Norwegian University of Life Sciences
Faculty of
Department of Animal and Aquacultural Sciences

Master Thesis 2014
30 credits

EFFECTS OF HAMMER MILLING, ROLLER MILLING AND PELLETING ON TECHNICAL AND NUTRITIVE VALUE OF BARLEY FOR RUMINANTS

GHULAM QASIM KHAN

Effect of hammer milling, roller milling and pelleting on technical and nutritive value of barley for ruminants

Master Thesis in Feed Manufacturing Technology

(30 credits)

By

Ghulam Qasim Khan

Department of Animal and Aquacultural Sciences

Norwegian University of Life Sciences

Ås, Norway

August, 2014

Acknowledgements

Abstract

Barley is world's fourth grain with respect to its production. To understand its characteristics and effects of different processing methods upon its utilization by ruminants, a comprehensive literature review was conducted which was followed by own study. The own study was initiated and financed by Felleskjøpet Fôrutvikling (Trondheim, Norway) and consists of two parts. In the first part, experimental feeds (pure barley) were produced at Center of Feed Technology (Fôrtek), NMBU to study the effects of processing on particle size distribution and pellet quality along with energy consumption. In the second part, selected feeds were fed to animals in metabolism unit of Department of Animal and Aquacultural Sciences (IHA), NMBU to evaluate effects of processing on digestibility and production. Total 12 feeds were produced; three were hammer milled (HM) by using screen size 2mm, 4mm, 6mm and three were roller milled (RM) with the gap distance between the rolls 0.25mm, 0.75mm, 1.5mm. All the six feeds were then pelleted with 75ºC conditioning temperature. Hammer mill resulted in lower mean particle sizes than roller mill. Roller mill yielded uniform particle size distribution than hammer mill however hammer mill gave more durable pellet with less energy consumption. Three feeds HM 2mm (mash), RM 1.5mm (mash) and RM 1.5mm (pelleted) were selected and fed to animals along with a protein concentrate (FORMEL 140) and silage. Chemical composition of three barley feeds were not significantly ($P>0.05$) affected by the treatments. Likewise, feed (silage) intake, and ruminal and total tract digestibility of dry matter, starch, protein, fat, and ash were not significantly different among treatments ($P>0.05$). Total tract digestibility of neutral detergent fiber (NDF) was significantly higher ($P<0.05$) for HM 2mm (mash) feed. Numerically, total tract digestibility of protein was higher for RM 1.5mm (mash) diet whereas digestibility of starch was higher for HM 2mm (mash) diet. With the exception of protein and urea concentration in milk, no significance ($P>0.05$) effects of any treatment was found on milk production. RM 1.5mm (pelleted) feed significantly ($P<0.05$) increase the concentration of protein and decrease the concentration of urea in milk. Yield of milk was numerically higher for RM 1.5mm (mash) feed.

Table of contents

1. Introduction:

Barley is cultivated extensively all around the world and it is ranked as world's fourth grain in terms of production (FAO, 2012). Barley is rich in starch and is an efficient dietary energy source in dairy and beef farming. Barley also has relatively high content of non-starch polysaccharides (NSPs), mainly β-glucans and fibers. These NSPs are important fractions to prevent lactic acidosis in ruminants by decreasing the starch fermentation in rumen (Nikkhah, 2012). Although barley is a carbohydrate source, it has also considerable amount of proteins. As compared to wheat and corn, it is usually cheaper and thus cost efficient. All these above factors make barley an integral and efficient ingredient in dairy and beef diets.

However, whole barley kernel has thick fibrous outer covering (hull) which offers resistance to digestion in the rumen and making it largely indigestible (Beauchemin et al., 1994) .Also, 80 to 90% of barley starch is degraded in rumen (Nocek and Tamminga, 1991). This high degradation of starch in rumen can increase the risk of sub acute ruminal acidosis (SARA) (Krause and Oetzel, 2006) which often reduces feed intake in cattle (Allen, 2000). It is also important to note that increasing undegraded starch and protein flow to the small intestine is desirable to increase glucose absorption at duodenum and reduce gluconeogenisis which increase the productivity of animals (Kassem et al., 1987). Therefore, there is a need of optimum processing of barley grains to achieve maximum benefit of its nutritive qualities. Improper processing might result in no potential improvements, in terms of digestibility of different nutrients and animal productivity, of higher-quality barley (Hunt, 1996).

Particle size reduction is the main concept of processing. Grinding and dry rolling are the two most commonly used processing methods to reduce particle size. Either type of processing method can produce a satisfactory particle size for ruminants. However, extent of reducing particle size is usually higher for grinding than dry rolling giving different patterns of particle size distribution along with differences in energy consumption (Koch, 1996). But both processing methods can be adjusted to achieve desired particle size distribution. So, there is a need to figure out best suitable way to get desired particle size distribution out of these two methods while avoiding wasted electrical energy and possible digestive problems in ruminants. By reducing the particle size of whole barley kernel, the ruminal as well as total tract digestibility of dry matter is increased significantly in ruminants (Ørskov et al., 1978, Mathison et al., 1991a). Similarly, Offner et al. (2003) found increased ruminal starch degradation by grinding. Dry rolling also increases starch degradation in rumen but to lesser

extent than grinding. It is also important to note that extreme grinding may produce negative effects on productivity of cattle by increasing rate of fermentation of starch and elevating the acidity in rumen (Ørskov, 1979). Mathison (1996) reported less body weight gain for grounded barely diets *versus* rolled barley diets. Excessive starch fermentation in rumen yields more proportions of propionic acid than acetic acid (McDonald et al. 2002) and decreases milk fat contents. Pelleting is a more extreme method of processing then grinding and dry rolling which involves addition of steam and particle size reduction by its grinding ability. Steam addition causes swelling of starch granules and gelatinization of starch. A good quality pellet production is required which depends upon several factors like, type of ingredient, particle size, conditioning etc. The heat added during the process of pelleting, effects the digestibility of different nutrients. However, effects of steam addition on ruminal degradability of starch are varying among different cereal grains. For corn and sorghum, it increases starch fermentability in rumen, but for barley effects are less evident (Waldo, 1973 and Fiems et al., 1990). It has been shown that heat treatment like roasting can increase the starch fraction escaping rumen (McNiven et al., 1994). It may be due to the reason that starch granules are surrounded by protein matrix and heat treatment make this matrix more strengthen and resistant to proteolysis, thereby reducing rumen degradation of both protein and starch (McNiven et al., 1995). Ljøkjel et al. (2003a,b) reported decreased ruminal degradation of starch and crude protein by heat treatment of barley at at 100ºC and 125ºC, but not at 150ºC for starch. However, a number of studies showed improved dry matter digestibility in rumen and decreased milk fat concentration by pelleted diets than steam rolling (Von Keyserlingk et al., 1998 and Gardner et al., 1997). This variation is thought to be because of reduction in particle size by pelleting which effects digestion and performance of cattle (Dehghan-banadaky et al., 2006).

The current study consisted of two parts and aim was to evaluate the effects of the processing methods like grinding, dry rolling and pelleting upon particle size distribution and pellet quality in the first part and digestibility of different nutrients, production of milk and milk composition in the second part, by using pure barley based feeds. It was hypothesized that above processing methods would result in different particle size distributions along with addition of heat which would influence the pellet quality, digestibility of different nutrients (Dry matter, Starch, NDF, Protein, fat) and production of milk together with its content's concentrations. The thesis is divided into a literature review part that focus on physical and nutritive properties of barley grain with emphasis on chemical composition, digestion in

ruminants and physical processing and the own study part giving materials and methodology, results and discussion.

2.0. Literature Review:

2.1. Structure physical properties of barley grain:

Barley grain is bright yellow-white in color, has a plumy uniform shape and is medium hard in consistency (Pomeranz, 1974) (Fig. 1). A typical barley grain is covered by a hull (or the husk) that acts as protective covering of the kernel (Fig. 1). Surrounded by a layer of aleurone cells, the endosperm and a germinating embryo are present under this covering (Fig. 2) (Samuel, 1991). The endosperm is mainly composed of starch and some proteins and provides support to initial growth of germ. Depending upon variety, grain size and latitude (where it is grown) the starchy endosperm makes about 76.2% of the whole grain, whereas the hull forms about 13% of the total weight of barley (Evers et al, 1999).

Fig. 1. Barley Grain with hull (husk)
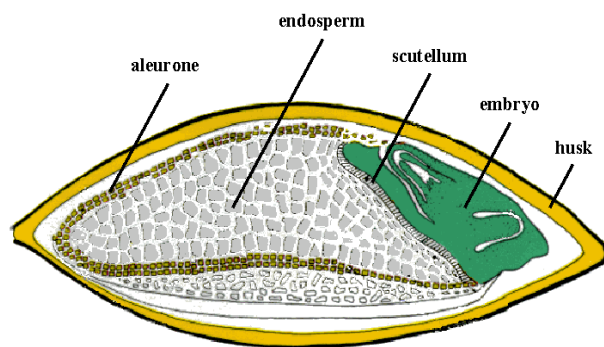
Fig. 2. Internal Anatomy of Barley Grain.

At storage, barley has about 11 to 13.5 % moisture content (Samuel, 1991). The moisture content is important for storing stability and processing properties of barley. The moisture content also determines physical properties of barley, like bulk density and true density. As shown in Fig. 3 and 4, bulk density decreases while true density increases with increasing moisture content (Öztürk and Esen, 2008). The fibrous hull offers resistance to digestion and gives barley special effect during processing (Dehghan-banadaky et al., 2006). However, compared to wheat the bran is less tough and shatters easy during processing like roller milling or grinding (Jadhav et al., 1998), improving digestion and nutritional utilization of the barley.
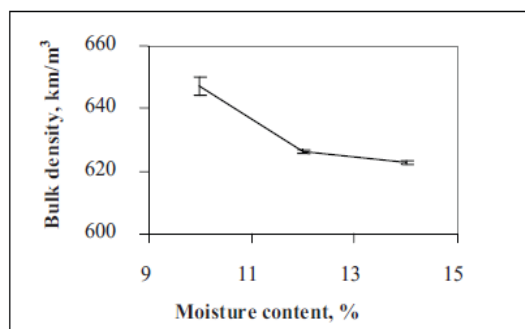
Fig, 3. Relationship between moisture content and bulk density (Öztürk and Esen, 2008).
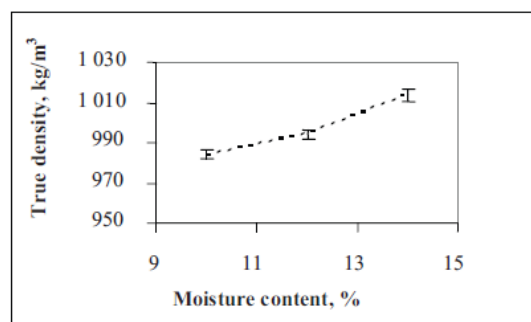
Fig, 4. Relationship between moisture content and true density (Öztürk and Esen, 2008).

2.2. Chemistry and Nutritive value of Barley:

Barley has high content of carbohydrates and is mainly used as a source of energy in animal feed. Starch is the predominant carbohydrate and makes about two third of the total dry weight of the barley grain (Table 1). Characteristics of barley starch will be discussed later. Barley also contains considerable amount of "Non-starch polysaccharides (NSP)". Like all cereals, these include β-D- glucans, pentosans (mainly arabinoxylans) and cellulose (Samuel, 1991). However, the concentration of NSP is higher in barley than other cereals like corn, wheat and sorghum. The NSPs are present in two forms with respect to solubility i.e. soluble NSPs and insolube NSPs. In barley, soluble NSPs are mainly β-glucans and in wheat, rye these are arabinoxylans. Maize and sorghum have less amount of NSPs. Cereal by products like wheat bran have high content of NSPs.

These NSPs together with proteins play an important role during digestion of starch especially in monogastric animals and poultry in particular (Rowe et al., 1999). The NSPs increase the viscosity of the digesta by complexing with glycocalyx of the intestinal brush boarder forming a thick watery layer. The high viscosity interferes the absorption of nutrients in small intestine by hindering the interaction of enzymes and nutrients. In monogastric animals, negative effects of NSPs can be minimized by the use of enzymes (Choct, 1997). In ruminants, the negative effects of soluble NSPs are not well known. This may be due to combination of fermentative and enzymatic digestion in the stomach and intestine along with hindgut fermentation where by undigested carbohydrates escaping small intestine are broken down and absorbed as volatile fatty acids. However, NSPs may create a bloat like condition also known as "gas colic" in the hind gut (Rowe et al., 1999). The insoluble NSPs have apparently no detrimental effects in both groups of animals. They can only affect the consistency of excreta as these have ability to hold large amount of water (Choct, 1997).

Compared to maize and sorghum, barley contains less starch and more fiber (NDF). Thus, since NSPs not are a problem in ruminants, barley is preferred in ruminant feeding because the reduced amount of rumen fermented starch will prevent the risk of rumen lactic acidosis (Nikkhah, 2012).

Table 1. Nutrients in barley compared to corn and wheat. Source: NRC 2001

Nutrients	Barley	Corn	Wheat
Dry Matter (%)	88	89	88
Crude protein (% of dry matter)	13	10	15
Starch (% of dry matter)	65	76	76
NDF[1]	20.8	3.1	13.4
ADF[2]	7.2	9.0	4.4
Ether Extract	2.2	4.2	2.3
Ash	2.9	2.5	2.0
Net energy for lactation (NEL, Mcal/Kg)	1.81	1.96	1.74

1. *Neutral Detergent Fiber*
2. *Acid Detergent Fiber*

In addition to carbohydrates, barely contain some proteins ranging from 10 to 13% of dry mater. This is higher than in corn but lower than in wheat (Table 1). Like all cereals, barley has a low content of essential amino acids but the concentration of lysine, cysteine, methionine and tryptophan is higher than corn.

Barley has less fat contents as compared to corn and wheat. It has less zinc, vitamin C and Vitamin B12 than other cereals. However it is rich in potassium, sulfur, Iron, molybdenum, Vitamin A and Vitamin E than corn and wheat. It has 5 time's high calcium then oats (Nikkhah, 2012).

Finely, it is important to note that different varieties of barley have different nutritional properties and thus can be selected to suit various livestock best. For example in poultry barley with lower NSPs and fiber content are best whereas ruminants require barley with higher content of fiber and soluble NSPs that may help the starch to escape ruminal degradation and thus provide bypass of starch to the small intestine (Nikkhah, 2012).

2.2.1. Characteristics of Barley Starch:

To determine the extent and rate of digestion, it is important to know the chemical characteristics of starch. Starch is a polymer of glucose made up of branch chained amylopectin and linear chained amylose. Amount of amylopectin and amylose varies in different cereals and also in different varieties of the same cereal. Normally amylopectin ranges from 72 to 82% while amylose ranges from 18 to 33% and both making 98 to 99% of the starch on dry matter basis. But waxy varieties of barley contain amylose as low as 1% and non-waxy varieties contain as high as 70% (Buléon et al., 1998). In barley starch, amylose proportion ranges from 30 to 460 g/kg where as in maize and wheat it ranges from 0 to 700 g/kg and 30 to 310 g/kg respectively (Svihus et al. 2005). With the increase of amylose content the temperature of gelatinization also increases (Peng et al., 1999). In waxy barley kernel, the amylose content gradually decreases from outer part of the kernel towards inside. But in normal barley kernel such distribution of amylose is not present (Andersson et al., 1999b).
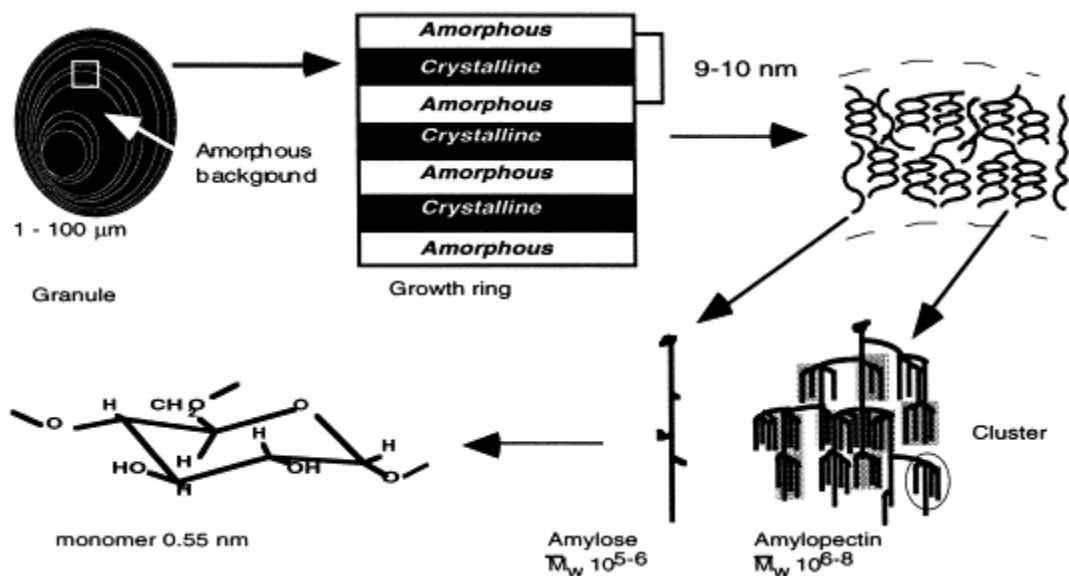
Fig, 5. Schematic representation of the different structural levels of the starch granule and the involvement of amylose and amylopectin (Buléon et al., 1998).

Amylopectin has two types of bonds α 1-4 and α 1-6 while amylose has mainly α1-4 bonds. Amylopectin has much higher molecular weight than amylose and is less crystalline in texture. It has greater solubility and degradation by amylase then amylose (Rowe et al., 1999). Starch is accumulated in the endosperm in the form of semi-crystalline granules having various polymorphic types and degrees of crystallinity. In granules it is deposited in amorphous and semi-crystalline layers with varying content of amylose and amylopectin. The

granules are found in various sizes and shapes and these are important for the functional properties of starch. The size of granules may vary from 1 to 50 μm. Starch granules in barely, wheat and rye follow trimodal distribution in sizes. For barley, the distribution curve has peaks at 18.4 μm for large granules, 12.3 μm for medium granules, and 2.2 μm for small granules (Tang et al., 2001).There are several other non-starch components which are associated with granules and these can be grouped into three categories i.e. particulate material (cell wall fragments), surface components (proteins, enzymes, amino acids, nucleic acidsand triglycerides) and integral (internal) components which include free fatty acids (FFA) and lysophospholipids (LPL). These internal lipids are special characteristic of cereal starches and in barley, wheat LPL are present in higher concentration than FFA. (Buléon et al., 1998).

Lipids are mostly associated with amylose in starch and due to high concentration of amylose at peripheral parts of barley kernel; these are found significantly more in peripheries (Andersson et al., 1999b). These non-starch component (lipids, Protein etc) complexes with starch are important with respect to digestion and processing. These complexes decrease the digestion of starch directly by blocking the digestive enzyme. Also due to hydrophobic nature of lipids swelling of starch granules is reduced which impairs digestibility of starch. During the processing of feeds, these complexes reduce the extent of gelatinization hence indirectly decreasing the starch digestibility (Svihus et al. 2005).

2.3. Digestive physiology of Ruminants:

Ruminants are compound stomach animals as their stomach is composed of four parts, the rumen, the reticulum, the omasum and the abomasums (Fig. 6). The rumen is the largest of all four compartments and can carry as much as 100 to 120kg digesta. Here bacterial fermentation of carbohydrates takes place. Fiber particles stay in rumen for longer time where as starches are digested more rapidly. Anaerobic condition in rumen favors the production of bacteria that can degrade cellulose into glucose. The glucose is then fermented to produce volatile fatty acids (VFA) mainly acetic acid, propionic acid and butyric acid. This process of fermentation is aided by the "rumination" in which fibrous rumen contents are brought back in mouth where these contents are chewed again and broken down in to smaller particles. During rumination considerable amount of saliva (about 150 liters in cattle per day) is produced which acts as buffer to neutralize the acidic environment in rumen due to microbial fermentation; maintaining a pH of 5.5 to 6.5 (McDonald et al., 2002). This is important for

proper fiber digestion as well as microbial growth. Rumination is initiated by the stimulation of epithelium of anterior rumen by fiber contents and its duration depends upon the fiber content ranging from 6 to 8 hours. VFA produced are then absorbed into blood through rumen wall and gases, mainly CH_4 and CO_2, are eructed.
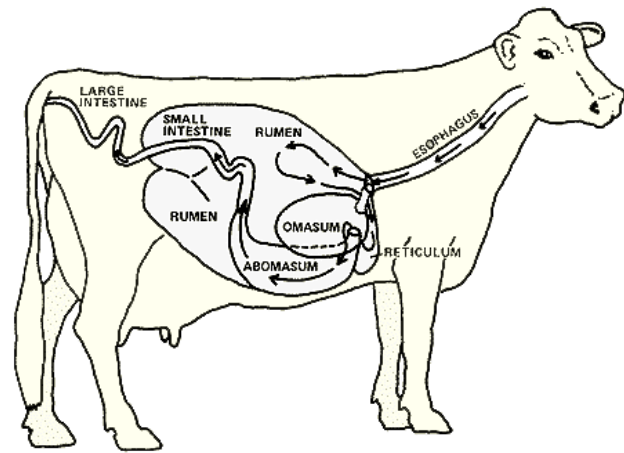

Fig. 6. Ruminant Digestive System

Reticulum acts as check point between rumen and omasum allowing specific particles (1-2 mm in size and 1.2 g/ml in density) to leave the rumen. Both reticulum and rumen are often called as reticulo-rumen because both have same contents and same culture system for anaerobic bacteria, protozoa and fungi. Undigested components of food, soluble nutrients and microbes are entered into omasum through reticulo-omasal orifice. Omasum is round in structure with a capacity of 10 liters. Its basic function is to absorb water, sodium, phosphorus and residual VFA. Abomasum is also known as "true stomach" because it acts like ordinary stomach where acidic and enzymatic digestion takes place. Here unfermented feed fractions like proteins along with bacterial proteins are digested. Food then enters the small intestine where enzymes are secreted from liver and pancreas to digest carbohydrates, proteins and lipids. Products of digestion like glucose, amino acids, and fatty acids along with some water and minerals are absorbed in small intestine. Undigested feed then enters large intestine and end part of large intestine is called cecum where some fermentation occurs. After that undigested feed components and microbial cells are excreted as feces.

2.3.1. Digestion of Carbohydrates:

The carbohydrate part of ruminant's diet includes cellulose, hemicelluloses & starch and water soluble carbohydrates. Cellulose and hemicelluloses are primarily found in plant's stem but as described earlier barley is also rich in these components as compared to other cereals. These are present in cell wall associated with lignin and are collectively called "neutral detergent fiber (NDF)". Another term "acid detergent fiber (ADF)" is used to quantify cellulose and lignin. These fibers are important for proper rumination and milk fat percentage. Lignin is resistant to bacterial fermentation in rumen. Cellulose is broken down by the action of extracellular bacterial enzymes (beta-glucosidases) in to cellobiose and then

either into glucose or glucose-1-phosphate while hemicelluloses are broken down into pentoses (mainly xylose). Fructans are converted in to fructose. Starch is attacked by amylases and maltases and is broken down in to glucose or glucose-1-phosphate. Then all these simple sugars are taken up by microbes and first converted to pyruvate which, thorough series of different pathways, is converted in to volatile fatty acids(VFAs; acetic acid, propionic acid and butyric acid), methane and carbon dioxide.
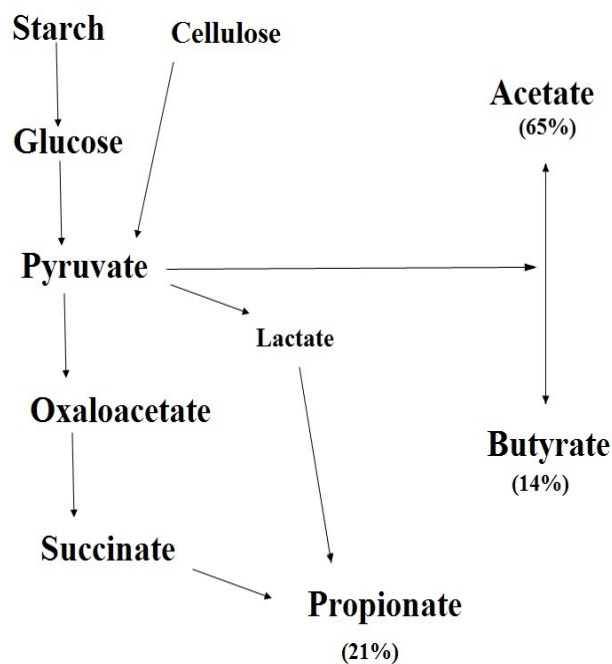
Fig. 7. Digestion of Carbohydrates. (McDonald et. al. (2002)

The percentages of VFAs shown in figure are general and these can differ from the actual values and it depends upon animal, type of diet and rumen micro flora. If the diet is rich in concentrates (starch) then it favors the production of propionate by following the lactate pathway while mature fibrous forages yield higher acetic acid proportions. In cattle, by barley base diet, the proportion of acetic acid is increased if ciliate protozoons are present in rumen and in the absence of protozoon; proportion of propionic acid is increased. Mostly these VFAs are absorbed through the walls of rumen, reticulum and omasum but 10-20% also absorb in small intestine by passing through abomasum. About 75 to 80% of starch intake is digested in rumen. Unfermented starch is digested in small intestine and about 35 to 60% of the starch entering small intestine is digested here. Also about 35 to 50% of the starch leaving the small intestine is digested in large intestine (Harmon et al., 2004)

Digestion of cellulose in the rumen is most important phenomenon whereas ruminal starch digestion is still not clear. According to some (like Huntington, 1997; Ørskov, 1986), ruminal fermentation of starch is more beneficial than intestinal digestion. This is due to poor starch digestibility in small intestine leading to risk of acidosis in large intestine. Also ruminal starch fermentation yields more microbial nitrogen. Similarly, Nocek and Tamminga (1991) found no clear evidence to enhance milk yield by post-ruminal starch digestion. However, they also suggested that intestinal starch degradation may be beneficial for milk synthesis. Others like Black (1971), Owens et al. (1986), McLeod et al. (2001) favors intestinal starch

degradation to provide more energetic and efficient nutrient like glucose instead of volatile fatty acids (VFAs). It also helps to reduce the energy loss during fermentation process in rumen in the form of heat and methane. About 13 to 18% of gross energy is lost during ruminal fermentation process (Harmon and McLeod, 2001). So, efficient digestion of starch is more complex process and it can be manipulated by source & intake of starch and processing (Rowe et al., 1999, Harstad et al., 2002, Offner et al., 2003, Svihus et al. 2005 etc).

2.3.2. Degradation of Proteins:

Feed proteins are degraded by rumen microbes into peptides and amino acids. Some amino acids are broken down further into ammonia, branched chain fatty acids and carbon dioxide. Non-protein nitrogen either from external source like feed or from internal source like recycling of urea in to rumen, also add to ammonia pool in rumen (McDonald et al., 2002).
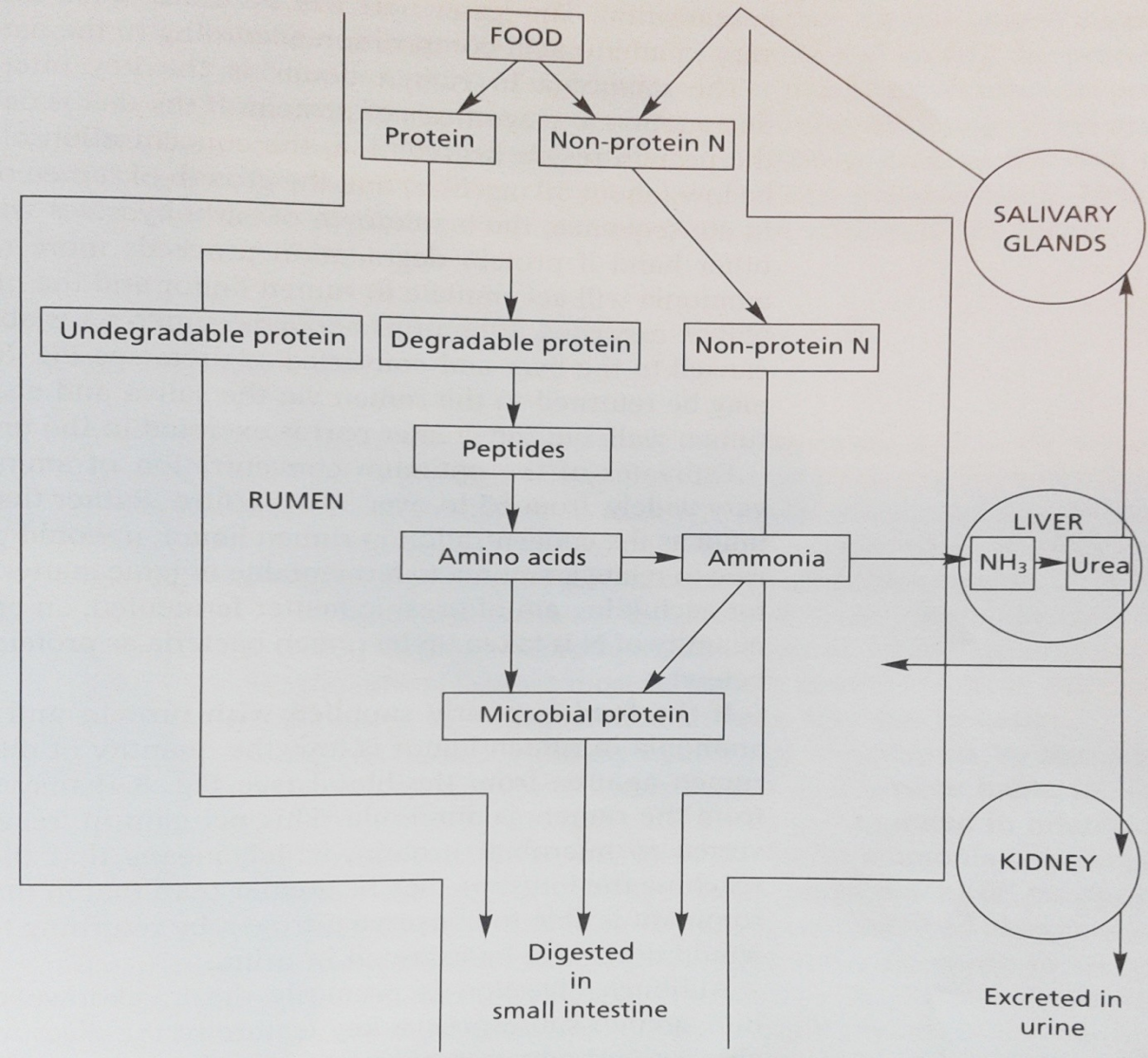

Fig. 8, Digestion and Metabolism of nitrogenous compounds in rumen. (McDonald et. al. (2002)

The products of protein digestion, like free amino acids, peptides and ammonia, are engulfed by rumen microbes to form microbial proteins. This synthesis of microbial proteins depends upon the availability of energy derived from carbohydrate fermentation. About 38 to 55% protein is present in bacteria. Not all proteins are degraded in rumen; a small part of dietary proteins remain undegraded and this resistance to ruminal breakdown depends upon many factors such as source of protein, diet formulation, method of processing etc. The microbes together with undigested proteins then enter the abomasum and small intestine where these proteins are digested by strong acid and digestive enzymes into amino acids. These amino acids are absorbed through the walls of small intestine. Clark et al. (1992) reported that an average of 59% of the non-ammonia nitrogen is supplied by microbial nitrogen which passed to small intestine in dairy cow and it has a range of 34 to 89%.

The presence of ammonia plays important role in the microbial breakdown and production of proteins in rumen. If the concentration of ammonia becomes low due to less degradation of protein in rumen then microbial growth will be slowed and consequently carbohydrate fermentation will be reduced. If the concentration of ammonia is increased by increased degradation of proteins then ammonia will start absorbing through rumen wall in to blood. This ammonia is converted into urea in liver. Majority of this urea is excreted in urine however some may be returned into rumen either by saliva or through rumen wall. Similarly effect of carbohydrate (energy source), as mentioned earlier, is also important for efficient microbial protein synthesis with respect to enhancing microbial activity and altering the rumen pH (Stern et al. 1994a). So, carbohydrate fermentation and microbial protein synthesis are closely interrelated which can be manipulated by dietary crude protein and carbohydrates. So by manipulating these feed ingredients we can optimize ruminal fermentation and increase passage of amino acids to small intestine which, in turn, will affect the synthesis of milk nutrient (Clark et. al., 1992).

Like starch fermentation in rumen, ruminal protein degradation is also under investigation; either it should be increased or decreased. Stern et al. (1994a) emphasized the degradation of dietary protein and synthesis of microbial protein in rumen especially for dairy cow. However they also demonstrated that with the increase of milk production, a considerable amount of dietary protein, provided by protein supplements, must leave the rumen undegraded to meet the protein requirements of cow.

2.4. Processing of Barely:

Whole barley grain is not efficiently digested by ruminants because of its outer covering. Digestibility of whole barley grain is 16% less then processed barley (Mathison, 1996). Thus, before feeding barley needs to be processed, to increase the exposure of endosperm to the rumen microbes and digestive enzymes. It is also important to note that barley endosperm is rapidly degradable i.e. about 78% for DM, 90% for starch and 91 % for crude protein after wheat and oats (Herrera-Saldana et al., 1990b). So, a well optimized processing along with proper dietary inclusion rates of barley grain are necessary because extensive processing and over-feeding increases ruminal fermentation of starch which may lead to sab-acute ruminal acidosis (SARA) in ruminants (Nikkhah, 2012). Extensive processing of grains also interferes with cellulose digestion when grains are fed as supplement concentrates with roughages (Ørskov, 1979).

Different processing techniques are available now a day which can be selected according to need and with respect to animals. For example, sheep can chew grain and can be fed with whole grain. Also grain processing for sheep & goat has negative effects like decreased carcass quality (soft fat) and rumenitis (Ørskov, 1979). But for cattle, the chewing ability is limited, so there is need to break seed coat either mechanically or chemically. However, cattle can utilize oat grain efficiently (Rowe et al., 1999). Most used processing techniques includes grinding, dry rolling, tempering, steam flaking, pelleting, expanding, and extrusion. But with respect to ruminants only grinding, dry rolling, steam flaking and pelleting will be discussed here.

2.4.1. Grinding & Dry Rolling:

Although Grinding and dry rolling are not identical but can be group together as both break the seed coat and reduce the particle size allowing the microbes and digestive enzymes to interact with endosperm. These processes are also known as "cold physical processes" because no heat or steam is used to reduce the particle size (Dehghan-banadaky et al., 2006). Grinding or milling is achieved by hammer mill and by this fine particles can be produced depending upon the screen being used. Grinding is most economical method to break the hull and pericarp to expose the endosperm. It increases the surface area for the action of enzymes and microbes up to higher extent because of production of very fine particles. Hemmingsen et al. (2008) finely grinded different ingredient and found that grinding of wheat yielded more fine fractions than barley. It is due to presence of fibrous hull around barley kernel. Rate of

starch degradation also increases as it is inversely related to particle size of grain (Galyean et al., 1981). Later Fiems et al. (1990) also compared grinding with other processing methods and he noticed higher digestibilities for grinding. The main disadvantage of hammer mill grinding is the production of extremely fine particles or dust.

In dry rolling, grain kernels are passed through rotating roller to crack the outer layers of grain and expose endosperm. Dry rolling produce more uniform particles with fewer fines than grinding. Finely ground barley grains may have negative effect on

Fig. 9. Hammer Mill. (Koch, 1996)

productivity of cattle because these ferment more rapidly and increase the acidity in rumen than rolled or cracked barley grains (Ørskov, 1979). Increased acidosis reduces the feed intake and which in turn decrease the rate of gain. While dry rolling improves the whole track digestibility of barley. A number of studies conducted on steers by Tolland (1976), Ørskov et al. (1978), Mathison et al. (1991a), Mathison (1996) showed improved performance by rolled barley then whole and finely ground barley.

Tempering is refinement on dry rolling in which moisture content of barley is raised to 200-250 g/Kg by the addition of water then after mixing it is stored for 12-24 hours prior to rolling (Oba, 2006). Tempering has similar but less extreme effects than dry rolling and produces fewer fine particles. In tempering individual grain typically remains intact (Rowe et al., 1999).
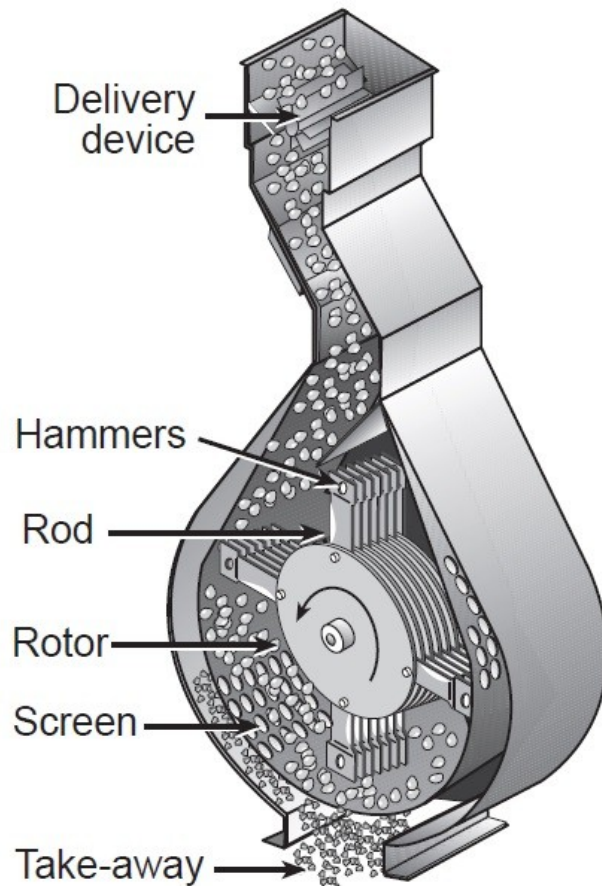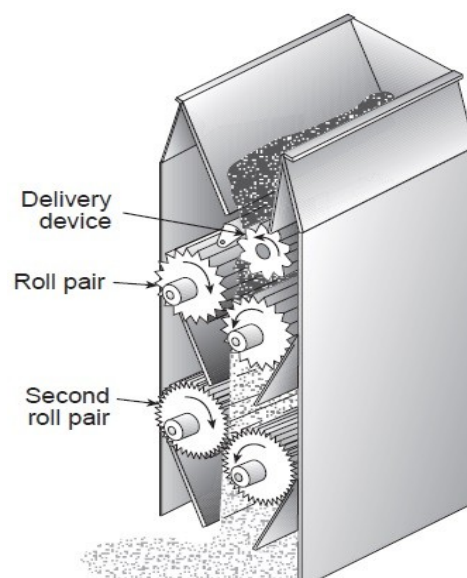
Fig. 10. Roller Mill. (Koch, 1996)

It effects by increasing the moisture content of kernel which reduces shattering as the kernel pass between the rollers (Yang et al., 1996). Also tempering helps in the activation of endogenous enzymes of grain which affect the cell walls of grain making it more soluble and fermentable(Rowe et al., 1999). It is also an energy efficient method and it consumes 11.3% less energy than dry rolling (Combs and Hinman, 1983).

Tempering has varying effects on animal performance for different groups of animal i.e. in some cases it enhance animal performance but not in others and these effects on animal performance are affected by roller setting, moisture content of whole grain and composition of the diet(Oba, 2006). Bradshaw et al., (1996) and Wang et al., (2003) showed no effect on dry matter intake, average daily gain and feed efficiency for growing cattle when tempered rolled grain was used. But tempering reduces the rate of ruminal dry matter degradation with respect to extent of processing (Wang et al., 2003; Yang et al., 1996). Tempered rolled barley also has profound effects in terms of increased whole tract dry matter digestibility, milk production and improved feed conversion to milk when used for dairy cows and these effects have been shown by Christen et al., (1996). They reported that tempered rolled barley produced 5% more milk with 10% increase in feed efficiency, 6% in dry matter digestibility, 4% in starch, 15% in NDF, 10% in CP than dry rolled barley and tempered whole barley.

2.4.2. Steam Rolling and Steam Flaking:

These processes are also termed as "hot physical processes" because of the use of heat and moisture. Steam rolling is the process in which steam is added to grains for 3 to 5 minutes prior to rolling. While in steam flaking there are two methods by the application of low and high pressure. In low pressure method, low pressure steam is applied for 30 to 60 minutes to get the temperatures of 95 to 99 °C and moisture content is increase to 150-200 g/Kg before rolling. In high pressure method moist stream at a pressure of about 3.5 kg/cm² is used for 3 minutes and then grains are cooled to 95-99 °C before rolling (Oba, 2006). Steam rolling produces less fine particles then dry rolling but it is more costly than dry rolling. Nikkhah et al. (2009) reported that steam rolling of barley increased the feed efficiency at inclusion rate of 30% and 35% in total mixed ration (TMR) compared to grinding. There was increase in energy-corrected milk yield for steam rolling, compared with grinding, at only 35% barley grain. However there was similar lactation performance at 30% dietary barley grain for both grinding as well as steam rolling. Steam rolling positively affects slowly degradable cereals like corn and sorghum. It decreases the starch degradation of barley while it increases the

fermentation of corn and sorghum (Nikkhah, 2011a). Steam rolling reduces the in situ degradability of barely starch and dry matter as compared to dry rolling but increases the degradation by enzymes (Mathison, 1996). Hayer et al. (1961) reported increased concentration of volatile fatty acids (VFA) in rumen of the cattle fed dry rolled barley as compared to steam rolled barley with no effect on the digestibility of gross energy, crude protein or starch. In feedlot system, steam rolling or steam flaking did not improve the carcass quality of growing-finishing cattle as compared to dry rolling. Also there was reduced in sacco digestibility of dry matter and starch for steam rolled barley relative to dry rolled (Engstrom et al., 1992). In contrast to steam rolling, it is suggested that steaming for longer time (>20 min) followed by flaking can improve the digestibility of barley slightly (Mathison, 1996). Osman et al. (1970) observed increase starch degradation after steam flaking in vitro studies. It is important to note that steam flaking has less effect on cereal like wheat, barley and oat with naturally high digestibility, relative to maize and sorghum which are affected most. However steam flaking brings most of the cereal grains at almost same level of rumen fermentation and digestibility (Rowe et al., 1999). Steam flaking improves total starch digestibilities together with ruminal degradation in cattle fed corn-based diet as compared to dry rolling (Theurer, 1986). In lactating dairy cows steam flaking of barley showed higher ruminal starch digestibility and lower ruminal pH than dry rolled barley at 4 hours after feeding (Plascencia et al., 1998). Zinn et al., (1996) observed an increase in total starch digestibility for steam flaked barley than dry rolled barley. In contrast to all above beneficial effects, Fiems et al. (1990) found lowered *in sacco* protein degradability for flaked grains. He also observed reduced dry matter degradability for wheat and barley but for maize it was higher. A similar study was conducted by Malcom and Kiesling (1993) in which they compared steam flaked barley and dry ground barley and found that both processes were equally effective at increasing ruminal degradability of grain. After all this it is evident that steam flaking is less beneficial in case of readily degradable gains like barley irrespective of the fact that it causes starch gelatinization and protein matrices disruption.

2.4.3. Pelleting:

Pelleting is the pressing of bulk feed material, with or without steam addition, through a hole in a metal plate with specific dimensions of opening and thickness. Pelleting is the high energy consuming process (up to 60%) but it is being used intensively in feed industry due to numerous advantages which are mainly described with respect to technical and nutritional aspects. Some of the advantages are higher bulk density, easier to convey, less duct

production, reduced feed wastage and less feed segregation (Behnke, 1994). Pelleting increases the surface area and gelatinization of starch granules which may be beneficial in starch degradation in ruminants. The purpose of pelleting is to get small units of feed with improved nutritional and physical qualities so that it will increase the feed intake while meeting the requirements of respected animal. Pelleting also acts as grinder and coarser particles produced by roller mill are grinded by the pellet press up to more extent then particles produced by hammer mill. This is due to the increase of friction by coarse particles. Svihus et al., (2004b) evaluated the pellet quality (PDI %) of different feeds using hammer mill and roller mill with varying degrees of coarseness of particles. They noted that there was small difference between the roller mill and hammer mill grinded feed having almost similar particle size.

Pelleting of poultry and pig feeds have proved much beneficial however with respect to ruminants its effects are not consistent. Gardner et al., 1997 noted a lower milk fat yield and milk fat percentage in lactating dairy cows fed the pelleted grains compared to textured grains containing both 50% barley grains. They also showed 1.16 Mcal NEL kg^{-1} DM efficiency of dry mater utilization for pelleted grains as compared to 0.86 Mcal NEL kg^{-1} DM for textured grains. However, there was no significant difference in dry mater intake and milk production. A more detailed study was conducted by Von Keyserlingk et al. (1998) in which they compared two types of concentrates. In one concentrate they pelleted all ingredients together while in other one they stream rolled barley and corn and pelleted the non grain part. Ruminal degradation of crude protein and effective degradability of dry mater were higher for pelleted concentrate but total tract dry mater disappearance was not affected by the form of concentrate. Milk and milk proteins yields and protein content were higher for pelleted concentrate but milk fat content was lower.

2.4.4. Expanding:

This process is also termed as "high pressure conditioning". In this process feed material is pushed through a barrel towards resister with the addition of steam. It creates high pressure and shear and temperature of feed stuff is increased but for very short time. After passing the outlet, pressure drops and feed material expand in volume with the decline in temperature.

This process is commonly used for monogastric animal's feed production but it can be used to improve the protein value of barley and oats for ruminants (Prestløkken, 1999a). Later, Prestløkken and Harstad (2001) compared effects of simple pelleting and expanding on

nutrient utilization and animal performance by using as barley-based concentrate. They observed increased ruminal starch digestion but decreased crude protein degradation. However intestinal digestibility was unaffected. Also, they observed increased milk production along with increased milk fat and protein content for expander treated concentrate. In another study, conducted by Tothi et al. (2003) noted no effect on effective barley starch degradability although decrease in the rate of starch degradation which was counterbalanced by increased soluble starch fraction.

2.4.5. Geletinization of Starch:

Both pelleting and expanding process results in gelatinization of starch which is accomplished by addition of heat and water during the process of conditioning. Process of gelatinization starts with the swelling of amorphous regions in starch granules in the presence of water (Donald, 2001) and it increases with the increase of temperature. Swelling of amorphous regions exerts pressure on crystalline regions by breaking the bonds between two regions resulting in the loss of crystallinity (Svihus et al. 2005). Swelling also increases viscosity by leaching of starch amylose. The onset of gelatinization occurs at 60 C and this temperature is characteristic for each starch type (Evers et al. 1999).
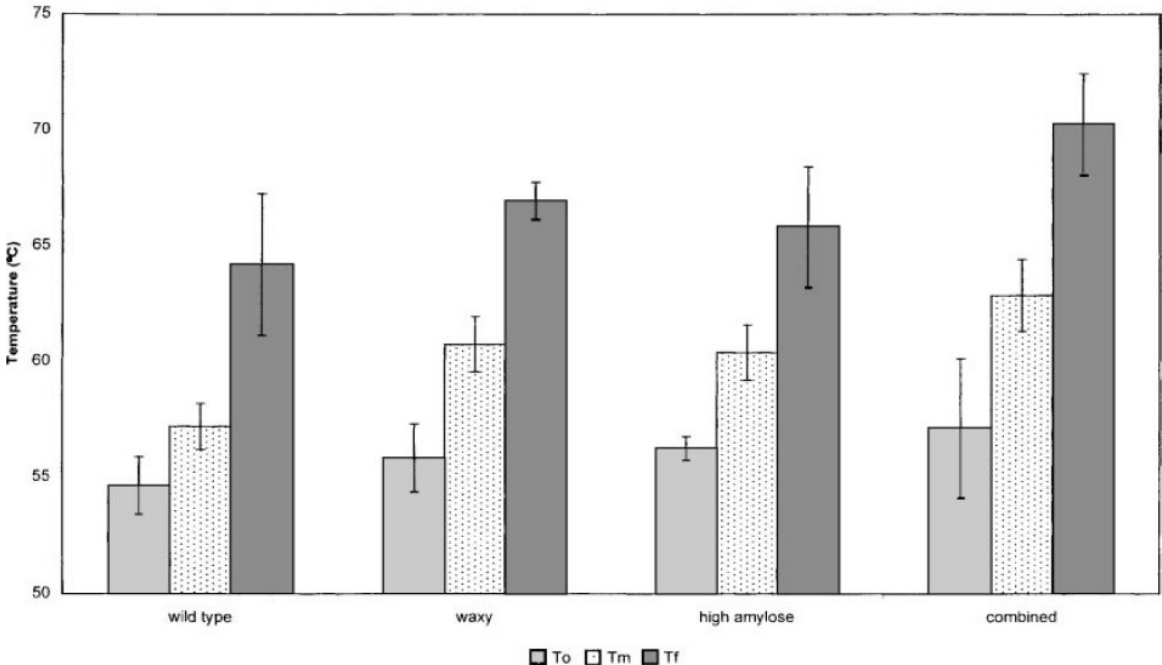

Fig, 11. Gelatinization temperature profile parameters of four different barley starches, given as mean values over three environments. To, Tm and Tf are onset, mid-point and final temperatures respectively. (Source: Swanston et al., 2001)

Swanston et al., (2001) showed temperature of gelatinization for different varieties of barley and found lower gelatinization temperature for normal barely as compared to high-amylose and high-amylopectin barleys (Fig. 11)

Gelatinization of starch has both technical and nutritional effects. Technically, it enhances the physical quality of processed feed by increasing the binding between particles (Wood, 1987). Nutritionally, it increases the starch digestion by making more susceptible for amylase action (Holm et al. 1988).

3.0. Own Study:

3.1. Materials and Methodology:

The experiment was conduct in two parts. In first part, different diets were processed and produced to analyze the technical aspects of feed and in the second part 3 selected diets were fed to animals to examine the digestibility of ingredients and performance of animals.

Processing of diets:

Total 12 pure barley based feeds were produced at Fortek (Center for Feed Technology) with three different treatments. Three diets were hammer milled with screen size of 2mm, 4 mm and 6mm by a hammer mill (E-22115 TF, Muench - Wuppertal, Germany). Samples of mash were taken for analysis and then these diets were pelleted to 5mm diameter by the pellet press (RPM 350.100, Munch-Edelsthal, Wuppertal, Germany). Three diets were roller milled with roller gap distance of 0.25mm, 0.75mm and 1.5mm by roller mill (DT900-12, CPM - Roskamp, USA). Samples of mash were taken and then these diets were pelleted as before. In both milling treatments, pelleting was done at similar as possible conditions. Conditioning temperature was 75 $^\circ$C and capacity 1000 kg per hour. Energy consumption was recorded. From above different treatment, three diets were selected and fed to animals. These diets were (1) 2mm hammer milled mash, (2) 1.5mm roller milled mash and (3) 1.5mm roller milled and pelleted (5mm). In all these 3 diets 5% molasses was added by twin shaft paddle mixer (Forberg AS, Larvik, Norway) for 300s. Protein Concentrate FORMEL 140 was purchased from Felleskjøpet Agri, Gardermoen, Norway. It was grinded by hammer mill with 2mm screen size and pelleted separately.

Analysis of particle size distribution and pellet quality:

Particle size distribution of mash was measured by both dry sieving and wet sieving on Retsch AS200 sieving machine (Retsch GmbH & Co., Haan, Germany) while particle size distribution of pelleted feed was determined by only wet sieving method. In wet sieving method, 100 grams of feed samples were soaked in water for 2 hours prior to sieving so that all the pellets were dissolved completely. Then these samples were sieved through series of sieves for 10 minutes at amplitude of 1.5 with excess of water. All sieves with remaining feed material were placed in oven at 103 °C overnight. The particle size distribution was then calculated by measuring the material left on each sieve. The mean particle size distribution was determined by ASAE Method S319.4 (ASAE, 2008). The pellet quality was determined by Holmen Tester, NHP 200 (TekPro Ltd., UK).

Animal Experiment:

Animal Experiment was conducted at metabolism barn, IHA. Three lactating dairy cows, fitted with a permanent rumen cannula, were selected. Standard animal's experiment conditions were maintained as directed by Norwegian Animal Research Authority. Average milk production was 33kg per cow. A balance ration was formulated comprising of 8.5 kg of processed barley, 3.5 kg of protein concentrate and 8 kg dry matter (DM) silage, with a concentrate to roughage ratio of 60:40, as shown in Table 2.

Table 2. Expected daily milk yield and planned feed intake animal experiment.

Animal ID	3954	4240	4288
Expected Milk Yield, kg	30-35	30-35	30-35
Planned feed level			
Silage, kg DM	8.0	8.0	8.0
Processed Barley, kg	8.5	8.5	8.5
Protein Concentrate, kg	3.5	3.5	3.5

The experiment was conducted in 3 periods with 10 days in each period following a 3x3 Latin square design. In each period, each cow was fed with same amount and quality of silage and protein concentrate but different processed barley as HM 2mm (mash), RM 1.5mm (mash) and RM 1.5mm (pelleted). The amount of feces was determined by use of Yb-acetate and Co-EDTA as markers. Representative samples of silage, protein concentrate, barley concentrate, ruminal contents and feces were taken in each period for chemical analysis. Samples for feces and rumen contents were taken on day 9 and 10 in each period. Milk production was recorded everyday in each period and sample of milk was taken for analysis.

Chemical Analysis:

Feed and fecal samples were analyzed for dry matter, ash, crude protein (Kjeldahl-N * 6.25), starch, NDF and starch at the IHA laboratory. Dry matter, ash, fat and Kjeldahl-N was analysed as described by European Commission Regulation ((EC) No 152/2009). Neutral detergent fiber (NDF) was analyzed as described by Mertens (2002) without ash adjustment using the Ankom fiber analyzer (Ankom Inc., USA) whereas starch was analyzed as described by McCleary et al. (1994). Fecal samples were in addition analysed for the markers Cr og Yb mainly as described by Siddons et al. (1985), using atomic absorption.

Statistical Analysis:

The effect of treatment s on digestibility of dry matter, protein, starch, NDF, fat and ash was tested by GLM procedure in SAS (SAS, 1996). Differences were determined using pdiff in the LSMEANS statement. Differences between means were considered significant at *P* < 0.05, unless stated otherwise.

3.2. Results:

Paritcle size distribution and Pellet quality:

There was increase in particle sizes with the increase in screen sizes in hammer mill and gap between the rolls in roller mill as shown in Fig 12 and Fig 13. The mean particle size for hammer mill with screen size 2mm, 4mm, 6mm were 504μm, 820μm, 985μm and for roller mill with gap distance between rolls 0.25mm, 0.75mm, 1.5mm were 1069μm, 1552μm, 2199μm. Hammer mill produced more fine particles then roller mill. Wet sieving analysis yielded significantly more fine particles in case of both hammer mill and roller mill, especially with small screen sizes in hammer mill and smaller gap distance between rolls in roller mill.
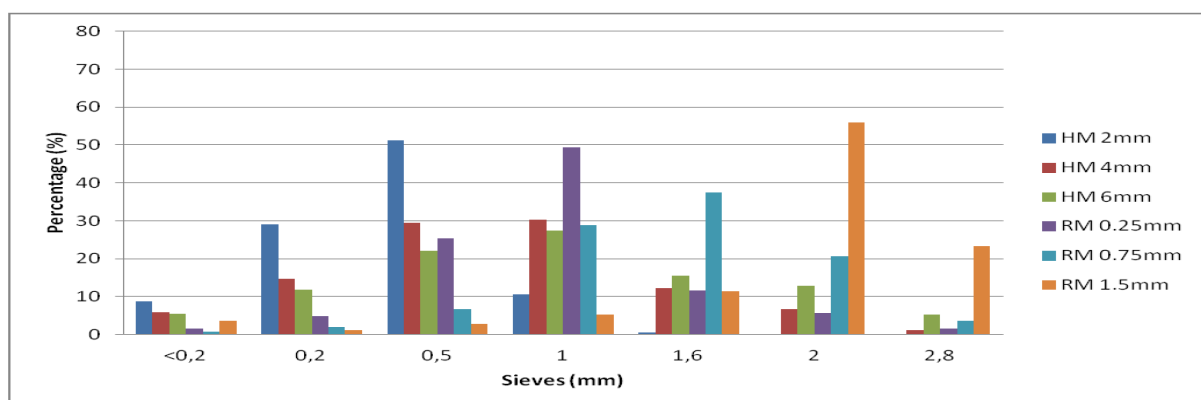
Fig 12. Particle size distribution in hammer mill and roller mill by dry sieving. HM= Hammer mill, RM= Roller mill
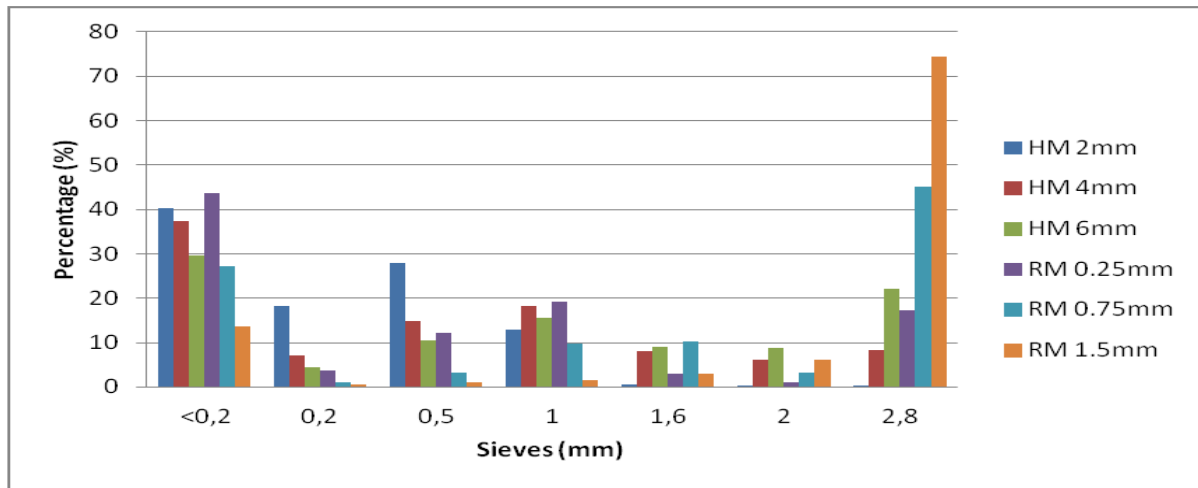
Fig, 13. Particle size distribution in hammer mill and roller mill by wet sieving. HM= Hammer mill, RM= Roller mill

Wet sieving showed more fine particles for RM 0.25mm as compared to HM 2mm although in case of dry sieving analysis numbers of fines were quite higher for HM 2mm than RM 0.25mm.
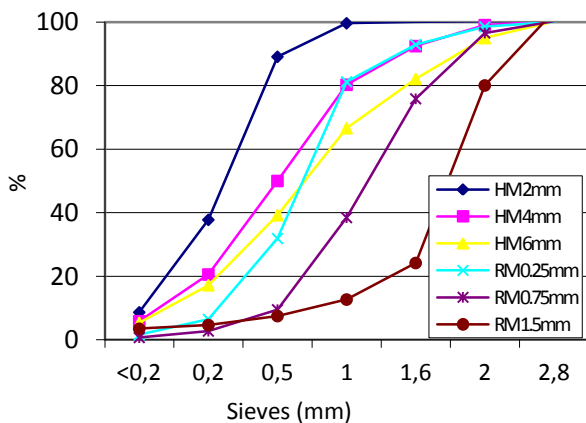
Fig 14. Cumulative Particle size distribution hammer mill and roller mill by dry sieving analys HM= Hammer mill, RM= Roller mill

Fig 15. Cumulative Particle size distribution in hammer mill and roller mill by wet sieving analysis. HM= Hammer mill, RM= Roller mill

Cumulative particle size distributions, by wet sieving and dry sieving analyses, for both hammer mill and roller mill have been shown in figures below (Fig, 14 & Fig, 15). It is obvious that curves for hammer mill are steeper than roller mill which means less variation in particle sizes for hammer mill. Wet sieving analysis showed less steep curves for hammer mill and roller mill then dry sieving.

Pelleting, acting as grinder, resulted in increase of fine particles (Fig. 16). Mean particle size was reduced to 247μm, 411μm, 568μm, 364μm, 540μm, 827μm for hammer mill 2mm, 4mm, 6mm and roller mill 0.25mm, 0.75mm, 1.5mm grinded feeds respectively. It also

decreased the differences in particles size between hammer mill and roller mill, making feed samples more homogeneous (Fig. 17)
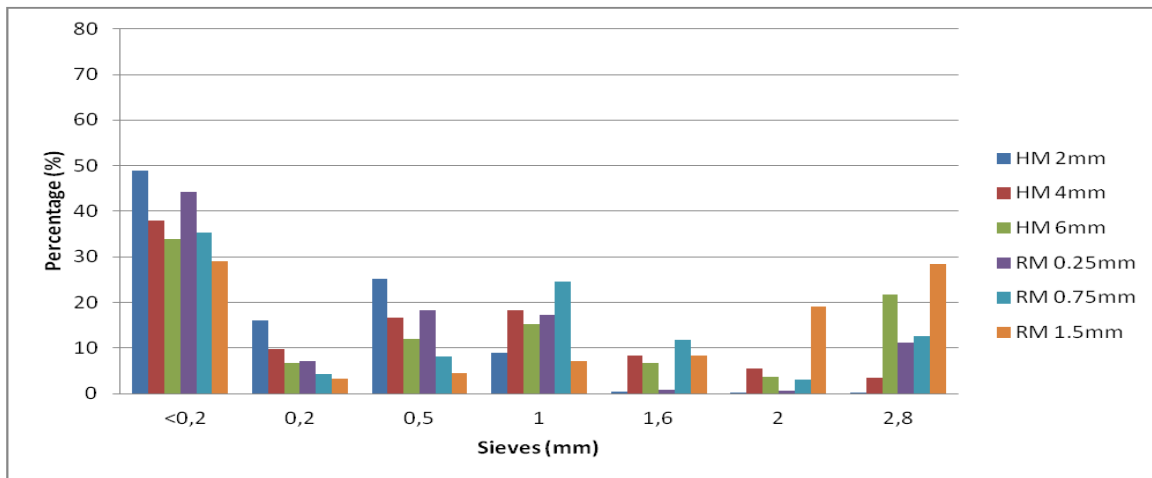
Fig 16. Particle size distribution after pelleting(5mm) by hammer mill and roller mill (wet sieving analysis). HM= Hammer mill, RM= Roller mill

Processing data for pelleting along with energy consumption in milling process are shown in table, 3. Energy consumption decreased with the increase of screen size in hammer mill but increased with increase of gap distance between the rolls in roller mill. However, overall energy consumption for roller mill grinding was significantly higher than hammer mill.
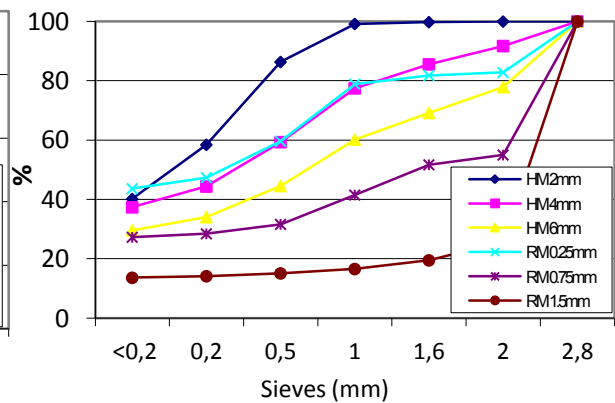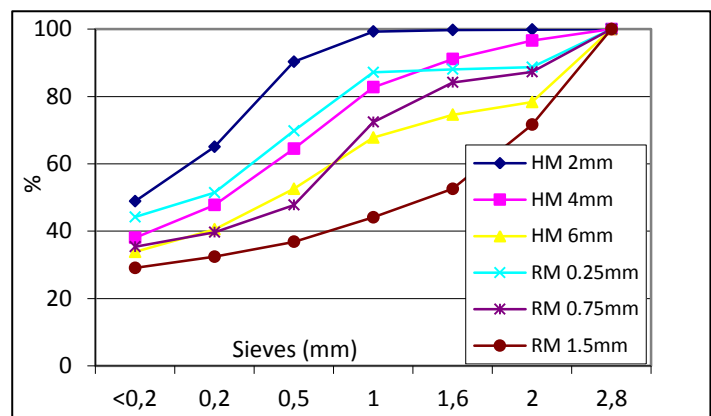

Fig 17. Cumulative Particle size distribution after pelleting by hammer mill and roller mill (wet sieving analysis). HM= Hammer mill, RM= Roller mill

Table, 3. Processing data for pelleting with energy consumed in milling process

Processing Data	Hammer Mill			Roller Mill		
	2mm	4mm	6mm	0.25 mm	0.75mm	1.5mm
Density Kg/t	0.56	0.52	0.48	0.41	0.39	0.44
Feeding Rate, %	55	56	58	66	70	64
Capacity, Kg/t	1000	1000	1000	1000	1000	1000
Motor Load, %	36	34	33-34	36	37-38	39-40
Conditioning Temperature, ° C	75	75	75	75	75	75
Motor Load , amps	32-33	30-31	30-31	32	34	34-35
Specific Energy Consumption (kWh/t) for Milling	15.7	15.3	14.6	16.6	15.7	15.1
Specific Energy Consumption (kWh/t) for Pelleting	19.9	19	18.7	19.6	20.8	21.1

Similarly pelleting of hammer mill grinded feeds consumed less energy than roller mill grinded feeds. A higher energy was consumed during the pelleting of roller mill grinded feed with 0.75mm and 1.5mm gap distance between the rolls. Overall pellet durability values were higher for hammer mill grinded feeds as compared to roller mill grinded. There was decrease in pellet quality with increase in coarseness of feed particles as shown in figure and roller mill 1.5mm grinded feed gave lowest PDI value.
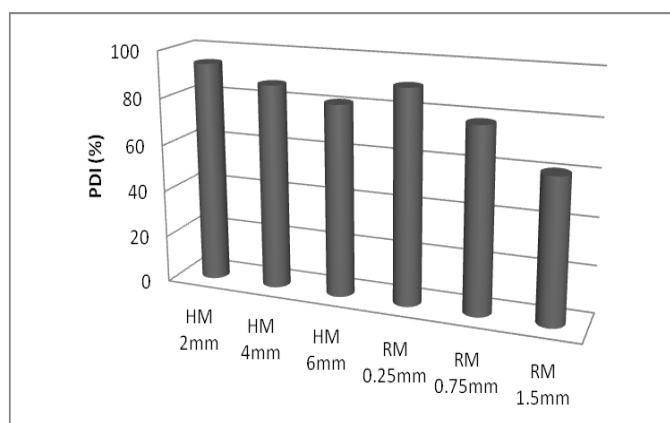
Fig 18. Pellet Durability Index (PDI),

Feed Intake & Nutrient Digestibility and Milk Production:

Results for chemical composition of feed are shown in Table 4 whereas for feed intake and digestibility of different ingredients are shown in Table 5. There was no any significant effect of treatment on composition of barley. Starch and NDF contents were decreased, numerically, for RM 1.5mm pelleted feed as compared to other two treatments. Protein concentrate was also a source of fats and mineral, not only protein.

Table 4. Chemical composition of experimental feeds (g/kg DM if not stated otherwise).

	Barley					Protein Conc.	Silage
	HM 2mm (Mash)	RM 1.5mm (Mash)	RM 1.5mm (Pelleted, 5mm)	Std. Dev.	P-Value		
Dry Matter (DM), g/kg	951.0	951.7	953.0	2.19	0.606	964.3	360.0
Protein	19.9	19.7	19.9	0.39	0.705	325.8	159.1
Starch	568.5	583.9	564.8	15.92	0.453	137.6	17.1
NDF	191.4	183.2	174.5	14.68	0.503	153.5	531.6
Fat	20.9	16.8	18.4	1.86	0.216	80.4	54.1
Ash	26.5	26.3	28.9	0.75	0.083	147.5	56.0
Residue	68.0	66.8	88.7	24.25	0.565	155.2	182.1

HM: Hammer Mill, RM: Roller mill
NDF: Neutral Detergent Fiber.
a, b means with in row significantly difference at 5% level.
Std. Dev.: Standard Deviation.

All the treatment did not affected dry matter intake (silage) significantly (P> 0.05). Numerically, feed intake was lowest for hammer mill treated diet and highest for pelleted diet. Ruminal digestibility of all nutrients was not significantly different (P> 0.05) for all treatment of diets. Ruminal digestibility of dry matter was numerically lowest for HM 2mm treated mash diet. Also, ruminal digestibility of NDF was higher for RM 1.5mm pelleted diet whereas it was similar for HM 2mm and RM 1.5mm treated mash diets. Ruminal digestibility of

protein was higher for RM 1.5mm mash diet. Ruminal digestion of fat for RM 1.5m treated mash diet and pelleted diet, was negative.

Table 5. Feed Intake, ruminal and total tract digestibility of different ingredient. (On dry matter bases)

	Treatment			Std. Dev.	P-value
	HM 2mm (Mash)	RM 1.5mm (Mash)	RM 1.5mm (Pelleted, 5mm)		
Actual Feed Intake , kg/day:					
Silage	10.50	10.75	10.92	1.04	0.891
Barley diet	8.08	8.09	8.10		
Protein concentrate	3.38	3.38	3.38		
Total	21.96	22.22	22.40	1.05	0.867
Ruminal Digestability, %:					
Dry Matter	34.04	36.52	36.53	3.09	0.608
Protein	3.60	5.24	2.79	2.58	0.588
Starch	82.72	80.11	80.78	2.21	0.470
NDF	57.82	57.82	65.69	5.32	0.311
Fat	4.07	-4.82	-1.15	7.92	0.511
Ash	-176.8	-160.0	-168.9	9.78	0.311
Total Tract Digestability, %:					
Dry Matter	76.0	75.8	75.8	0.24	0.625
Protein	72.4	73.8	72.4	0.73	0.197
Starch	98.2	96.9	97.2	1.32	0.547
NDF	66.0[a]	65.3[b]	65.4[ab]	0.18	0.078
Fat	71.5	69.3	72.3	2.30	0.434
Ash	58.9	55.8	59.7	3.04	0.413

HM: Hammer Mill, RM: Roller mill
NDF: Neutral Detergent Fiber.
a, b means with in row significantly difference at 5% level.
Std. Dev.: Standard Deviation.

The total tract digestibility of dry matter, protein, starch, fat and ash was not significantly different (P> 0.05) for all three treatments of barley. In case of NDF, digestibility of HM 2mm treated mash diet and RM 1.5mm treated mash diet was significantly different from each other (P= 0.044), having higher digestibility of NDF for HM 2mm treated mash diet . Also, there was tendency for RM 1.5mm pelleted diet to be significantly different from HM 2mm treated diet (P= 0.067) but not from RM 1.5mm treated mash diet (P= 0.438). However, numerically, digestibility of protein was higher for RM 1.5mm treated mash diet as compared to other two treatments. But digestibility of starch was highest for HM 2mm treated mash diet and was lowest for RM 1.5mm treated mash diet.

Milk production and its composition data is shown in Table 6 for three different treatments of diets. There was no significant difference (P> 0.05) in overall milk production for all three treatments. However, milk production for RM 1.5mm treated mash diet was numerically slightly higher than other two treatments. Concentration of protein for RM 1.5mm pelleted diet was significantly higher (P = 0.032) from RM 1.5mm treated mash diet but not from HM

2mm treated mash diet (P = 0.187). Concentration of fat was numerically higher for RM 1.5mm treated diet than both HM 2mm treated and RM 1.5mm pelleted diets. There was significant difference in concentration of urea for HM 2mm mash diet and roller mill 1.5mm pelleted diet (P=0.013).

Table 6. Daily milk Production and its contents

	Treatment			Std. Dev.	P-value
	HM 2mm (Mash)	RM 1.5mm (Mash)	RM 1.5mm (Pelleted, 5mm)		
Milk, kg	32.1	32.6	32.4	0.31	0.325
Protein, kg	1.11	1.12	1.13	0.015	0.422
Fat, kg	1.17	1.24	1.19	0.042	0.342
Lactose, kg	1.54	1.56	1.56	0.022	0.426
ECM, kg	31.3	32.3	31.8	0.69	0.401
Protein, %	3.47[ab]	3.42[b]	3.49[a]	0.02	0.062
Fat, %	3.66	3.78	3.66	0.10	0.399
Lactose, %	4.78	4.80	4.80	0.02	0.473
Urea, mmol	4.71[a]	4.58[ab]	4.43[b]	0.04	0.026
FFA, meqv	0.52	0.65	0.59	0.10	0.462

HM: Hammer mill, RM: Roller mill
ECM: Energy Corrected Milk
FFA: Free Fatty Acids
a, b, means with in row significantly difference at 5% level.
Std. Dev.: Standard Deviation.

3.3. Discussion:

Effect of processing on Particle size distribution and Pellet quality:

Particle size reduction of grains is the important process with respect to nutritional and physical quality of feed. Nutritionally, it improves digestibility by exposing grain's interior to digestive enzymes and thus performance of animals, whereas physically, it results in improved mixing behavior and pellet quality (Behnke, 1996). The aim of first part of the present study was to discuss pattern of particle size distribution by hammer mill and roller mill along with pelleting process and specific energy consumption during these processes. In the present study, lower values of mean particle size for hammer mill as compared to roller mill were found (Fig. 12) which is in accordance with previous studies (Koch, 1996; Waldroup, 1997; Boyles et al., 2001). Impact is the primary force used in hammer mills to reduce particle size, while, in roller mills, particle size reduction is accomplished through a combinations of forces (compression and shearing) and design features of the rolls (Koch, 1996). In hammer milling, fine particle are produced by the transfer of energy from high-speed rotation hammer tips (high kinetic energy) to slow moving grains (low kinetic energy).

The process is aided by a fluidized bed of material swept along the face of the screen by the hammers (Koch 1996; Anderson, 1994). Thus, the speed of hammers and the screen size determine particle size in hammer milling. In roller mills, particle is determined by distance between the rolls and number of pairs of rolls together with uniform and constant supply of material. Roller mills produce a more uniform particle size distribution, give fewer fines and are more energy efficient than hammer mills (Koch, 1996; Waldroup, 1997; Boyles et al., 2001) which is in agreement with the present study (Fig. 14 & Table 3).

Reduced particle sizes by pelleting (Fig. 16) are in accordance with previous studies (Wodra et al., 1995; Svihus et al., 2004b). The reduction in particle size is due to grinding action of the rolls in the pellet press. The effect of grinding is higher on coarse particles than fine particles (Svihus et al., 2004b) and this can be seen by differences in particle size before and after pelleting. Thus, in practice, pelleting even out differences in particle distribution both between and within hammer and roller milling, resulting in increased homogeneity (Fig. 17). As expected, the pellet durability index (PDI) values are higher for finer grinding (Fig. 18) and hammer milling gave more durable pellet than roller milling. A probable explanation is that fine grinding increase water absorption capacity of feed particles (Hemmingsen et al., 2008), aiding gelatinization and making starch stickier. In addition compression of feed material becomes easier with small particles, improving pellet durability (Wodra et al., 1995). Since, the roller mill has less effect on fiber (Koch, 1996); large fibers might have induced a weak spot in the pellet due to their stiffness and elasticity (Thomas et al., 1998). However, Zimonja et al., (2008) reported higher pellet durability for inclusion of fine fibers than control (without fibers), but, inclusion of coarse fibers affected negatively. Usually, small particles offer less resistance while passing through the pellet die than course particles. Lower consumption of specific energy when pelleting hammer milled compared to roller milled material confirm this (Table 3). Also, large fiber particles produced by roller mill have higher coefficient of friction and low treatability by press (Thomas et al., 1998; Kulig, 2007; Manickam et al., 2011), thus, increasing energy consumption. However, lower values of energy consumption for the pelleting of coarse hammer milled feeds contradicts above explanation. This may be due to two reasons; firstly, high water absorption capacity by fine particles (Hemmingsen et al., 2008) and secondly, very slow absorption of water by insoluble fibers (Jonsson et al. 2003). So, under same conditioning, more water could be available for lubrification during pelleting by coarse fiber particles and thus, consuming less energy.

However, Zimonja et al., (2008) found same values of energy consumption for fine and coarse fibrous material.

Effect of processing on Nutrient digestion:

Extent and site of starch, protein and fiber digestion in cattle is affected by grain processing (Mathison, 1996). Processing of highly degradable grains like barley needs more attention because responses in animal performance owing to different methods of processing are more variable (Hunt, 1996). Effects of different processing methods used for barley for ruminants like grinding, dry rolling, tempering, steam rolling, pelleting and expanding have been discussed by many researchers. However limited research is available on comparative study of grinding, dry rolling and pelleting of barley as cattle feed. Sadri et al. (2007) compared ground, dry-rolled and steam rolled barley grain and found that processing methods did not affect the rumen pH, apparent nutrient digestibility, yield and composition of milk. Bengochea et al. (2005) comparing coarsely rolled barley (2,770 µm), moderately rolled barley (2,127 µm), and finely rolled barley (1,385 µm), reported no effect of processing on total tract digestibilities of crude protein and NDF but total tract digestibility of starch was increased linearly from coarsely rolled to finely rolled barley. Arieli et al., (1995) showed lower dry matter and starch digestiblities for heat treated barley as compared to control by in sacco trial. Similarly, Ljøkjel et al. (2003a,b) noted decreased starch and protein digestibility for heat treated barley. Von Keyserlingk et al. (1998) reported a lower rumen pH at 4h post-feeding and higher ruminal dry matter digestibility for pelleted feed as compared to steam rolling. In the present study, all three treatments (hammed milled, roller milled and pelleted) had no statistically significant effect, just numerical effects, on the feed (silage) intake, total tract as well as ruminal digestibilities of dry matter, starch and protein. Although not significant, these findings are in line with Nikkhah and Ghorbani (2003), Sadri et al. (2007), Bengochea et al. (2005). However, significantly higher total tract digestibility of NDF for hammer milled diet (Table 5) is in correspondence with Owens et al. (1986), but ruminal degradation of NDF was equal for hammer mill and roller mill treated except pelleted feed. Reason for difference in NDF digestibility will be discussed together with starch digestion.

Since, the feeding of barley was constant, the effect of processing on feed intake (silage) is in accordance with Hironaka et al., (1978) where a diet with geometric mean particle size of 867µm showed higher feed intake then finely ground (476µm) and coarsely ground (1525) barley based feed. Increased feed intake for the pelleted diet can also be due to increased

ruminal digestion of NDF (Oba and Allen, 1999). However, Sadri et al., (2007) did not found such differences in feed intake for ground, dry-rolled and steam rolled barley grain. Numerically, higher digestibility of starch for hammer mill treated diet is in agreement with Galyean et al., (1981) as starch digestion in the rumen increases with the decrease in particle size. Larsen et al., (2009) also reported a higher starch digestibility for hammer mill (3mm screen) grinded barley than rolled. A lower ruminal digestibility of starch for roller milled mash is due to course particles which have tendency to pass to small intestine (Rowe et al., 1999; Fiems et. al., 1990). However, total tract digestibility of starch was also lower which indicates inadequate post-ruminal starch digestion and it favors the notion espoused by Ørskov (1986) and Huntington (1997) who preferred ruminal degradation of starch because of apparently poor digestibility of starch in small intestine. This lower digestibility of starch in small intestine may be due to limited capacity of enzymatic hydrolysis of starch (Ørskov, 1986) but according to Owens et al. (1986) it is the form of the dietary starch which determines the starch utilization. The processing method which tends to increase the starch digestion in rumen also increases post ruminal digestion of starch (Nocek and Tamminga, 1991). The current study (Table 5) showed the same pattern of ruminal and total tract digestibilities of starch. However, reducing particle size to increase post-ruminal starch digestion also increases ruminal fermentation of starch which may leads to sub acute ruminal acidosis (SARA) (Krause and Oetzel, 2006). Owens et al. (1986) suggested a particle size of larger than 250µm and smaller than 1000µm to get maximum intestinal starch digestibility as well as avoiding ruminal acidosis problems and these findings are in correspondence with current studies. In other studies contacted by Taniguchi et al. (1992 &1993), Okine and Kennelly (1994) showed correlation of bypass protein supply to small intestine and post ruminal utilization of starch. They found that increasing the level of protein in small intestine, increases the release of pancreatic enzymes to digest starch. A comparatively lower digestibility of starch for pelleted feed than hammer mill treated feed is in agreement to Dehghan-banadaky et al., (2006) who suggested that particle size reduction during pelleting process has more effect on starch digestion than gelatinization of starch especially in case of barley. Normally, due to gelatinization of starch by heating, accessibility of starch to microbial degradation increases (van Soest, 1994) but due to limited extent of starch gelatinization during ordinary pelleting (Svihus et al., 2005) such affects are minimal.

A higher total tract digestibility of NDF for hammer mill is may due to pattern of fermentation taking place in large intestine although ruminal digestion is the same for hammer

mill and roller mill. NDF digestion mostly takes place in rumen and the rest in large intestine. With the increase of fermentation, pH of the rumen liquor drops, inhibiting fiber fermenting microbes and thus depresses NDF digestion (McDonlad et al., 2002). However, an equal ruminal digestion of NDF for hammer mill and roller mill treated diets despite higher starch fermentation in hammer mill treated diet can be attributed to buffering mechanism of saliva which maintains ruminal pH. However, in large intestine such buffering system is not present. In case of hammer mill treated diet, much of starch is already digested in rumen and small intestine so a relatively higher quantity of starch is reaching large intestine incase of roller mill treated diet. This favors the elevated starch fermentation for roller mill treated diet as compared to hammer mill which lowers the pH and, thus, inhibiting digestion of cell wall contents (Owens et al. 1986). An increased ruminal digestion of NDF for pelleted diet may be due to increased solubility of fibers by processing (Vranjes and Wenk, 1995).

Beauchemin et al. (2001) reported that with increase processing of barley, flow of crude protein to small intestine can be increased. Ljøkjel et al., (2003a) found reduced degradation of protein in rumen. Prestløkken (1999b), comparing pelleting and expanding, showed decreased ruminal degradation of protein by pelleting as well as expanding without affecting the total tract digestibility thereby shifting the site of protein digestion from the rumen to the small intestine. Same affects were obtained in the current study (Table 5) where addition of heat as well as reduction of particle size during the process of pelleting decreased the ruminal degradation of protein. Addition of heat disrupts three dimensional structure of protein thereby exposing the hydrophobic groups and hence decreasing protein solubility (Voragen et al., 1995) and consequently ruminal degradation of protein is reduced (Prestløkken, 1999b). However, ruminal and total tract digestibility was higher for roller mill processed diet. This can be attributed to leveling effect of rumen microbes under reduced fermentation of starch (McDonald et al., 2002) and effect of pH on solubility of protein. As the ruminal pH decreases with increasing starch digestion in rumen (Nikkhah, 2012), it may reduce protein degradation (Satter, 1986) by altering the solubility of proteins (Yalçin and Çelik (2007).

Negative values for ruminal digestion of fat mean that fatty acids are produced in the rumen. Most likely it is fat produced by the microbes (phospholipids in membranes) that flows out of the rumen with the microbes (Perrier et al., 1992). However, total digestibility of fat was higher for pelleted diet which may be due to affect of heat.

Influence of processing on milk production and composition:

Except for the concentration of protein and urea in the milk, no significant effects on milk production, was found. However, a numerically, higher yield of milk and energy corrected milk for the RM 1.5mm processed diet (Table 6) can be attributed to higher digestibility of protein (McDonald et al., 2002). Lower yields for the HM 2mm mash and RM 1.5mm pelleted diets, is in line with Ørskov (1986) and may be due to the increase of starch fermentation which increases the release of volatile fatty acids. Then these fatty acids can increase blood insulin and depress milk yield. But it is not consistent with Poore et al., (1993), Yang et al., (2001) where diets containing more ruminally degradable starch resulted in higher yields of milk. However, amino acids produced due to higher digestibility of protein in case of RM 1.5mm processed diet can be used by liver during the gluconeogensis process to synthesize glucose (Huntington, 1990). As milk production is dependent on resorption of glucose by the mammary glands (Kronfeld, 1976) thus milk yield increased. The decreased concentration of protein further strengthens this, because reduced amino acids supply to mammary glands due to increased gluconeogenesis from amino acids reduces protein content of milk (McDonald et al., 2002). However, this is in contrast to Huntington (1997) where a 67% of glucose supply comes from organic acids (mainly propionate) from starch fermentation in rumen and 5% from other sources. A higher milk protein contents for pelleted diet can be attributed to more efficient digestion of protein by small intestine delivering adequate supply of amino acids to udder as well as increased production of propionate sparing glucogenic amino acids. These effects of processing on the milk protein and milk fat concentration are in line with previous studies (Poore et al., 1993; Von Keyserlingk et al. 1998; Yang et al., 2001) and increased milk fat content for RM 1.5mm treated mash diets are undoubtedly due to differences in patterns of ruminal fermentation (Moren, 1986). Under limited degradation of starch, proportion of cellulolytic organisms increases which favors higher delivery of fat synthesizing precursors (acetate and butyrate) to udder, thus, milk fat concentration is increased. A higher concentration of milk urea for RM 1.5mm pelleted is possibly due to low degradation of protein in rumen which favors the recycling of nitrogen as urea from the blood into rumen where it is converted to microbial protein and is utilized again (McDonald et al., 2002).

3.4. Conclusion:

Roller mill produced more uniform particle size distribution with fewer fines than hammer mill. However, hammer mill gave more durable pellets with less energy consumption than roller mill. Ruminal as well as total tract digestiblities of all nutrients except NDF were significantly unaffected by all three treatment. It can be concluded that ruminal digestion of starch is more influenced by particle size whereas digestion of protein is more influenced by heat treatment under ordinary pelleting. Also milk yield and concentration of its contents are more dependent on pattern of digestibility of different nutrients than feed intake. Pelleting significantly decreased the urea but increased the protein concentration in milk.

4.0. References:

- Anderson, S. 1994. Large Rotor High Speed Hammermills: Beyond Screen Size. Feed Management, Vol. 45, No. 9, 20-22.

- Andersson, L., Fredriksson, H., Oscarsson Bergh, M., Andersson, R., and Åman, P. 1999b. Characterisation of starch from inner and peripheral parts of normal and waxy barley kernels. J. Cereal Sci. 30: 165–171

- ASAE. Method of determining and expressing fineness of feed materials by sieving. ASAE standard S319.4. St. Joseph, MI: American Society of Agricultural and Biological Engineers; 2008

- Arieli, A., Bruckentalb, I., Kedaf, O., Wan, D., 1995. Anim. Feed Sci. and Technol. 51 287-295

- Allen, M.S., 2000. Effects of diet on short-term regulation of feed intake by lactating dairy cattle. J. Dairy Sci. 83, 1598–1624.

- Buléon et al., 1998. Starch granules: structure and biosynthesis, by A. Buléon, P. Colonna, V. Planchot, S. Ball. Int. J. of Biolog. Macromolecules, 23, 85-112

- Behnke, K.C. 1994. Factors affecting pellet quality. Maryland Nutrition Conference. Dept. of Poultry Science and Animal Science, College of Agriculture, University of Maryland, College Park.

– Beauchemin, K.A., McAllister, T.A., Dong, Y., Farr, B.I., Cheng, K.J., 1994. Effects of mastication on digestion of whole cereal grains by cattle. J. Anim. Sci. 72, 236–246.

– Behnke, K.C. (1996) Feed manufacturing technology: current issues and challenges. Animal Feed Science and Technology 62: 49-57.

– Boyles, S. L., Anderson, V. L., & Koch, K. B., 2001. Feeding barley to cattle. Beef Information, Ohio State University

– Bengochea WL1, Lardy GP, Bauer ML, Soto-Navarro SA., 2005. Effect of grain processing degree on intake, digestion, ruminal fermentation, and performance characteristics of steers fed medium-concentrate growing diets. J Anim Sci. 83, 2815-25.

– Choct, M., 1997. Feed non-starch polysaccharides: chemical structures and nutritional significance. Feed Milling International. *13-26.*

– Combs, J.J., Hinman, D.D., 1983. Energy requirements for rolling barley by Univ. of Idaho, R/E Center, Progress Rep. No. 232.

– Christen, S.D., Hill, T.M., Williams, M.S., 1996. Effects of Tempered Barley on Milk Yield, Intake, and Digestion Kinetics of Lactating Holstein Cows. J. Dairy Sci., 79, 1394-1399

– Clark. 1. H., Klusmeyer, T. H., Cameron, M. R., 1992. Microbial protein synthesis and flows of nitrogen fractions to the duodenum of dairy cows. J. Dairy Sci. 75, 2304-23

– Carl W. Hunt, 1996. Factors affecting the feeding quality of barley for ruminants, Anim. Feed Sci. and Technol., 62, 37-48

– Dehghan-banadaky M., Corbett R., Oba M., 2006. Effects of barley grain processing on productivity of cattle by. Anim. Feed Sci. and Technol., 137, 1-24

– Evers A. D., O'Brien L., Blakeney A. B., 1999. Cereal structure and composition. Aus. J. Agri. Research 50, 629–650.

– (EC) No 152/2009. Commission Regulation laying down the methods of sampling and analysis for the official control of feed. Official Journal of the European Union L54/1:1-130.

– Fiems, LO., Cottyn, BG., Boucque, CV., Vanacker, JM., Buysee, FX., 1990. Effect of grain processing on *in sacco* digestibility and degradability in the rumen. Arch. Anim. Nutr., 40, 713–72

– Galyean, ML., Wagner, DG., Owens, FN., 1981. Dry Matter and Starch Disappearance of Corn and Sorghum as Influenced by Particle Size and Processing. J. of Dairy Sci., 64, 1804-1812,

– Gardner, WC.,Von Keyserlingk, MAG., Shelford, JA., Fisher, LJ., 1997. Effect of feeding textured concentrates with alfalfa cubes to lactating dairy cows producing low fat milk. Can. J. Anim. Sci., 77, 735–737

– Herrera-Saldana, RE., Huber, JT., Poore., MH., 1990. Dry Matter, Crude Protein, and Starch Degradability of Five Cereal Grains. J. of Dairy Sci., 73, 2386-2393

– Hayer, WT., Taylor, RE., Hubbert, F., 1961. Apparent digestibility and volatile fatty acids studies with all-barley fattening rations for beef cattle. J. Anim. Sci., 20, 666

– Holm, J., Lundquist, I., Björck, I., Eliasson, AC., Asp, NG., 1988. Relationship between degree of gelatinisation, digestion rate in vitro, and metabolic response in rats. Am. J. Clin. Nutr., 47, 1010–1016

– Hemmingsen AKT., Stevik AM., Claussen IC., Lundblad KK., Prestlokken E., Sorensen M., Eikevik TM., 2008. Water adsorption in feed ingredients for animal pellets at different temperatures, particle size, and ingredient combinations. Dry. Technol., 26, 738-748.

– Harmon, DL., Yamka, RM., Elam, NA., 2004. Factors affecting intestinal starch digestion in ruminants: A review. Can. J. Anim. Sci., 84, 309–318

– Huntington, GB., 1997. Starch utilization by ruminants: From basics to the bunk. J. Anim. Sci., 75, 852–867

– Harmon, DL., McLeod., KR., 2001. Glucose uptake and regulation by intestinal tissues: Implications and whole-body energetics. J. Anim. Sci. 79, E59–E72.

– Huntington, GB., 1990. Energy metabolism in the digestive tract and liver of cattle: Influence of physiological state and nutrition. Reprod. Nutr. Dev., 30-35.

– Hironaka, R., Kimura, N. and Kozub, GC., 1978. Influence of feed particle size on rate and efficiency of gain, characteristics of rumen fluid and rumen epithelium, and numbers of rumen protozoa. Can. J. Anim. Sci., 59, 395-402.

– Jadhav, S.J., Lutz, S.E., Ghorpade, V.M., Salunkhe, D.K., 1998. Barley: chemistry and value-added. Crit. Rev. Food Sci. Nutri. 38, 123–171

– Kassem, MM., Thomas, PC., Chamberlain, DG., Robertson, S., 1987. Silage intake and milk production in cows given barley supplements of reduced ruminal degradability. Grass Forage Sci. 42, 175–183.

– Krause KM, Oetzel GR: Understanding and preventing subacute ruminal acidosis in dairy herds: A review. Anim. Feed Sci. Technol. 126, 215-236.

– Kronfeld, DS., 1976. The potential importance of the proportions of glucogenic, lipogenic and aminogenic nutrients in regard to health and productivity of dairy cows. Adv. Anim. Physiol. Anim. Nutr. 7, p5.

– Kulig, R., 2007. Effect of conditioning methods on energy composition during pelleting. Kom. Mot. Energ. Roln., 7A, 52-58.

– Koch, K. (1996). Hammermills and rollermills. MF-2048 Feed Manufacturing, Department of Grain Science and Industry, Kansas State University. 8 pp.

– Ljøkjel, K., Harstad, OM., Prestløkken, E., Skrede, A., 2003a. *In situ* digestibility of protein in barley grain (*Hordeum vulgare*) and peas (*Pisum sativum* L.) in dairy cows: influence of heat treatment and glucose addition. Anim. Feed Sci. Technol. 107, 87–104.

– Ljøkjel, K., Harstad, O.M., Prestløkken, E., Skrede, A., 2003b. *In situ* digestibility of starch in barley grain (*Hordeum vulgare*) and peas (*Pisum sativum* L.) in dairy cows: influence of heat treatment and glucose addition. Anim. Feed Sci. Technol. 107, 105–116.

– Larsen, M., Lund, P., Weisbjerg, MR., Hvelplund, T., 2009. Digestion site of starch from cereals and legumes in lactating dairy cows. Anim. Feed Sci. and Technol. 153, 236–248

– Mathison, GW., 1996. Effects of processing on the utilization of grain. Anim. Feed Sci. Technol., 58, 113-125

– Mathison, GW., Engstrom, DF., Macleod, DD., 1991. Effect of feeding whole and rolled barley to steers in the morning or afternoon in diets containing differing proportions of hay and grain. Anim. Prod., 53, 321–330

– Malcom, KJ., Kiesling, HE., 1993. Dry matter disappearance and gelatinization of grains as influenced by processing and conditioning. Anim. Feed Sci. Technol., 40, 321–330

- McLeod, KR., Baldwin, RL., Harmon, DL., Richards, CJ., Rumpler, WV., 2001. Influence of ruminal and postruminal starch infusion on energy balance in growing steers. Energy Metabolism in Animals. A. Chwalibog and K. Jakobsen, ed. Wageningen Pers, Wageningen, The Netherlands. pp 385

- McNiven, MA., Hamilton, RMG., Robinson, PH., deLeeuw, JW., 1994. Effect of grain roasting on the nutritional quality of common cereal grains for ruminants and non-ruminants. Anim. Feed Sci. Technol., 47, 31–40

- McNiven, MA., Weisbjerg, MR., Hvelplund, T., 1995. Influence of roasting or sodium hydroxide treatment of barley on digestion in lactating cows. J. Dairy Sci., 78, 1106–1115

- McDonald, P., Edwards, RA., Greenhalgh, JFD., Morgan, CA., 2002. Animal Nutrition. 6th ed., 179-198

- Moren, J.B., 1986. Cereal grains in complete diets for dairy cows: A comparison of rolled barley, wheat and oats and other method of processing oats. Anim. Prod. 43, 27-36.

- Mertens, D. R. 2002. Gravimetric determination of amylase-treated neutral detergent fiber in feeds with refluxing in beakers or crucibles: collaborative study. J. AOAC Int., 85,1217-1240

- McCleary, B. V., Gibson, T., Solah, V., Mugford, D., 1994. Total starch measurement in cereal products: Interlaboratory evaluation of a rapid enzymic test procedure. Cereal chemistry, 71, 501-504.

- Manickam, IN., Suresh, SR., 2011. effect of moisture content and particle size on bulk density, porosity, particle density and coefficient of friction of coir pith. Inter. J. Eng. Sci. Technol., 3, 2596-2602

- Nikkhah, A., 2012. Barley grain for ruminants: A global treasure or tragedy. J. Anim. Sci. and Biotech., 3:22

- Nikkhah, A., 2012. Postmodern Management of Starchy Grains for Ruminants: a Barley Grain Perspective. Russian Agri., Sci., 38, 14–21.

- Nikkhah, A., 2011a. Optimizing Barley Grain Use by Dairy Cows: A Betterment of Current Perceptions. *Prog. Food Sci. Technol.*, 1, 165–178

- Nocek, JE., Tamminga, S., 1991. Site of digestion of starch in the gastrointestinal tract of dairy cows and its effect on milk yield and composition. J. Dairy Sci., 74, 3598–3629

- Nikkhah A, Ghorbani GR: Effects of dry and steam processing on in situ ruminal digestion kinetics of barley grain. J. Anim. Sci., 81:338

- Öztürk, T., Esen, B., 2008. Physical and mechanical properties of Barley. Agri. Trop. Subtrop., 41, 117-121

- Ørskov, ER., 1979. Recent information on processing of grain for ruminants. Livest. Prod. Sci., 6, 335-347

- Ørskov, ER., Soliman, HS., Macdearmid, A., 1978. Intake of hay by cattle given supplements of barley subjected to various forms of physical treatment or treatment with alkali. J. Agric. Sci., 90, 611–615.

- Owens, FN., Zinn, RA., Kim, YK., 1986. Limits to starch digestion in the ruminant small intestine. J. Anim. Sci., 63, 1634–1648

- Offner, A., Bach, A., Sauvant, D., 2003. Quantitative review of in situ starch degradation in the rumen. Anim. Feed Sci. Technol., 106, 81–93

- Ørskov, ER., 1986. Starch digestion and utilization in ruminants. J. Anim. Sci. 63, 1624

- Okine, E., Kennelly, JJ., 1994. From fiber to starch: the evaluation of the cow. Adv. in Dairy Technol., 6, 187.

- Oba, M., and M.S. Allen. 1999. Evaluation of the importance of the digestibility of neutral detergent fiber from forage: Effects on dry matter intake and milk yield of dairy cows. J. Dairy Sci. 82, 589-596.

- Pomeranz, Y., 1974. Food uses of barley. CRC Crit. Rev. Food Technol., 4, 377–394.

- Peng, M., Gao, M., Abdel-Aal, ESM., Hucl, P., Chibbar, RN., 1999. Separation and Characterization of A- and B-Type Starch Granules in Wheat Endosperm. Cereal Chem. J., 76, 375-379

- Perrier, R., Michalet-Doreau, B., Bauchart, D. and Doreau, M., 1992. Assessment of an in-situ technique to estimate the degradation of lipids in the rumen. J. Sci. Food Agric., 59: 449-455.

- Plascencia, A., Calderon, JF., DePeters , EJ., Lopez-Soto, MA., Vega, M., Zinn, RA., 1998. Influence of processing on the feeding value of barley for lactating cows. West. Sec. Am. Soc. Anim. Sci., 49, 257–263

- Prestløkken, E., 1999a. Protein value of expander-treated barley and oats for ruminants. Agricultural University of Norway, Doctor Scientiarum Theses 1999:5, 142 pp

- Prestløkken, E., Harstad, OM., 2001. Effects of expander-treating a barley-based concentrate on rumen fermentation, bacterial N synthesis, escape of dietary N, and performance of dairy cows. Anim. Feed Sci. Technol., 90, 227–246

- Prestløkken, E., 1999b. Ruminal degradability and intestinal digestibility of protein and amino acids in barley and oats expander-treated at various intensities, Anim. Feed Sci. Technol., 82, 157-175

- Poore, MH., Moore, JA., Swingle, RS., 1993. Response of lactating Holstein cows to diets varying in fiber source and ruminal starch degradability. J. Dairy Sci., 76, 2235-2243

- Rowe, JB., Choct M., Pethick DW., 1999. Processing cereal grains for animal feeding. Aust. J. Agri. Res. 50, 721–736.

- SAS (Statistical Analysis System) 1996. Version 6.12. SAS Inst. Inc., Cary, NC, USA

- Samuel AM., 1991. Chemistry and Technology of Cereals as Food and Feed. 2nd edi.

- Svihus, B., Kløvstad, KH., Perez, V., Zimonja, O., Sahlström, S., Schüller, RB., Jeksrud, WK., Prestløkken, E., 2004. Physical and nutritional effects of pelleting of broiler chicken diets made from wheat ground to different coarsenesses by the use of roller mill and hammer mill. Anim. Feed Sci. Technol., 117, 281-293

- Swanston, JS., Ellis, RP., Morrison, IM., Mackay, GR., Dale, MFB., Cooper, A., Tiller, SA., Duffus, CM., Cochrane, MP., Prentice, RDM., Paterson, L., Lynn, A., 2001. Combining high-amylose and waxy starch mutations in barley. J. Sci. Food Agric., 81, 594–603

- Stern, MD., Varga, GA., Clark, JH., Firkins, JL., Huber, JT., Palmquist, DL., 1994a. Evaluation of Chemical and Physical Properties of Feeds That Affect Protein Metabolism In the Rumen. J. Dairy Sci. 77, 2762-86.

- Siddons, R., Paradine, J., Beever, D., Cornell, P., 1985. Ytterbium acetate as a particulate-phase digesta-flow marker. British J. Nutri., 54, 509-519.

- Sadri H., Ghorbani GR, Alikhani M, Babaei M, Nikkhah A., 2007. Ground, dry-rolled and steam-rolled barley grain for midlactation Holstein cows. Anim Feed Sci Technol., 138, 195-204

- Satter, LD., 1986. Protein Supply from Undegraded Dietary Protein. J. Dairy Sci., 69, 2734 – 2749

- Svihus, B., Uhlen, AK., Harstad, OM., 2005. Effect of starch granule structure, associated components and processing on nutritive value of cereal starch: A review, Anim. Feed Sci. Technol., 122, 303-320

- Tang H., Ando, H., Watanabe, K., Takeda, Y., Mitsunaga, T., 2001. Physicochemical properties and structure of large, medium and small granule starches in fractions of normal barley endosperm. Carbohydrate Research, 330, 241-248

- Thomas, M., van Vliet, T., van der Poel, AFB., 1998. Physical quality of pelleted animal feed. 3. Contribution of feedstuff components. Anim. Feed Sci., 70, 59-78

- Tolland, PC., 1976. The digestibility of wheat, barley or oat grain fed either whole or rolled at restricted levels with hay to steers. Aust. J. Exp. Agric. Anim. Husb., 16, 71-75

- Theurer, CB., 1986. Grain Processing Effects on Starch Utilization by Ruminants. J. Anim. Sci., 63, 1649-1662.

- Taniguchi, K., Sunada, Y., Obitsu, T., 1993. Starch digestion in the small intestine of sheep sustained by intragastric infusion without protein supply. Anim. Sci. Technol., 64, 892.

- Taniguchi, K., Huntington, G., Glenn, B., and Erdman, R., 1992. Energy metabolism in beef steers fed alfalfa hay and given ruminal (r) or abomasal (A) infusions of corn starch (s) and casein (C). J. Anim. Sci., 70, 316

- Voragen, AGJ., Gruppen, H., Marsman, GJP., Mul, AJ., 1995. Effects of some manufacturing technologies on chemical, physical and nutritional properties of feed. Rec. Adv. Anim. Nutri., 93–126

- Vranjes, MV., Wenk, C., 1995. The influence of extruded vs. untreated barley in the feed, with and without dietary enzyme supplement on broiler performance. Anim. Feed Sci. Technol., 54, 21–32

- van Soest, PJ., 1994. Nutritional Ecology of the Ruminant, 2nd Edition. Comstock, Cornell University Press, Ithaca, NY, 476 pp.

- Waldo, DR., 1973. Extent and partition of cereal grain starch digestion in ruminants. J. Anim. Sci., 37, 1062-1074.

– Wood, JF., 1987. The functional properties of feed raw materials and their effect on the production and quality of feed pellets. Anim. Feed Sci. Technol., 18, 1–17

– Yang, WZ., Beauchemin, KA., Rode, LM., 1996. Ruminal digestion kinetics of temper-rolled hulless barley. Can. J. Anim. Sci., 76, 629-632

– Yalçin, E. and Çelik, S. 2007. Solubility properties of barley flour, protein isolates and hydrolysates. Food Chem. 104, 1641–1647.

– Yang, WZ., Beauchemin, KA., Rode, LM., 2001. Effects of grain processing, forage to concentrate ratio, and forage particle size on rumen pH and digestion by dairy cows. J. Dairy Sci., 84, 2203–2216

– Zinn, RA., Montano, M., Shen, Y., 1996. Comparative feeding value of hulless vs. covered barley for feedlot cattle. J. Anim. Sci., 74, 1187–1193