine particles thereafter. Lower percentage of very fine particles is one of the advantages for this method.

4.2.3. Particle size distribution - Wet sieving

The results have shown that the pelleting process acts as a grinder, since there were great proportions of small particles (<0.2mm) in processed diets compared to the mash (Table 11). Feed 6 ground by RM showed higher distribution of the larger particles (>2.8mm, 2.0mm, 1.6mm) and lower distribution of the smaller sieves size (1.0mm, 0.5mm, and 0.2mm) compared to other treatments (HM and RM+HM).

Table 11. *Particle size distribution by wet sieving for wheat and barley diets*

	Wheat	Wet sieving		Barley	Wet sieving	
	Feed 1 wheat	**Feed 2 wheat**	**Feed 3 wheat**	**Fee 4 barley**	**Feed 5 barley**	**Feed 6 barley**
mm	***HM 3mm***	***Wheat RM+HM***	***RM 1.5mm***	***HM 3mm***	***RM+HM***	***RM 1.5mm***
2,8	0.90	2.13	-	0.02	1.52	8.55
2	1.78	6.95	-	1.39	1.61	14.47
1,6	3.69	8.43	-	4.13	4.39	10.85
1	16.71	20.29	-	16.49	16.25	12.42
0,5	18.62	10.35	-	14.77	15.89	4.42
0,2	13.35	10.25	-	14.84	15.08	7.83
<0,2	44.95	41.59	-	48.35	45.27	41.45

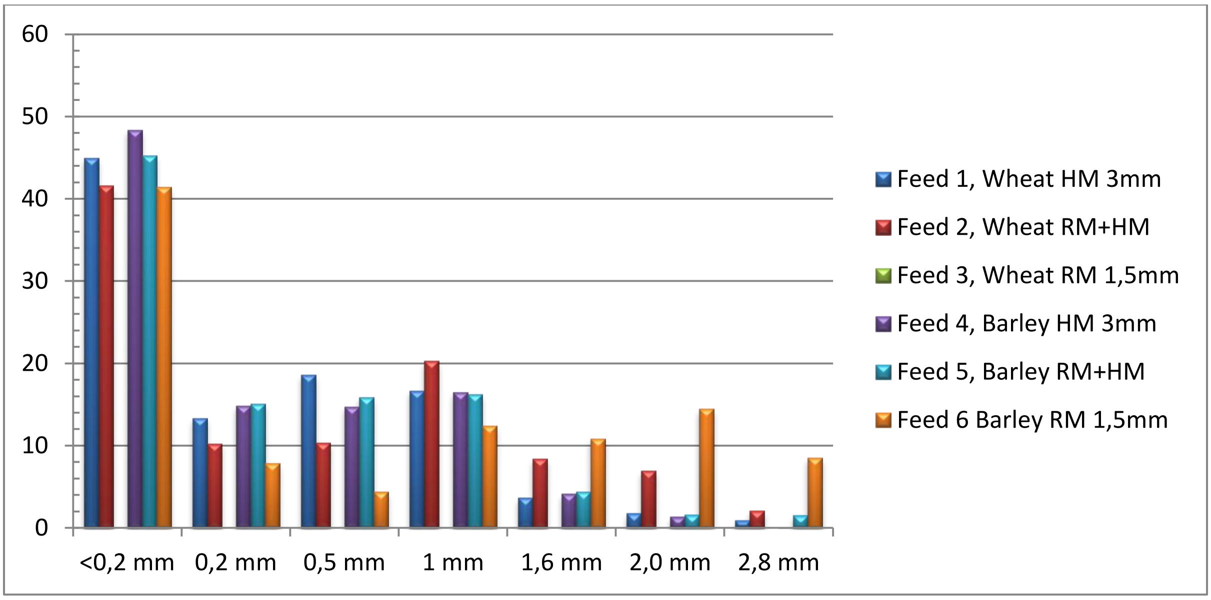

Figure 25. *Particle size distribution by wet sieving for wheat and barley diets*

As expected, this results shown that the proportion of fine particles (<0.2mm) was higher when the HM grinding technique was used compared to combination of the double grinding technique (RM+HM).

Wet sieving data of the pellets made from wheat mash (Feed 3) ground by roller mill are not presented because of the blockage of pellet press during pelleting.

4.2.4. *Pellet Durability Index (PDI)*

Barley based diets showed highest PDI for Diet 6 which is ground in the RM. Also the combination RM + HM shows a higher PDI than the HM only (Figure 26).

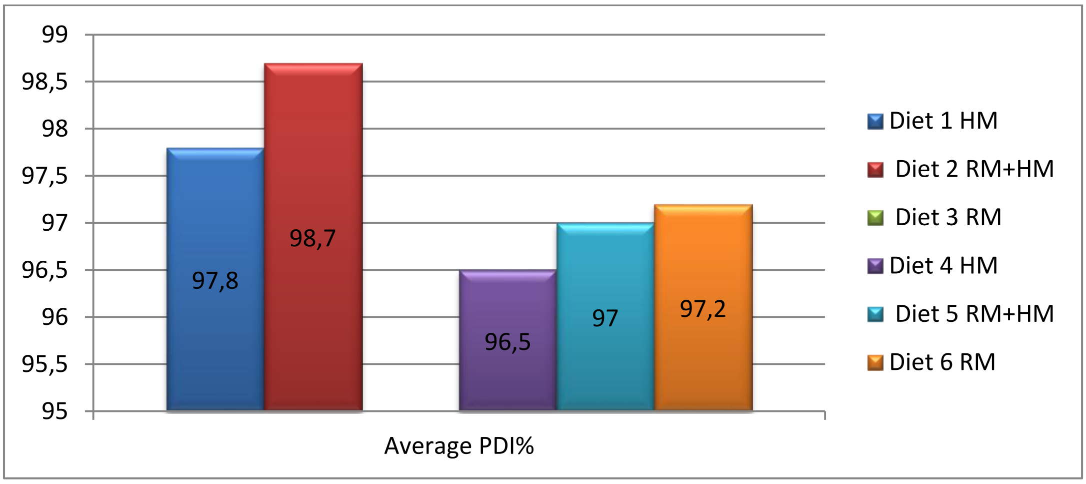

Figure 26. *Pellet Durability Index for wheat and barley based diets*

Wheat based diet ground by combination of hammer mill and roller mill resulted in higher PDI in comparison to hammer mill only. Durability of pellets was lower for the barley diets compared to wheat diets even though the amount of the fine particles was higher in barley diets.

5. DISCUSSION

5.1. Effect of the feed structure on the physical pellet quality

The results obtained by dry sieving analysis showed that the percentage of fine particles increased after grinding by HM compared with RM or RM + HM. This could be due to the fact that larger particles need more time to pass through HM chamber consequently resulting in increase of fine particles. These results are in agreement with some previous work (Tsujichi, 1988; Nir *et al.,* 1995; Hogg and Gho, 2000; Jackson *et al.,* 2001) where specificity of HM grinding resulted in excessive increase of fine particles. However, data from the present experiment shows that use of whole grains seems to improve particle size distribution in regards to presence of coarse material in the feed, which is in line with earlier research (Fincher and Sone, 1986; Bergström *et al.,* 2008; Birta *et al.,* 2009; Hemery *et al.,* 2011). This effect was seen both after grinding and on the full scale processing.

Wet sieving data shows that the amount of coarse particles was reduced and the amount of fine particle was increased as a consequence of pelleting. Similar result was also observed before (Goelema *et al.,* 1999; Svihus *et al.,* 2004; Perón *et al.,* 2005; Amerah *et al.,* 2008). Reason for this could be reduction of the particle size of the ingredients by the action of the pellet press. This is means that the pellet press acts as secoundary grinder in the full scale process. Larger amount of small particles (<0.2mm) for barley based diets in comparison to wheat diets indicates that barley is more susceptible for grinding in the pellet press then wheat.

Tendency for the higher durability of the diets containing whole grains may be explained by the fact that the addition of the whole grains produces less fines on the full scale process basis which is ultimately reflected on pellet durability. Higher pellet durability for the finely ground diets in comparison to coarsely ground diets in experiment 1 are in line with previous research (Wondra *et al.,* 1995; Svihus *et al.,* 2004). However, the data from the experiment 2 shows no numerical differences on pellet durability in respect to coarsens of the grinding. Similar results were found by Reece *et al.* (1986) who observed no differences on pellet durability by comparing maize based diets ground using either 4.76 mm or 6.35 mm screen. This indicates that correlation between extent of the grinding and pellet durability is not clear. Improvement in pellet durability by use HM+RM combination seems to be correlated with the narrow distribution of the particles of the ground and pelleted material. This indicates that distribution of the particles rather than the size of the particles may have major effect on pellet durability.

Use of the whole grains in the diets improved hardness of the pellets. However, this result may be influenced by the fact that the Kahl measurement revealed a hardness of the grain itself rather than the pellet per se. Reason for this is due to fact that the grain when applied in non-ground form will exist in the pellet as whole grain or as big particle (only partly reduced grains relative to the whole size), and thus influence measurement/analytics.

5.2. Effect of feed structure on the chemical status of the feed components

Many authors (Svihus *et al*., 2004; Svihus *et al*., 2004a) have shown that fine grinding increase starch gelatinisation and possibly protein denaturation. This effect may be related with increase of particles surface area in total feed mix of finely ground material consequently resulting in better steam or water absorption by those feed ingredients. Although in current experiment no measurement was performed in respect to chemical status of the feed components, a fine particle size structure obtained by grinding material through HM 3 mm screen size may be related to increase in starch gelatinisation as manifested by higher pellet durability (when fine and coarse diets were compared, only). Similar observation was also shown by Wondra *et al.* (1995) and Svihus *et al.* (2004). Application of the whole grains in the feed mix may interfere with starch gelatinisation as consequence of reduced possibility to water absorption and thus creation of the chemical bonds among feed particles. This effect has been shown before by Svihus *et al.* (2004a) where low extent of starch gelatinisation was strongly linked with coarsens of the feed particles.

5.3. Effect of the feed structure on the nutrition quality of the feed

Number of authors have shown that coarsely ground material positively effects development of the digestive system in the birds, specifically size of the gizzard (Nir *et al.*,1995; Svihus, and Hetland, 2001; Hetland *et al.,* 2002; Hetland *et al.,* 2005; Rodgers *et al.,* 2012). Results from the current experiment shows that the complete grinding of the ingredients by use of either hammer mill or roller mill (to different coarsens) does not result in sufficient coarseness of the material on the final product basis. One of the reasons may be secondary grinding of the pellet press as discussed above. However, application of the whole grains seems to overcome this problem. This indicates that the secondary reduction of the material in the pellet press is relative to the particle size of the material. In addition use of the roller mill as grinding tool (beside less energy requirements) results in more even distribution of the coarse material, which indicates that use of this machine may be recommended for chicken feed production.

Numerous of authors have shown that fine grinding is positively correlated with nutrient digestibility in pigs (Wondra *et al.,* 1995; Wondra *et al.,* 1995a). However, finely grinding of the material in pig feeds is also strongly correlated with ulcers creation and acidosis in pig stomach (Wondra *et al.,* 1995; Wondra *et al.,* 1995a; Dirkzwager *et al.,* 1998). Coarser grinding and use more fibrous material seems to be positively correlated with ulcers and acidosis reduction in pigs as shown by Wondra *et al.* (1995). Thus additions of the whole grains and use of RM may find application in production of the pig feeds.

5.4. Energy consumption

Reduction of the ingredients particle size by use of a hammer mill as a grinding tool in present experimental production resulted in considerably higher energy use in comparison to roller mill which is in line with previous research (Wondra *et al.*,1995a; Reece *et al.,* 1985; Reece *et al.,* 1986a). The differences in screen sizes and consequent influence on energy consumption was also shown by Arthure *et al.* (1982), where the energy consumption for grinding increases when the screen opening size are changed from coarse to fine.

When specific energy consumption data (SEC) were compared, barley needed more energy to be ground than wheat. Reason for higher SEC could be that barley contains about 25% to 45% more fibres in compression to wheat. In cereal grains fibres are distributed differently within the polymerized chain, in wheat typically in short chain orders, while long chain orders are more typical for barley. Specific distribution and quantity of the fibres relative to the retention time in the HM chamber may be a reason for the higher energy demands for barley in comparison with wheat. Similar result was observed in study of Lopo (2002). However, the total energy consumption was approximately the same for all diets on full scale basis.

6. CONCLUSION

No clear effect of the fine grinding was observed in respect to pellet quality. Combinative grinding by use of hammer mill and roller mill tend to improve pellet durability.

Coarse grinding or inclusions of the whole grains in the diets have positive influence on the reduction energy consumption during grinding. Use of energy by pellet press is influenced by particle size of the material rather than grinding equipment.

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