IMPROVING THE UTILISATION OF CEREALS AND PULSES BY PIGS: BACKGROUND AND RESEARCH OPPORTUNITIES
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Executive Summary

Starch in grains represents the main source of dietary energy for monogastric production animals. However, utilization of this energy is not complete due to the encapsulation of starch granules within complex carbohydrate cell walls which limit enzyme hydrolysis. Incomplete starch and protein digestion is a significant economic issue for the pork industry in Australia that dictates the need to explore ways of improving the efficiency of digestion of feed grains. Although a number of factors influence this process, particle size of the end product as it enters the gastrointestinal tract appears to be the most important. This review critically evaluates the influence of different feed and food processing technologies on the nutritional value of processed ingredients. It then defines potential new feed processing strategies that will enhance the use of the industry’s feed base.

The first step in feed processing is to reduce particle size by milling which is most commonly achieved with a hammer mill, roller mill or pin mill. Each mill provides specific benefits based on design differences for the feed industry. The rate of digestion decreases with increasing particle size, the inverse square relationship providing an \( r^2 \) value of 0.99 for barley by way of example. We have reviewed the major factors that affect particle size distribution within grain type, pre and post milling treatments to optimize the grinding process and fractionation technologies for milled grains. In most feed mills worldwide, thermal processing treatments are used to complement grinding technologies to optimize physical and nutritional value of processed grains. The impact of mild thermal treatments (such as pelleting) and high thermal treatments (such as extrusion) on nutritive value of processed milled grains is assessed. Among other grains, sorghum is considered the most difficult grain to digest due to the presence of a complex protein matrix within which the starch grains are encapsulated and the adverse nutritional response of sorghum grains to hydrothermal treatments. Whole grain expansion of sorghum provides a possible alternative processing approach.

The adoption of different feeding strategies on farm including fermented liquid feeding and diet formulation with the use of dietary enzymes will assist in attaining our goal of synchronizing peak concentrations of energy and protein in production tissues to maximize growth efficiency and minimize the wastage of dietary energy. The research opportunities identified herein are based on refining the separation of coarse fractions of milled grains and exposing them to further treatments including grinding, thermal conditioning in excess heated water and extrusion. Further processing on farm by soaking feed together with the use of feed enzymes and other strategic feed additives will lead to further incremental improvements in feed utilization.

However major advances will not be achieved until the industry develops new feeding technologies designed to synchronize the supply of energy and protein synthesis substrates to production tissues, the mammary gland and musculature. This in turn needs to link with the endogenous metabolic cues and rhythms that control growth processes over the course of the day.
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1. Introduction

Cereal grains are the primary ingredient in most pig diets because they are widely grown, easily transported and handled, readily consumed by pigs and the most economical source of energy (Thomas and Owens, 2000). Although inclusion of certain grains in pig diets depends on price and availability, feed costs have been reported to represent 60-70% of the total cost of pig meat production, with the energy component forming the major contribution (Noblet et al., 1993).

Starch in cereal is the most abundant energy source for most domestic production animals (Svihus et al., 2005) though the availability of energy from starches is not complete. Various in vivo pig digestibility studies have revealed that up to 30% of diet gross energy is not utilized (Regmi et al., 2008) and this is a significant economic issue for the pork industry worldwide. Starch that escapes enzymatic digestion by amylase in the small intestine is fermented in the large intestine to volatile fatty acids (VFA). Using VFA as a source of energy is reported to be 85% to 90% as efficient as using glucose directly (Black et al., 2009). In comparison to starch in cereals, starch in legumes is more resistant to digestion compared to cereals grains. Generally, starch in legumes has been reported to have low digestibility characteristics because the starch is encapsulated by thick cell walls (Wursch et al., 1986) and because of the presence of anti nutritional factors.

Once the ingredients that formulate pig diets have been ground and mixed, they can either be fed as mash or subjected to further processing. Processing treatments may involve moisture treatment, heat, and pressure or combinations thereof (Sajilata et al., 2006). Modern methods that focus on feed processing include steam flaking, pelleting, expansion and extrusion (Svihus et al., 2005). Such processing methods can affect starch and protein availability by altering their properties or by interacting with other components in the feed (Rowe et al., 1999; Svihus et al., 2005). From a practical point of view, processing choice is determined by finding a balance between improvement in overall nutritive value due to feed processing and the cost of feed processing itself.

Incomplete starch utilization has been attributed to many factors including source and starch structure, other grain constituents such as protein and fibre, the presence of anti-nutritional factors, the use of feed additives such as enzyme supplementation, feed processing, particle size and animal factors such as age and genotype. From these factors, it seems that particle size is the major factor that affects the digestibility of starch in cereals (Oryschak et al., 2002; Al-Rabadi et al., 2009) and protein in legumes (Crévieu et al., 1999). Milling the grains (cereals and legumes) is the first processing step, breaking the seed coat and reducing particle size for enzymatic attack by the animal digestive system. The effect of grinding on whole grains is described by measuring average particle size (dgw) and standard deviation (Sgw). As reported by Baker and Herman (2002), geometric standard deviation measures the distribution of particle size (i.e. by dividing and multiplying the Dgw by the Sgw, a range into which 68 percent of the particles will fall and can be calculated). In other words, a range of 32 percent of particles will fall in to upper (d84) and lower (d16) fraction sizes.

However, most of experiments until now have been designed to evaluate the effects of average particle size and have not been planned to address the effects of distribution of particle size within that average. The effect of particle size distribution has been reported to have nutritional (Al-Rabadi et al., 2009) and health implications (Wolf et al., 2010). The purpose of the review is to provide an overview to milling methods, approaches used to achieve optimized and efficient milling and fractionation technology of milled grains. In addition, an overview to selected processing methods will be discussed with particular focus on areas where processing methods can be optimized to ensure that the availability of dietary energy and amino acids coincide to maximise protein synthesis and muscle accretion.
2. Cereals and Pulse Composition

Australia offers a diverse range of cereal and pulse crops that are potentially available for animal feeding (Table 0.1). The composition and digestibility of these grains varies widely between for example species, variety, year and location (O’Brien, 1999), while the digestibility is also affected by grain structure and the presence and level of anti-nutritional factors. Should detail be required on these aspects, a summary of published reviews or recent research studies is presented in Table 0.2.

Pulses show a wide variation in their macronutrient composition depending on factors such as species and cultivar. A range of published information is available covering the macronutrient profile and amino acid profile, as well as the levels of anti-nutritional factors (Gilani et al., 2005, Zilstra et al., 2008)). While pulses are generally high in protein (225 to 381 g/kg DM) compared to cereal crops, they are often deficient in essential amino acids necessitating their blending with other protein sources.

2.1. Processing Characteristics

Grain mechanical properties (hardness or endosperm texture) are important characteristics as they influence the milling process and characteristics of the milled product (Haddad et al., 1999). Particle size reduction processes are generally energy inefficient, so selecting grains that are relatively easy to mill could improve the efficiency.

The physical properties of cereal crops have received considerable attention, with reviews or detailed studies on maize (Fox and Manley, 2009; Blandino et al., 2010), and wheat (Haddad et al., 1999; Turnbull and Rahman, 2002; Pasha et al., 2010), though less information is available on pulses (Laskowski and Lysiak, 1999)

3. Feed Mill Technology Optimisation Gains

3.1. Particle size reduction

3.1.1. Milling method

Different types of milling and variations in operating conditions will produce a wide range of particle sizes in animal feed and human food. These mills include but are not limited to the hammer mill, roller mill, pin mill, stone mill, disc mill and plate mill.

Because the optimum particle size of most farm animals feed material is greater than 400 μm and due to the need for high milling production capacity, roller and hammer milling will be the primary focus for this review. Roller-milling has been reported to be more efficient as it requires less energy for particle size reduction than hammer-milling (Goodband et al., 2002) and the shape of ground particle looks more cubic (Amerah et al., 2007). The extent of energy saving is dependent on the target particle size: for example the advantage for corn relative to other grains is <5% at sizes smaller than 500 μm, which increases to 25-30% at 800 μm, and up to 80% at a size of 3000 μm (Kim, 2008). Hammer-mills are more widely used in feed mills because they are easier to operate and maintain and produce particles spherical in shape (Kim et al., 2002; Amerah et al., 2007). To increase production capacity of hammer mills, they are equipped with an air-assist system that draws air into the hammer mill with the product to be ground, thus allowing particles to exit through screen holes (Kim et al., 2002).

Hammer mills have been reported to produce a wide range of particle sizes compared to roller mills (Seerley et al., 1988; Douglas et al., 1990; Audet, 1995). During roller milling each grain passes through the mill independently of surrounding grains (Campbell et al., 2001). For that reason, the breakage patterns for each grain depends mainly on the interaction between the grain, the roller mill design and operation conditions (Campbell
Roller mills have at least two pairs of rollers, often accompanied by two or three additional pairs, that usually crush the grains as it passes between rollers (Laurinen et al., 2000). Reducing geometric standard deviation along with particle size has been achieved by using mills employing three high-rollers mills (Healy et al., 1994a). Alternatively, further reduction of geometric standard deviation has been reported when corn grains are firstly ground by roller mill and then milled using a hammer mill (Healy et al., 1994a; Wondra et al., 1995a).

Adjustment of operating conditions within a mill can affect particle size distribution. In a milling trial with corn, reducing the hammer mill screen size from 9.6 mm to 1.2 mm resulted in a linear reduction in geometric standard deviation (Wondra et al., 1995b; Wondra et al., 1995d). When hammer mill screen size was plotted against geometric standard deviation, each 1 mm reduction in milling screen size resulted in a 0.09 reduction in geometric standard deviation ($R^2=0.82$, n=7). Use of multiple stages of grinding using a roller mill has been reported to reduce geometric standard deviation. However, a series of test grindings is required using a double pair roller mill to establish the optimal distance between the rollers to obtain the required particle size (Svihus et al., 2004).

Pin milling is of great interest as it has applications in macronutrient enrichment in fractionated particles although this technique does tend to produce fine particles (Mathew et al., 1999). It is generally used in nutrient fractionation by separating less dense protein particles from the denser starch particles (Drew et al., 2007). Pin milling is used mainly in grinding of legumes as this method is capable of producing a fine grind which facilitates better separation between protein and starch granules without damaging starch granules (Jones et al., 1959). During pin milling, the number of particles increases greatly and thus the number of contacts required for further size reduction also increases (Mani and Tabil, 2002). Therefore, production output of the mill decreases and energy consumption of the infrastructure increases. After pin milling, air classification is used to produce legume flour and a protein concentrate fraction (Tyler, 1984; Han and Khan, 1990). To achieve nutrient enrichment/fractionation objectives, a pin mill must produce a narrow distribution of particle size to facilitate fraction by air classification (Mani and Tabil, 2002).

Multi-stage milling processes have been shown to reduce the total energy required for milling (Dziki, 2011). In a study of wheat milling, initially grinding of the grains through a roller mill before hammer milling reduced the total energy required from 32.6-79.0 kJ/kg (hammer milling only) to 23.1-44.4 kJ/kg (roller milling and hammer milling). The change in particle size distribution in multi-stage milling processes is also of importance (Dziki, 2008). Soft wheat grains crushed before milling had a lower particle size and a higher proportion of material that was smaller than 200 μm than samples milled without crushing. Depending on the moisture content, some hard wheat samples also had a lower particle size and higher proportion of material smaller than 200 μm.

### 3.1.2. Particle size reduction and nutrition

Irrespective of milling method, the effect of average particle size (dgw) on pig performance has been widely studied at different production stages, such as in weaner pigs (Seerley et al., 1988; Healy et al., 1994b; Kim et al., 2002), growing pigs (Seerley et al., 1988; Oryschak et al., 2002), finishing pigs (Wondra et al., 1995b; Wondra et al., 1995c), lactating sows (Wondra et al., 1995d) and sow litter performance (Wondra et al., 1995d). A problem found in the reduction of particle size was ulcer formation (Hedde et al., 1985; Wondra et al., 1995a). An improvement in pig growth performance at different production stages was achieved in these studies and it was concluded that the optimum average particle size for digestion was in the range of 0.4 to 0.6 mm. However, a range of particle size from 0.6 to 0.8 mm was recommended for swine feed when milling production cost, dust production, feed handling problems (bridging) and gastric ulcers is taken in consideration (Wondra et al., 1995a; Goodband et al., 2002). For example, if monitored, pig meal diets showed a deviation from recommended distribution (>15-20% of particles...
>1 mm; <20% of particles <0.2 mm) then pathological consequences have been identified (Wolf et al., 2010).

### 3.1.3. Grain treatment before and after milling

Several attempts have been used to optimize the grinding process of grains. Tempering grain before rolling has been reported to reduce mechanical wear on processing equipment (Mathison et al., 1997) and causes the germ to swell and increase endosperm friability (Bradbury et al., 1960). Tempering has been reported to be achieved by raising the moisture content of the barley to 200-250 g/kg by adding water, mixing, and storing for 12-24 h prior to rolling (Dehghan-banadaky et al., 2007). Tempering helps maintain the integrity of the kernels and reduces shattering when grains pass between the rollers (Yang et al., 1996). Altering the moisture content also affected the milling of field peas processed through a combined mill and air classifier. As the moisture content increased, the energy required to create new surface area through the fracturing of grain particles also increased (Dijkstra and Langelaan, 2002a; Dijkstra and Langelaan, 2002b). A comparison of legume seeds showed that their mechanical properties during crushing depends on a combination of moisture content, type of legume and the characteristic being studied (force required for deformation through different physical transitions) (Laskowski and Lysiak, 1999).

For that reason, tempering increases the proportion of particles retained on the coarsest screens while decreasing the particles on the finer screens when compared to dry rolling (Combs and Hinman, 1989; Wang et al., 2003; Dehghan-banadaky et al., 2007). Alternatively, moisture can be added as steam instead of water (liquid phase) as an efficient method to decrease presence of fines after rolling (Hironaka et al., 1992).

In an in vitro study evaluating field peas, roller or hammer milling treatments were combined with heating to 85°C or 95°C to generate grits with different particle size ranges (Le Gall et al., 2005). It was shown that protein extraction and degree of hydrolysis decreased with increasing particle size, which was attributed to an decreased surface area and less destruction of physical barriers to solvent penetration.

Microwave heating is based on the transformation of alternating electromagnetic field energy into thermal energy by affecting the polar molecules of a material (Vadivambal and Jayas, 2007). In microwave heating, heat is generated throughout the material, leading to faster heating rates, compared to conventional heating where heat is usually transferred from the surface to the interior part of a grain fragment (Gowen et al., 2006). The microwave drying helps in removing the moisture content from the food products without the problem of case hardening (Schiffmann, 1986; Prabhanjan et al., 1995). In addition, exposure of grains to microwave treatment has been reported to increase of intra-grain cracks within the wheat kernel (Błaszczak et al., 2002).

The energy consumption of a hammer mill has been shown to decrease after maize is exposed to microwave treatment indicating that maize grains are easier to grind (Velu et al., 2006). Softer grain varieties have been reported to have lower geometric standard deviation than harder varieties when milled by roller mill (Healy et al., 1994b).

### 3.1.4. Post-milling treatment

Ground grains are often further processed by a variety of methods that influence the particle size distribution before being fed to pigs. In a study of the influence of post grinding processes it has been shown that pelleting/crumbling has a secondary grinding effect resulting in a further reduction in particle size distribution (Wolf et al., 2010) which further decreases geometric standard deviation in particle size. A study comparing meal, expanded pellets and crumble showed that the average particle size consistently decreased with further processing in starter, grower and finisher meals (Millet et al., 2012). Overall, feed form affected feed intake (meal > expandate > crumble), and feed
conversion ratio (meal FCR 2.58 g feed/g liveweight gain; expandate FCR 2.5 g/g; crumble FCR 2.45 g/g).

3.1.5. Particle size reduction in legumes

Grain legumes are important sources of protein and energy for monogastric animals and can be used to replace traditional protein sources of animal origin such as meat and bone meal or fish meal (Jezierny et al., 2010). In addition, they represent a protein rich feed ingredient alternative for soybean meal and other oilseed meals when their prices are high (Sève, 2004). In comparison to cereal, starch in legumes is characterized by having lower digestibility due to factors related to:

- the crystallinity pattern of starch (i.e. starch in legumes possess C-type pattern based on X-ray diffraction which is resistant to digestion by α-amylase) (Englyst et al., 1996; Sun et al., 2006),
- encapsulation of starch granules by a thick plant cell wall (Wursch et al., 1986),
- the absence of pores on the granule surface (Hoover and Sosulski, 1985),
- the higher amylose content (Chung et al., 2010) (Hoover and Zhou, 2003), and
- the stronger interactions between amylose chains (Hoover and Sosulski, 1985).

Previous work has shown that the reduction of particle size can result in better growth performance and improvement in nutrient digestibility (Hedde et al., 1985; Healy et al., 1994b; Wondra et al., 1995a; Kim et al., 2002; Oryschak et al., 2002; Callan et al., 2007). Al-Rabadi et al. (2009) showed that in cereals different particle size fractions altered starch digestibility by as much as 10-fold between the smallest and the largest particle size in cereals. This suggests that particle size is a key factor in influencing starch digestibility.

Due to their relatively high starch (e.g. faba bean, peas) and oil (lupins) contents (Jezierny et al., 2010), grain legumes are used in animal nutrition as sources of both protein and energy.

However, very limited studies have been conducted on the effect of particle size reduction on nutrient digestibility in legume grains used in swine diets. From limited studies, pea was the most used legumes grain because of their relatively high energy and lysine content (Stein et al., 2004). Montoya and Leterme (2011) conducted a study to evaluate the influence of wide range of particle size of peas (averages of 156, 649 and 1035 µm) on starch and energy digestibility. They reported that the digestible energy decreased linearly with increasing average particle size and this (i.e. digestible energy) was positively correlated with the degree of in vitro starch hydrolysis (r=0.62). In the same study, an in vivo experiment showed a wide range of ileal starch hydrolysis (0.55–0.81) in adult pigs, which suggests that factors other than particle size can influence the extent of starch digestibility in pigs such as the presence of amylase inhibitor (Sandhu and Lim, 2008).

The effect of the dietary particle size of peas (at inclusion level of 35%) on the performance of weaned piglets showed that a fine size (610 µm) significantly improved growth and feed conversion ratio compared to a medium (750 µm) or coarse (1020 µm) size (Albar et al., 2000).

An increase in particle size significantly reduced the degree of protein hydrolysis in peas when the particle size increased over a range of 200 to 1000 µm showing a quadratic effect (i.e. a smaller difference between 200 and 500 µm than between 500 and 1000 µm in median diameter) (Le Gall et al., 2005). In another study it was found that micro grinding of three different cultivars of peas increased ileal protein digestibility in growing pigs (Hess et al., 1998). In this study, the micro-grinding of the pea (25 µm) enhanced the real digestibility by about 10% compared to grinding with a 2.4 mm hammer mill screen size. Micro grinding of three different cultivars of faba beans has been also reported to increase ileal protein digestibility in growing pigs (Hess et al., 2000).
In lupins, Kim et al. (2009) reported that smaller particle size increased apparent ileal and total-tract digestibility of crude protein and the apparent and standardised ileal digestible amino acid content. In their study, the reduction of average particle size from 1304 to 567 µm increased standardized ileal digestibility of lysine (from 0.58 to 0.88), methionine (from 0.46 to 0.71), threonine (from 0.48 to 0.82) and total amino acids (from 0.59 to 0.88).

These responses of legume grains to particle size reduction are also dependent on the variety used in the diet (Montoya and Leterme 2011). They concluded that the variation in the starch digestibility of field pea was dependent on the interaction between the resistance of the structure of their starch granules to enzyme hydrolysis which is dependent on particle size. However, there was no such interaction (variety and particle size) in lupins (Kim et al., 2009) or in faba bean (Hess et al., 2000) with amino acid ileal digestibility in pigs. Further investigation is required to determine the optimum particle size that is generally obtained under industrial grinding conditions to ensure a good bioavailability of amino acids (Le Gall et al., 2005) which must coincide with energy availability to maximise the efficiency of protein synthesis.

### 3.2. Factors that affect particle size distribution within grain type

#### 3.2.1. Grain hardness

Grain characteristics play a role in determining the particle size distribution of the milled product in both pulses (Indira and Bhattacharya, 2006) and cereals. Within cereal varieties, the surface protein (e.g. friabilin in wheat) can affect the endosperm hardness which alters the milling characteristics (Baldwin, 2001). Svihus et al. (2005) reported that friabilin reduces bonding properties between starch granules and matrix protein, and this can give rise to softer endosperm that fractures more easily during milling, and results in a finer textured product. They also reported that the number of broken starch granules was affected by the strength of the bond between the protein and the starch matrix surrounding the starch granules. For example, in corn, the bond between the protein and starch is very strong which results in production of a large number of broken starch granules during milling (Hoseney, 1994). Production of large numbers of broken grains may indicate lower average particle size.

Within cereal type, softer sorghum varieties have been reported to have lower geometric standard deviation in particle size than harder sorghum varieties when milled with a roller mill (Healy et al., 1994b). However the effect of grain type on particle size distribution is not consistent. Healy et al. (1994b) reported that when roller mill is used to obtain a specific particle size, the geometric particle standard deviation of ground corn was smaller than that of hard sorghum and was almost similar to that for soft sorghum. However, Ohh et al. (1983) reported that geometric standard deviation of fine and coarse milled corn, using both hammer and roller mill, was always higher than for fine and coarse milled sorghum.

In a comparison of different pulses milled coarsely or finely, particle size distribution varied between pulse type (Indira and Bhattacharya, 2006). However it was very clear that grain hardness and possibly particle size chosen played key roles.

In a study of maize milling (Blandino et al., 2010), it was found that milling time and energy used in the process were significantly correlated with protein (0.73 and 0.71 respectively) and starch content (-0.73 and -0.78 respectively) although the impact of the amylose / amylopectin ratio was more equivocal (0.47 and 0.31 respectively). In contrast ash and oil content had little effect. The mechanical properties of the grain can also play a role, with break force (0.59 and 0.44 respectively) and break energy (0.50 and 0.35 respectively) correlated with milling time and milling energy.
3.2.2. Sieve analysis

3.2.2.1. Sieving equipment

Sieving is an easy, portable, cheap and widely-used method of classifying milled grains according to their physical size irrespective of their chemical or physical properties. Baker and Hermann (2002) conducted a study to compare the performance of two items of equipment (the RoTap and the portable shaker) and a full set of sieves (thirteen sieves compared with a short stack of sieves (five sieves). The aim of their study was to look at the practicability of using a cheaper dry sieving option compared to the standard 13 sieves mentioned in the official ASAE procedure for particle size determination (ASAE, 1993). The geometric standard deviation was approximately 0.2 and 0.3 points higher when using the short stack (i.e. 5 sieves) compared to long stack sieves (i.e. 13 sieves) for RoTap and portable shaker, respectively (Baker and Hermann, 2002). Other factors that can affect geometric standard deviation values include particle shape, extent and aggregation of fine particles, amount of initial sieve loading and method and time of shaking (Olaisen et al., 2001). However and to the best of our knowledge, no solid data are available to assess the impact of these variables on particle size distribution.

3.2.2.2. Analysis Method (wet vs dry sieve)

Wet sieving is used when dry sieving cannot separate individual fractions, for example in pelleted feed. The wet sieving process uses water from a spray nozzle inserted above the upper sieve. The sprayed water leaves the sieve stack together with the last fraction through the exits into the collector. Rinsing continues until the water leaving the sieve stack is no longer cloudy, but clear. Experiments conducted by Wolf et al. (2010) showed that wet sieving is a more accurate way of separating on particle size to provide fine and coarse meal diets than dry sieving as shown in Figure.
Figure 1 - Effects of the analysis method (dry or wet sieve analysis) on the particle size distribution of (A) fine meal diet (%; mean ± SD, n=4) and (B) coarse meal (%; mean ± SD, n=5). Modified from Wolf et al. (2010). Error bars indicate standard deviation.

3.3. Fractionation of milled grains

Fractionation technology of milled grains has been adapted to achieve two main objectives:

- Nutrient enrichment
- Increased nutrient digestibility

Smaller grain particles generally have a higher starch digestibility due to the increase in surface area exposed to enzymatic attack (Healy et al., 1994b; Wondra et al., 1995a; Brunsgaard, 1998; Blasel et al., 2006). The rate coefficients for starch digestion showed a decrease with increasing particle size, and could be well fitted by an inverse square relationship (Al-Rabadi et al., 2009). As digestion rates of grain particles are substantially slower than those of isolated starches, it seems likely that diffusion of enzymes through the endosperm matrix is rate-limiting. Within the same cereal type, the high dependence of digestion time on particle size shows that the distribution of particle size after milling is important in determining the rate of digestion of ground (non-fractionated) unprocessed (Al-Rabadi et al., 2009) and processed grains (Al-Rabadi et al., 2009). For example, glucose yields from starch digestion varied about ten-fold between the smallest and largest particles (Al-Rabadi et al., 2009). This will be important for coarse milling applications where a wide range of hammer mill screen sizes is used.

Resistance of starch digestion of coarse fraction can be also magnified by the cereal type from which the starch is derived. A recent study has shown that the amylase diffusion
coefficient \(0.76 \times 10^{-7} \text{ cm}^2 \text{ s}^{-1}\) for sorghum is lower than for barley \(1.7 \times 10^{-7} \text{ cm}^2 \text{ s}^{-1}\) (Al-Rabadi et al., 2009), which indicates ultrastructural differences that limit enzyme penetration in milled sorghum compared to barley grain. This is reflected by complete starch digestion after 24 hours for barley particles, whereas starch digestion in sorghum particles is incomplete at this time (Al-Rabadi et al., 2011b). Slower starch digestion in ground sorghum particles may be due to the presence of a protein matrix (Rooney and Pflugfelder, 1986; Kotarski et al., 1992) and/or anti-nutritional factors, such as polyphenols and phytate that may bind to amylase and reduce its activity (Björck and Nyman, 1987). These results suggest that fractionation of some grains is not sufficient to ensure complete starch digestibility.

In legumes, starch digestibility seems to be more challenging for the nutritionist. Montoya and Leterme (2011) concluded that the variation in the starch digestibility in legumes was multifactorial with the resistance of the structure of their starch granules to enzyme hydrolysis, reduced accessibility in coarse particles and presence of antinutritional factors like amylase inhibitors all contributing. The amylose/amylopectin ratio has been also reported to influence starch hydrolysis between legume varieties (Skrabanja et al., 1998).

Nutrient enrichment of cereals and pulses has the potential to increase the economic value of products enriched with specific nutrients that have beneficial effects on animal health and production (Srinivasan and Singh, 2008; Gunawardena et al., 2010a; Gunawardena et al., 2010b). Enrichment of particular nutrients in certain fractions has the potential to increase or decrease energy density in diets. Consequently, they can provide the flexibility of formulating diets at a lower cost while meeting the energy requirements of animals at different production stages.

Target enrichment of certain nutrients is dependent mainly on grain type. For example, particle size separation after milling of barley has been reported previously to lead to particle fractions enriched in starch or fibre, depending on fraction size and method of particle size separation (Sundberg et al., 1995). However a subtle balance between starch and fibre enrichment of each fraction is often found with an increase in starch content in one fraction being accompanied by a decrease in NDF content within the same fraction size compared to the unsieved milled barley (Wu et al.1994).

A similar inverse relationship between starch and fibre content has been reported elsewhere (Sundberg et al., 1995). Size fractionation of milled cereals has been shown to give fractions enriched or depleted in macronutrients (protein, carbohydrate, and fat) for oats (Wu and Stringfellow, 1995), sorghum (Rooney and Sullins, 1969), wheat (Wu and Stringfellow, 1992) and maize (Srinivasan and Singh, 2008). Similarly, a studies of sieve fractionated pea flour showed fractions enriched or depleted in starch, protein and fibre (Maaroufi et al., 2000; Maaroufi et al., 2009). The study showed that the whole flour had a bimodal particle size distribution, with the lower peak interpreted as containing starch granules, while the larger fraction was enriched in pea hull. Air classification methods have been reported to be successful in nutrient enrichment in a wide range of legume grains. For example, out of eight different legumes (mung bean, lentil, field pea, cow pea, navy bean, lima bean, northern bean and faba beans), only lima beans and cowpeas flour did not show good fractionation and separation of protein rich and starch rich fractions when milled using a pin mill (Tyler et al., 1981).

Two main fractionation technologies, air classification and wet processing, are used commercially, mainly for nutrient enrichment (mainly starch and protein) with legume grains. In most grains, protein bodies are mainly present on the surface of starch granules (i.e. adherent proteins) and between starch granules (wedge or interstitial proteins) (Hess, 1954). Thus, efficiency of protein purification depends on the ability to isolate protein bodies from non protein bodies.
3.3.1. Air classification

Air classification is considered as a quick and easy processing method that has the ability to separate light from heavy particles in legume grains after fine milling by using an air steam (Vose et al., 1976; Schutyser and van der Goot, 2011). There are many variations in the design of air classifiers, with some largely relying on air velocity to separate large and small particles, while other types use a combination of centrifugal forces and frictional forces. There are many variations in air classifier design (Klumpar et al., 1986; Shapiro et al., 2005), including combined mills and air classifiers (Figures 2a and 2b).

Figure 2a - Designs for the separation zone in a classifying device for particle separation (a) gravitational-counterflow zone, (b) gravitational-crossflow zone, (c) centrifugal-counterflow zone, (d) centrifugal-crossflow zone (Shapiro and Galperin, 2005)
The mechanism by which air classification can carry out separation has been described by Wilhelmi et al. (2007). Air classification separates heterogeneous mixtures of particles that are floating in an air stream. Two forces act on the particles as a result of the airflow and inertial force generated from the increased speed action of the particles. Larger particles are dominated by the mass dependent centrifugal power while small particles are affected by the frictional power. Controlling the cut point (the particle size where a particle is equally likely to go into either the fine or coarse fraction (Dijkink et al., 2007) is achieved by manipulation of these two forces within the classifier. The fine fraction consists of particles below the target particle size while those that exceed this size comprise the coarse fraction. To ensure higher protein purification, Tabil et al. (1995) reported that the coarse fraction needs to be reprocessed by further pin milling and repeated air classification.

Dry milling using a pin mill is essential to reduce legume grain particle size into flour (Fedec, 2003). Within the flour generated by pin milling, two types of fraction can be generated:

- Fine fraction rich in protein bodies
- Coarse fraction rich in starch granules that remained intact together while milling, (Owusu-Ansah and McCurdy (1991)

The significant difference in size and density between the fine and coarse fractions with flour obtained with air classification shows that this is an effective practical process (Al-Abbas et al., 2006). A linear correlation between levels of protein, starch, fibre and ash has been found in pin milled legume flour and their levels in air classified fractions (Tyler et al., 1981).

Depending on the type of legumes used for protein purification, starch-rich coarse fractions contain 58.0-76.1% starch and 7.7-20.1% protein, while protein-rich fine fractions contain 49.3-75.1% protein and 0.0-4.6% starch (Emami and Tabil, 2002). If a second stage of air classification is applied, starch fractions have been reported to contain up to 71.0-85.9% starch and 4.0-10.4% protein, whereas, the protein fractions contain 38.0-68.2% protein and 0.4-16.6% starch (Tyler et al., 2007).
Protein contents of air classified pulse in a second high protein fraction have been reported to range from 40% to 62% (Patel et al., 1980; Aguilera et al., 1984; Gujska and Khan, 1991a; Gujska and Khan, 1991b). Conducting a second milling and classification of the coarse fraction is dependent on the benefit and cost with little further increase in protein content and yield when more than two runs are applied (Emami and Tabil, 2002). To generate sufficient of the purified protein rich fraction, the two fine fractions are usually pooled (Owusu-Ansah and McCurdy, 1991; Fedec, 2003).

Operating variables have been reported to affect the fractionation yield of starch-rich and protein-rich fractions by pin milling and air classification (Emami and Tabil, 2002). As the pin mill grinding intensity increased, the yield and protein content of the high protein fraction increased (Wu and Nichols, 2005).

Compositional effects can also influence air classifier operation. Moisture and oil content, and protein or starch type and content affect the purification efficiency. The optimum moisture content for fractionating protein in legumes covers a narrow range of between 7 and 9% (Emami and Tabil, 2002). A reduction in moisture content below this range, however, has resulted in increasing separation efficiency of pea protein (Owusu-Ansah and McCurdy, 1991). Air classification efficiency of a blend of wheat starch and wheat protein was not affected by storage at a relative humidity of up to 60%, but decreased markedly beyond this level (Dijkink et al., 2007). The presence of lipid/oil can also affect fractionation efficiency. Most lipids are stored in oil bodies or spherosomes or lipid containing vesicles, which are located in the endosperm (Emami and Tabil, 2002). Increased oil content decreases air classification efficiency in legumes (Swanson, 1990) and in cereals (Wu and Stringfellow, 1995; Wu and Doehlert, 2002). The impact of oil in reducing fractionation efficiency can be attributed to three possible factors. Firstly, the absence of oil can make starch granules less aggregated and consequently enhance the separation of starch and other flour components (Stevenson et al., 2008). Secondly, low-oil milled grains can be milled much finer flour to loosen starch granules which then enhances the separation process (Sibakov et al., 2011). Thirdly, heat generated from fine milling can enhance lipid fusion with structural proteins which might reduce separation efficiency (Heneen et al., 2009). Lipid removal in oats can affect both the particle size reduction after milling and air classification (Sibakov et al., 2011).

Air-classified fractions of zero-tannin faba bean and field pea contained concentrated sources of amino acids and energy for pigs thereby enhancing their nutrient profile and digestibility (Gunawardena et al., 2010a). In contrast, however, pea protein concentrates produced by air classification reduced average daily gain and feed conversion in pigs (Valencia et al., 2008). A number of factors may have contributed to this including the presence of anti-nutritional factors and compounds that reduce palatability. Thus, further processing might be required to overcome their presence in protein purified fractions when fed to pigs.

### 3.3.1.1. Combined sieve and air classification

Combining processes can be used to improve the enrichment of fractions. A combination of sieve fractionation and air classification can increase the degree of enrichment of the final fractions. Sieve fractionation combined with air classification increased protein content and decreased fibre content in cotton seed meal, soybean meal and wheat middlings (Challa et al., 2010), and also increased starch content in hammer milled or roller milled
barley (Srinivasan et al., 2010; Srinivasan et al., 2012). The extent of enrichment or depletion for a particular nutrient varied with feed material and size fraction being studied. It has also been proposed that air classification could be combined with electrostatic separation to produce protein enriched samples. Several studies have evaluated electrostatic separation in wheat bran (Hemery et al., 2009; Dascalescu et al., 2010; Hemery et al., 2011), whole and broken wheat grain (Salam et al., 2004), sunflower flour (Levic et al., 2012) and wheat flour (Noguchi et al., 1981). In spite of these successes, the potential for processing pig feed has not been reported.

3.3.1.2. Wet processing

In comparison to air classification, wet processing is used to produce more highly purified protein and starch fractions (Emami and Tabil, 2002). Wet processes are limited by high viscosity of the aqueous extracts that produce large liquid volumes (using flour : water ratios ranging from 1:5 to 1:20 ) which then lead to high energy costs for drying or time consuming costly solvent recovery steps (Tabil et al., 1995; Boye et al., 2010; Naguleswaran and Vasanthan, 2010; Sibakov et al., 2011). Wet processing is based on protein solubilisation and followed by precipitation to recover proteins (Swanson, 1990; Owusu-Ansah and McCurdy, 1991; Tabil et al., 1995).

Techniques for wet processing legume protein flours, protein concentrates and isolates include: alkaline extraction, acid extraction, water extraction, salt extraction (micellization) and ultrafiltration. Each of these techniques has been reviewed previously and described in detail by many authors (Emami and Tabil, 2002; Boye et al., 2010). The resulting products differ based on their protein level: protein flour (<60% protein), protein concentration (>60% protein) and the ability to isolate the protein (>90% protein) (Boye et al., 2010).

While effective in producing protein and starch rich fractions, the potential for wet processing is limited in animal feeds. When used to produce products for human consumption, the benefits of high protein functionality (e.g. gel forming ability, foaming, emulsification capacity) can justify the costs associated with this technique. However, for animal feed where the digestibility is the main objective, wet processing shows limited potential.

3.3.2. Thermal processing

3.3.2.1. Steam pelleting

Once the ingredients that formulate pig diets have been ground and mixed, they can either be fed as mash or processed further. Steam pelleting can affect starch availability by altering starch properties or its interaction with other components in the feed (Rowe et al., 1999; Svihus et al., 2005). The impact of steam pelleting on feed properties and its digestibility can differ with the nature of feed material and specific operating conditions. Holm et al. (1988) found that starch digestion is linearly correlated with starch gelatinisation (correlation of 0.96 between extent of starch gelatinisation and digestion rate).

Little is known of the effect of different pellet processing variables on starch gelatinization and starch digestibility. Most of the emphasis has been on the physical quality of feed, production capacity of the pelletizer and pig growth performance. For further information, the reader is referred to the following papers:

- Factors that affect physical quality of pelleted feed (Thomas and van der Poel, 1996; Thomas and Owens, 2000)
- Effect of feed pelleting in swine (Chae and Han, 1998; Hancock and Behnke, 2000)
The scope of the present review will include potential approaches for steam pelleting used routinely for pig feed and the effect of moisture, temperature and frequency of pelleting on the process.

Moisture is added during preconditioning before the start of the pelleting process to increase the quality of pellets (durability) and the production capacity of the feed mill. Moisture can be added in two forms: as water (liquid) and steam (gas). The level of the steam that can be added to mash feed during the process of conditioning is termed “steam quality” (Gilpin et al., 2002). Steam quality is defined as the fraction of steam present in the vapour phase and is calculated as the steam mass divided by the mass of steam and water (Stultz and Kitto, 1992; Gilpin et al., 2002). Leaver (1988) reported that more than 6% steam cannot be added to mash feed during the conditioning process to optimize mash pressing and to prevent possible blockage in the die. This means that the maximum temperature that the mash feed can reach during conditioning is around 100 °C (assuming mash temperature before conditioning is room temperature). The moisture from steam can form a cohesive bridge between feed particles (Smallman, 1996), and this can improve pellet durability (Fairfield, 2003). Wood (1987) reported that water coming from condensing steam is superior to adding liquid water, for pellet hardness and durability. This is because the additional heat that results from adding steam can modify the physicochemical properties of feed components, such as starch gelatinization, to enhance binding between particles.

Gilpin et al. (Gilpin et al., 2002) studied the effect of steam flow rate on starch gelatinization in swine finishing diets containing 73.8% corn using two different conditioning systems. They reported that there was a significant negative correlation between steam flow rate and starch gelatinization. A similar result has been reported by Skoch et al. (1981). The reduction in starch gelatinization after steam conditioning was attributed to the lubrication of the mash with extra water, which reduces the friction within the die (Gilpin et al., 2002). Stevens (1987) reported that conditioning the mash feed, containing 74% corn, to 80 °C caused limited gelatinization (28%) compared to dry pelleting (41.9%) and that most starch gelatinization occurred as the feed material passed through the die. However, pelleting mash feed (containing 30.2% corn and 39.3% sorghum) without steam conditioning resulted in only 20 to 25% of starch being gelatinized (Skoch et al., 1981). Differences in the degree of starch gelatinization reported here may have been due to the presence of sorghum which has low starch digestibility for reasons related to sorghum endosperm structure. Svihus et al. (2005) reported that during steam conditioning and pelleting, only between 10 to 200 g starch/kg starch was usually gelatinized. These results indicate that friction of mash feed across the die may be more important than the conditioning step, on starch gelatinization. The limited extent of starch gelatinization (10 to 200 g starch/kg starch) may be related to physicochemical differences of feed material at the surface and internal components of pellets (Svihus et al., 2005). The surface region is exposed to greater friction across the die, compared to the internal portion of pellets. Double pelleting processes have been reported to improve pellet quality of swine feed even at high inclusion levels of fat in the diet (Robohm and Apelt, 1989). Although the effect of double pelleting on starch diet was not investigated, it would be expected that a second exposure of the pellet to the press may enhance starch gelatinization under the influence of shearing. In addition, a second pelleting process may enhance further particle size reduction. These contentions are supported by Wolf et al. (2010), who reported a marked reduction in particle size from pressing pellets through a die with wet sieving. Thus, double pelleting may enhance starch digestibility by enhancing starch gelatinization and by reducing particle size which are so important for starch digestion (Al-Rabadi et al., 2009). However, double pelleting will impact on higher energy consumption (Robohm and Apelt, 1989). Further research is required to characterize the influence of the double pelleting process on pig diets in which the initial process acts as a pre-compaction step through a thin die and the second uses a thick die.
Fractionation technology, based on particle size, can also increase nutritive value of processed grains by using extrusion (Al-Rabadi et al., 2011a). In theory, a similar approach to that used with steam pelleting can be adapted to improve nutritive value where water is added to induce starch gelatinization and thus grain digestibility (Svihus et al., 2005). Limiting extrusion to medium and coarse sized fractions ensures efficient utilization of thermal energy input per unit mass extruded, compared with ground but non-fractionated grains (Al-Rabadi et al., 2011a). Increasing water addition during steam pelleting to medium and coarse size fractions above the conventional 5-6% followed by mixing with small size fractions can improve energetic efficiency during steam pelleting, compared with the use of ground but non-fractionated grains. This could be a useful processing strategy as the rate and extent of starch digestion is relatively high for uncooked small particle size fractions (Al-Rabadi et al., 2009). The mixing for the medium/coarse size fractions (higher moisture content from steam treatment) and the small size fractions (no moisture addition) can reduce overall moisture content and hopefully eliminate any chance of die blockage. Small size fractions have a higher water affinity than medium and coarse size fractions which might help in increasing the level of steam addition when fractionating medium and coarse sized particles Al-Rabadi et al. (2011b). Fortunately, water hydration properties (water absorption index and water solubility index) for different sized fractions are additive and can be predicted from the weighted summation of sieved fractions and non-fractionated milled grains (Al-Rabadi et al., 2011b).

However, more capital investment is required for grain fractionation and mixing before grain/complete feed can be pressed though the die.

### 3.3.2.2. Effect of retention time in the conditioner

The retention time of mash feed before pelleting can affect both pellet quality and starch gelatinization (Thomas et al., 1997; Gilpin et al., 2002). Conditioners used in the feed industry have many physical differences that can affect the retention time of mash feed in the conditioner before pelleting Gilpin et al. (2002). These differences include: diameter, length, type of picks (single or double picks), number and placement of picks, pick angles, and steam inlet location. For example, the average retention time of mash feed in the conditioner was lower (5 seconds) for picks at 45° than at 90° (15 seconds) (Biggers et al., 1999). Gilpin et al. (2002) reported that the conditioner retention time, in combination with moisture content, has a significant effect on starch gelatinization. Extending the conditioning process for several minutes can increase starch gelatinization (Hancock and Behnke, 2000). A longer retention time may increase starch gelatinization as a result of the assumed increased dry surface area of feed particles that are exposed to greater friction through the die. From a practical point of view, however, the increase in retention time will lower the pelleting capacity of the plant (Thomas et al., 1997).

Based on these findings, two strategies can be adopted to increase or maintain starch gelatinization during the pre-conditioning process without affecting production capacity. Firstly, the size of the pre-conditioner could be increased. Secondly, another pre-conditioner could be added (i.e. having two pre-conditioners). However, this may entail extra cost for maintenance and power supply.

### 3.3.2.3. Sorghum popping

Starch and protein components in sorghum have lower digestibility among other grain types due in part to the presence of the protein matrix that surrounds starch granules (Rooney and Pfugfelder, 1986). For example incomplete starch digestion of sorghum fragments of less than 0.1 mm has been reported after a 24 hour in vitro incubation (Al-Rabadi et al., 2011a). A recent study has shown that water plays an important role in the deleterious effects of cooking sorghum (Correia et al., 2010). This process decreases protein digestibility through the formation of sulphydryl-disulphide interchanges that make them less digestible (Weaver et al., 1998). Rupturing the sorghum microstructure through whole
grain expansion or popping has the potential to open endosperm and protein matrix structure and thus increase nutrient intake without the need to mill the grain. Popping is an explosive process that fragments the cell wall thus improving the accessibility of starch reserves in the endosperm to digestive enzymes (Parker et al., 1999; Correia et al., 2010). Ultrastructural analysis has shown that popping sorghum grain changed the starch granules into thin lattices of interconnecting sheets, without altering protein bodies (Harbers, 1975). Hoseney et al. (1983) reported that each bubble of the endosperm foam represents an individual starch granule of the vitreous endosperm. During the explosive popping process, starch granules gelatinize and then inflate through increasing internal steam pressure (Parker et al., 1999). Unlike wet cooking, popping sorghum has been reported not to reduce protein digestibility (Parker et al., 1999), and in fact may have a higher protein and starch digestibility and a higher glycaemic index compared to raw grains (Nathakattur et al., 2011).

Moisture content is the most important factor in popping because it affects both rate and extent of pressure build up inside starch granules (Eldredge and Thomas, 1959; Hoseney et al., 1983). Many factors can affect popping quality (popping yield and expansion ratio) of sorghum grains such as grain variety, grain structure, chemical composition and also the method of popping (Gundboudi, 2006). Viraktamath et al. (1972) conducted a study to evaluate the influence of fourteen sorghum variety on popping yield and found that it ranged from 21 to 75%. However, other hybrid cultivars of sorghum have been reported to reach a popping yield of 100% (Kasturiba et al., 1994). Singh and Srivastava (1993) also concluded that suitable grain moisture for popping of sorghum varied from genotype to genotype, although a moisture gain of 12% was suitable for most of the sorghum genotypes resulting in popping rate range from 82-86%. Most appropriate sorghum grains that have been found suitable for popping have a small grain size, are white in colour, have a medium thick pericarp, a breaking strength of about 7 kg, a hard endosperm and a very low endosperm size ratio (Gundboudi, 2006). Popping quality has been reported to be negatively correlated with the quantity of milled sorghum passing through the 75 µm sieve (Murty et al., 1983). Thus, sorghum grains characterized by having a large coarse fraction after milling might be popped as an alternative processing method to milling.

From a quality point of view, popped sorghum should have an expansion volume between 4.8 to 11.6 ml/g (Malleshi and Desikachar, 1985). A lower expansion ratio can be the result of a decrease in the ability of the pericarp to hold the initial water vapour pressure created by heating (Hoseney et al., 1983). The extent of damage to the pericarp can also decrease this expansion ratio due the increased rate of water vapour loss during heating (Mitchum, 2002). Singh and Srivastava (1993) found that mechanical damage on grain for popcorn seems to affect popping process by two ways. Firstly, the damaged site on pericarp works as a conduit for the release of water vapour from the endosperm during the heating of the grain, thus decreasing water vapour available to induce expansion. Secondly, the damaged pericarp reduces the mechanical strength of the pericarp and thus permits the grain to pop earlier. The different processing methods such as dry and moist heat application through using different heating media (sand/salt/oil) and microwave for popping of the various sorghum cultivars can lead to different outcomes (Gundboudi, 2006). They concluded that popping of moist grain with dry heat and oil as heating media provided the highest popping yield, whereas it was lowest in a microwave oven.

### 3.3.2.4. Extrusion

Several strategies have been adopted to maximize utilization of cereals by pigs after milling such as applying low, mild and high thermal processing as mentioned previously. From a processing prospective, extrusion is considered as one of the most effective processing methods in inducing changes in nutrient structure in grains and legumes. This is due to exposure of nutrients to high temperature and moisture addition which induce starch gelatinization and other chemical changes such as the Maillard reaction (Lai and
Kokini, 1991) and reducing the activity of antinutritional factors (Alonso et al., 2010). For further information on the effect of the extrusion process on nutritional quality of feeds, the reader is referred to review papers published by Singh et al. (2007); Camire et al. (1990) and Areas (1992).

During extrusion, grains can be heated to 150 - 170°C at a pressure of 15 - 40 atm (Lai and Kokini, 1991; Hancock and Behnke, 2000): thus, extrusion is considered as an expensive processing choice. Despite the high thermal input of extrusion, starch present within coarse grain fractions still escapes complete starch gelatinization as indicated recently by scanning electron micrographs (Al-Rabadi et al., 2011a).

There are many ways in which particle size can affect the rate and extent of water penetration, and thus gelatinization, of starch within grain fragments. The physical structure of the grain can play a role, particularly in the coarse fraction. This coarse fraction basically comprises half or whole grains, with the seed coat still covering much of the grain fragment surface. As it is difficult for water molecules to penetrate the seed coat, water penetration into the coarse fraction may be significantly slowed. Furthermore, with the increase in particle size, the surface area to volume ratio is lower, which may also reduce the rate of water penetration into the coarse fractions (Hsu, 1983; Addo et al., 2006). This lower water absorption results in lower starch gelatinization after extrusion (Garber et al., 1997). This slower water absorption is thought to contribute to a higher gelatinization temperature (Onwulata and Konstance, 2006). The competition between non-starch components (such as protein and non-starch polysaccharide) for available water can be also a limiting factor for starch gelatinization (Brennan et al., 2008b) and thus potential starch hydrolysis (Brennan et al., 2008a). Pre-conditioning of coarse particles of corn before extrusion has been reported previously to result in improved starch gelatinization to that for fine particles (Mathew et al., 1999). Even under less severe heat treatments, such as steam pelleting, the duration of pre-conditioning is highly correlated with the extent of starch gelatinization (Gilpin et al., 2002). Furthermore, coarse particles have a reduced contact area with the extruder barrel than fine particles, causing them to be less affected by temperature (Onwulata and Konstance, 2006), due to the limitations of heat transfer. However, despite all these considerations, the fractional digestion rates for all (ground) extruded grains were at least five times greater than for any non-extruded grain fractions (Al-Rabadi, 2011a).

To the best of our knowledge, no reports on the influence of particle size, after segregation by sieving, on nutritional quality of extruded legumes are available. Most reports of extrusion of legumes relate to the nutritional and functional properties of fine milled legumes (legume flour) used in food industry (Filli and Nkama, 2007; Boye et al., 2010; Smith and Hardacre, 2011). Further studies are needed to enrich our knowledge of how coarse legumes particles can be used in the development of animal feed.
3.4. Feeding strategy to optimize enzyme activity in swine diet at farm level through liquid feeding

3.4.1. Introduction

Many recent review articles have served to clarify methodologies for grain processing and the nomenclature for enzymology for phytase, NSP enzymes and proteases and then proceeded to identify their application in pig nutrition (Johansen and Poulsen, 2003; Selle and Ravindran, 2008; Adeola and Cowieson, 2011; Knudsen et al., 2012). Previous review articles indicate that enzyme technologies have been unreliable. Suggesting that there is significant room for improvement. Some examples of the influence of different enzymes usage in pig nutrition at different production stages are summarized in Table 1.

On the other hand, the use of fermented liquid feed and/or liquid feed has been extensively reviewed and reported to possess two main advantages if material is handled carefully (Brooks, 2008; Plumed-Ferrer and Von Wright, 2009; Missotten et al., 2010; Niba et al., 2010). Firstly, application in the peri-weaning period when feed as an alternative source of nutrients to milk and water are required simultaneously is of great importance. Secondly and in case of fermented liquid feeding, offering liquid feeding with a low pH may enhance the defence of the gastro-intestinal tract against possible pathogenic organisms.

The objective of this report is to summarize factors that influence phytase and NSP enzymes activity in pig nutrition since they seem to be the most effective, among other digestive enzymes, in inducing significant nutritional and economic consequences for pig nutrition. In addition, the joint application of liquid feeding with dietary enzyme technologies based on the use of phytase and NSP enzymes, will be assessed.

Table 1 - Summary of literature on digestibility and performance responses to exogenous enzymes in pigs (research studies conducted before 2003 was adapted from Kim (2003). Digestibility data are total tract digestibility unless otherwise stated.
<table>
<thead>
<tr>
<th>Weight (kg)</th>
<th>Diet</th>
<th>Enzyme (U/kg diet)</th>
<th>Digestibility (%) response to phytase</th>
<th>Performance response</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>11-25</td>
<td>Maize, barley</td>
<td>Phytase (1450 U/kg diet)</td>
<td>DM 85→83.6 (-2%); CP -; P 38.3-59.9 (+22%); Ca -</td>
<td>DG (+20%); DFI (+13%); FCR (+8%)</td>
<td>1</td>
</tr>
<tr>
<td>37</td>
<td>Corn, SBM</td>
<td>Phytase (1500 U/kg diet)</td>
<td>Ileal 70.0→67.9 (-3%); Fecal 12.9→42.6 (+70%)</td>
<td>Ileal 26.4-44.9 (+41%); Fecal 27.8→54.8 (+49%)</td>
<td>2</td>
</tr>
<tr>
<td>37</td>
<td>Tapioca, SBM</td>
<td>Phytase (1500 U/kg diet)</td>
<td>Ileal 48.8→45.2 (+10%); Fecal 27.8→54.8 (+49%)</td>
<td>Ileal 16.4→45.8 (65%); Fecal 27.8→54.8 (+49%)</td>
<td>2</td>
</tr>
<tr>
<td>37</td>
<td>Corn, SBM</td>
<td>Phytase (1350 U/kg diet)</td>
<td>Ileal 70.0→67.9 (-3%); Fecal 12.9→42.6 (+70%)</td>
<td>Ileal 26.4-44.9 (+41%); Fecal 27.8→54.8 (+49%)</td>
<td>2</td>
</tr>
<tr>
<td>7.4</td>
<td>Corn, SBM</td>
<td>Phytase (1350 U/kg diet)</td>
<td>DM 24.3→69.6 (+65%); CP 40.1→68.6 (41%); Ca 70.9→83.6 (+15%)</td>
<td>DG (+38%); DFI (+21%); FCR (+21%)</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>Corn, SBM</td>
<td>Phytase (750 U/kg diet)</td>
<td>DM 46.4→69.0 (+33%); CP 70.9→83.6 (+15%)</td>
<td>DG (+22%); DFI (+17%); FCR (+4%)</td>
<td>4</td>
</tr>
<tr>
<td>9.4</td>
<td>Corn, SBM</td>
<td>Phytase (1500 U/kg diet)</td>
<td>DM 57.8→75.5 (+25%); CP 57.8→58.0 (ND)</td>
<td>DG (+37%); DFI (+37%); FCR (+37%)</td>
<td>5</td>
</tr>
<tr>
<td>10-90</td>
<td>Corn, SBM</td>
<td>Phytase (1200 U/kg diet)</td>
<td>Ileal 79.9→82.9 (4%); Fecal 12.9→42.6 (+70%)</td>
<td>Ileal 26.4-44.9 (+41%); Fecal 27.8→54.8 (+49%)</td>
<td>6</td>
</tr>
<tr>
<td>19-108</td>
<td>Corn, SBM</td>
<td>Phytase (500 U/kg diet)</td>
<td>DM 88.5→88.6 (ND); CP 38.0→50.4 (+25%); Ca 63.2→64.1 (+1%)</td>
<td>DG (+15%); DFI (+13%); FCR (+2%)</td>
<td>7</td>
</tr>
<tr>
<td>19-108</td>
<td>Corn, SBM</td>
<td>Phytase (500 U/kg diet)</td>
<td>DM 86.1→85.5 (-1%); CP 38.0→50.4 (+25%); Ca 63.2→64.1 (+1%)</td>
<td>DG (+15%); DFI (+13%); FCR (+2%)</td>
<td>7</td>
</tr>
<tr>
<td>30-38</td>
<td>Corn, Tapioca, wheat middling</td>
<td>Phytase (500 U/kg diet)</td>
<td>DM 76.2→75.2 (-1%); CP 23.0→36.6 (+37%); Ca 39.3→43.9 (+10%)</td>
<td>DG (+6%); DFI (+3%); FCR (+3%)</td>
<td>8</td>
</tr>
<tr>
<td>40-100</td>
<td></td>
<td></td>
<td>DM 78.2-78.2 (ND); CP 26.6→43.2 (+40%); Ca 39.2→43.2 (9%)</td>
<td>DG (+6%); DFI (+3%); FCR (+3%)</td>
<td>8</td>
</tr>
<tr>
<td>Pregnant sow</td>
<td></td>
<td></td>
<td>DM 81.8-81.2 (ND); CP 16.0→26.8 (40%); Ca 18.6→16.4 (-12%)</td>
<td>DG (+6%); DFI (+3%); FCR (+3%)</td>
<td>8</td>
</tr>
<tr>
<td>Lactating sow</td>
<td></td>
<td></td>
<td>DM 81.0-81.7 (ND); CP 19.4→40.9 (+53%); Ca 30.6→31.3 (+2%)</td>
<td>DG (+6%); DFI (+3%); FCR (+3%)</td>
<td>8</td>
</tr>
<tr>
<td>7.4</td>
<td>Corn, SBM</td>
<td>Phytase (750 U/kg diet)</td>
<td>DM 80.8→82.4 (+2%); CP 23.4→56.6 (+59%); Ca 54.3→79.4 (32%)</td>
<td>DG (+6%); DFI (+3%); FCR (+3%)</td>
<td>9</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>Diet</td>
<td>Enzyme (U/kg diet)</td>
<td>Digestibility (%) response to phytase</td>
<td>Performance response</td>
<td>Ref</td>
</tr>
<tr>
<td>------------</td>
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</tr>
<tr>
<td>9.6</td>
<td>Corn, SBM</td>
<td>Phytase (500 U/kg diet)</td>
<td>DM: 79.3→79.1 (ND)</td>
<td>DG(+5%) FCI(+8%)</td>
<td>9</td>
</tr>
<tr>
<td>37</td>
<td>Corn, SBM</td>
<td>Phytase (900 U/kg diet)</td>
<td>CP: 16.1→13 (ND)</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>Corn, SBM</td>
<td>Phytase (900 U/kg diet)</td>
<td>P: 53.5→67 (ND)</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Corn, SBM, whey</td>
<td>Phytase (1200 U/kg diet)</td>
<td>Ca: 53.5→67 (ND)</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Corn, SBM</td>
<td>Phytase (2500 U/kg diet)</td>
<td>86.0→86.8 (+1%)</td>
<td>DG(+18%) FCI(+10%)</td>
<td>13</td>
</tr>
<tr>
<td>9-14</td>
<td>High available-P corn</td>
<td>Phytase (600 U/kg diet)</td>
<td>91.0→90.2 (ND)</td>
<td>DG(+5%) FCI(+6%)</td>
<td>14</td>
</tr>
<tr>
<td>9-14</td>
<td>Normal corn</td>
<td>Phytase (600 U/kg diet)</td>
<td>91.1→92.1 (+1%)</td>
<td>DG(+11%) FCI(+4%)</td>
<td>14</td>
</tr>
<tr>
<td>25</td>
<td>Corn, starch, SBM</td>
<td>Phytase (1500 U/kg diet)</td>
<td>Apparent ileal 82.5→82.2 (ND)</td>
<td>DG(+4%) FCI(+4%)</td>
<td>15</td>
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<tr>
<td>25</td>
<td>Barley, pea</td>
<td>Phytase (374 U/kg diet)</td>
<td>True ileal 89.8→89.6 (ND)</td>
<td>16</td>
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<tr>
<td>45</td>
<td>Not known</td>
<td>Phytase (625 U/kg diet)</td>
<td>81.5→83.0 (+2%)</td>
<td>17</td>
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</tr>
<tr>
<td>7</td>
<td>Wheat, SBM</td>
<td>Phytase (750 U/kg diet)</td>
<td>DG(ND) FCI(ND) FCR(ND)</td>
<td>18</td>
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</tr>
<tr>
<td>7</td>
<td>Wheat (phytate-P=2.2 g/kg)</td>
<td>Phytase (625 U/kg diet)</td>
<td>DG(+14%) FCI(+10%) FCR(+5)</td>
<td>18</td>
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</tr>
<tr>
<td>7</td>
<td>Wheat (phytate-P=3.2 g/kg)</td>
<td>Xylanse (4950 U/kg diet)</td>
<td>DG(+11%) FCI(+5%) FCR(+11%)</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Wheat, SBM</td>
<td>Phytase (750 U/kg diet)</td>
<td>DG(+3%) FCI(+10%)</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>Diet</td>
<td>Enzyme (U/kg diet)</td>
<td>Digestibility (%) response to phytase</td>
<td>Performance response</td>
<td>Ref</td>
</tr>
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<td>DM</td>
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</tr>
<tr>
<td>22.9-41.7</td>
<td>Sorghum, SBM</td>
<td>Xylanase (4950 U/kg diet) + phytase (750 U/kg diet)</td>
<td></td>
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<tr>
<td>22.9-41.7</td>
<td>Sorghum, SBM</td>
<td>Phytase (350 U/kg diet)</td>
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<td>22.9-41.7</td>
<td>Sorghum, SBM</td>
<td>Phytase (700 U/kg diet)</td>
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<td>22.9-41.7</td>
<td>Sorghum, SBM</td>
<td>Phytase (1050 U/kg diet)</td>
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<tr>
<td>86.1</td>
<td>Sorghum, SBM</td>
<td>Phytase (500 U/kg diet)</td>
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<tr>
<td>52</td>
<td>Corn, SBM (high Ca and P diets)</td>
<td>Phytase (500 U/kg diet)</td>
<td>Apparent Ileal 70.4→75 .3 (+7%)</td>
<td>Apparent Ileal 75.0→78 .1 (+4%)</td>
<td>Apparent Ileal 43.5→52 .8 (+21%)</td>
</tr>
<tr>
<td>52</td>
<td>Corn, SBM (low Ca and P diets)</td>
<td>Phytase (500 U/kg diet)</td>
<td>Apparent Ileal 75→75.3 (ND)</td>
<td>Apparent Ileal 78.6→78 .2 (ND)</td>
<td>Apparent Ileal 34.7→50 (+41.1%)</td>
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<tr>
<td>22.2</td>
<td>Maize; rice; rapeseed; cottonseed meals (normal P level)</td>
<td>Phytase (500 U/kg diet)</td>
<td>Apparent Ileal 73.7→74 .5 (+1%)</td>
<td>Apparent Ileal 74.4→75 .4 (+1%)</td>
<td>Apparent Ileal 44.9→46 .3 (+3%)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>Diet</td>
<td>Enzyme (U/kg diet)</td>
<td>Digestibility (%) response to phytase</td>
<td>Performance response</td>
<td>Ref</td>
</tr>
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<tr>
<td></td>
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<td>DM</td>
<td>CP</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(+1%)</td>
<td>(+1%)</td>
<td>(+6%)</td>
</tr>
<tr>
<td>22.2</td>
<td>Maize; rice; rapeseed; cottonseed meals (Low P level)</td>
<td>Phytase (500 U/kg diet)</td>
<td>Apparent Ileal 70.1→73 .9 (+4%)</td>
<td>Apparent Ileal 72.3→74 .4 (+3%)</td>
<td>Apparent Ileal 42.4→45 .9 (+8%)</td>
</tr>
<tr>
<td>7.6</td>
<td>Corn; SBM</td>
<td>Phytase (500 U/kg diet)</td>
<td>Apparent Ileal 76→76.2 (ND)</td>
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<tr>
<td>7.6</td>
<td>Corn; SBM</td>
<td>Phytase (1000 U/kg diet)</td>
<td>Apparent Ileal 76→76.8 (+1%)</td>
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<tr>
<td>8.6</td>
<td>Wheat; SBM</td>
<td>Phytase (500 U/kg diet)</td>
<td>Apparent Ileal 83.3→83 .6 (ND)</td>
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<td></td>
</tr>
<tr>
<td>8.6</td>
<td>Wheat; SBM</td>
<td>Phytase (1000 U/kg diet)</td>
<td>Apparent Ileal 83.3→84 .5 (+1%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.3</td>
<td>Wheat; SBM; canola meal</td>
<td>Phytase (500 U/kg diet)</td>
<td>Apparent Ileal 72.0→74 .8 (+4%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.3</td>
<td>Wheat; SBM; canola meal</td>
<td>Phytase (1000 U/kg diet)</td>
<td>Apparent Ileal 72.0→74 .7 (+4%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Barley; peas; canola meal</td>
<td>Phytase (500 U/kg diet)</td>
<td>Apparent Ileal 73.3→73 .5 (ND)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Barley; peas; canola meal</td>
<td>Phytase (1000 U/kg diet)</td>
<td>Apparent Ileal 73.3→73 .9 (+1%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40.6</td>
<td>Corn, rice bran, wheat, barley (high phytate diet)</td>
<td>Phytase (2000 U/kg diet)</td>
<td>Apparent Ileal 72.1→71 .9 (ND)</td>
<td>85.0→85 .6 (+1%)</td>
<td></td>
</tr>
<tr>
<td>40.6</td>
<td>Corn, rice bran, wheat, barley</td>
<td>Phytase (2000 U/kg diet)</td>
<td>Apparent Ileal 75.2→75 .7 (+1%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>Diet</td>
<td>Enzyme (U/kg diet)</td>
<td>Digestibility (%) response to phytase</td>
<td>Performance response</td>
<td>Ref</td>
</tr>
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<td></td>
<td></td>
<td>DM</td>
<td>CP</td>
<td>P</td>
</tr>
<tr>
<td>49.6-51.4</td>
<td>Barley, (low phytate diet)</td>
<td>Phytase (1000 U/kg diet)</td>
<td>82.3→79 .5 (ND)</td>
<td>57.3→60 .3 (+5%)</td>
<td>24</td>
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<tr>
<td>49.5-50.5</td>
<td>SBM</td>
<td>Phytase (1000 U/kg diet)</td>
<td>93.0-92.3 (-1%)</td>
<td>56.5→69 .0 (+22%)</td>
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<tr>
<td>50.6-51.4</td>
<td>Barley, SBM</td>
<td>Phytase (1000 U/kg diet)</td>
<td>85.1→85 .1 (ND)</td>
<td>57.2→60 .0 (+5%)</td>
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<tr>
<td>10</td>
<td>Corn, wheat middling, SBM, Canola meal</td>
<td>Phytase (500 U/kg diet)</td>
<td>80.2→80.1 (ND)</td>
<td>80.1→80 .2 (ND)</td>
<td>38.0→49 .4 (+30%)</td>
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<tr>
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<td></td>
<td>Phytase (1000 U/kg diet)</td>
<td>80.2→80.3 (ND)</td>
<td>80.1→79 .2 (-1%)</td>
<td>38→56.2 (+47%)</td>
</tr>
<tr>
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<td>Cocktail enzymes (400 U of xylanase/kg, 4,000 U of amylase/kg, and 2,500 U of protease/kg)</td>
<td>80.2→82.3 (3%)</td>
<td>80.1→81 .2 (+1%)</td>
<td>38→48.3 (+27%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Phytase (500 U/kg diet)+ Cocktail enzymes</td>
<td>80.2→80 .0 (ND)</td>
<td>80.1→80 .0 (ND)</td>
<td>38→51.1 (+35%)</td>
</tr>
<tr>
<td>23-24</td>
<td>Corn, wheat middling, SBM, Canola meal</td>
<td>Phytase (500 U/kg diet)</td>
<td>91.2→91 .2 (ND)</td>
<td>68.1→74 .2 (+9%)</td>
<td>78.2→80 .0 (+2%)</td>
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<td></td>
<td>Xylanase (400 U/kg)</td>
<td>91.2→91 .3 (ND)</td>
<td>68.1→67 .3 (-1%)</td>
<td>78.2→78 .2 (ND)</td>
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<td></td>
<td>Phytase (500 U/kg diet)+ Xylanase (400 U/kg)</td>
<td>91.2→92 .4 (+1%)</td>
<td>68.1→77 .2 (+13%)</td>
<td>78.2→82 .3 (+5%)</td>
</tr>
<tr>
<td>19.7</td>
<td>Wheat, SBM</td>
<td>Xylanase (4000 U/kg)</td>
<td>82→80 (-2%)</td>
<td>79→78 (-1%)</td>
<td>46→32 (-30%)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>Diet</td>
<td>Enzyme (U/kg diet)</td>
<td>Digestibility (%) response to phytase</td>
<td>Performance response</td>
<td>Ref</td>
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<td></td>
<td></td>
<td>DM</td>
<td>CP</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td>Phytase (500 U/kg diet)</td>
<td>82→83 (1%)</td>
<td>79→81 (3%)</td>
<td>46→62 (34)</td>
<td>76→81 (7%)</td>
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<td>Phytase (500 U/kg diet)+Xylanase (400 U/kg)</td>
<td>82→84 (2%)</td>
<td>79→84 (6%)</td>
<td>46→60 (30)</td>
<td>76→79 (4%)</td>
</tr>
<tr>
<td>40</td>
<td>Wheat, barley, SBM</td>
<td>Phytase (750 U/kg diet)</td>
<td>42→54 (29%)</td>
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<tr>
<td></td>
<td>Phytase (750 U/kg diet) + low Ca diet</td>
<td>43→52 (21%)</td>
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<tr>
<td></td>
<td>Phytase (750 U/kg diet) + medium Ca diet</td>
<td>40→47 (18%)</td>
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<tr>
<td>26-57</td>
<td>Wheat, barley, Peas, SBM</td>
<td>Benzoic acid (0.5%)</td>
<td>80→83 (4%)</td>
<td>25→32 (28%)</td>
<td>50→49 (2%)</td>
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<td></td>
<td>Wheat, barley, Peas, SBM</td>
<td>Phytase (750 IU/kg diet)</td>
<td>80→82 (3%)</td>
<td>25→30 (20%)</td>
<td>50→57 (14%)</td>
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<tr>
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<td>Wheat, barley, Peas, SBM</td>
<td>Phytase (750 IU/kg diet)+benzoic acid (0.5%)</td>
<td>80→78 (3%)</td>
<td>25→28 (12%)</td>
<td>50→52 (4%)</td>
</tr>
<tr>
<td>57-109</td>
<td>Wheat, barley, Peas, SBM</td>
<td>Benzoic acid (0.5%)</td>
<td>85→86 (1%)</td>
<td>30→37 (23%)</td>
<td>50→53 (6%)</td>
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<td>Wheat, barley, Peas, SBM</td>
<td>Phytase (750 IU/kg diet)</td>
<td>ND</td>
<td>30→37 (23%)</td>
<td>50→62 (24%)</td>
</tr>
<tr>
<td></td>
<td>Wheat, barley, Peas, SBM</td>
<td>Phytase (750 IU/kg diet)+benzoic acid (0.5%)</td>
<td>ND</td>
<td>30→38 (27%)</td>
<td>50→54 (8%)</td>
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<td>11</td>
<td>Wheat, barley, SBM</td>
<td>Phytase (500 U/kg diet)</td>
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<tr>
<td>11-30</td>
<td>Wheat, barley, SBM</td>
<td>Phytase (500 U/kg diet)</td>
<td>85.3→85 .5 ND</td>
<td>82.0→82 .1 ND</td>
<td>57.1→65 .3 (+14%)</td>
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<tr>
<td>Weight (kg)</td>
<td>Diet</td>
<td>Enzyme (U/kg diet)</td>
<td>Digestibility (%) response to phytase</td>
<td>Performance response</td>
<td>Ref</td>
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<tr>
<td></td>
<td></td>
<td>Phytase (500 U/kg diet)</td>
<td>DM CP P Ca</td>
<td></td>
<td></td>
</tr>
<tr>
<td>37.1</td>
<td>Corn starch, DDGS (wheat and corn)</td>
<td>Phytase (500 U/kg diet)</td>
<td>Apparent Ileal 80.8→80 .5</td>
<td>Apparent Ileal 48.9→55 .7 (+14%)</td>
<td>Apparent Ileal 49.4→55 .9 (+13%)</td>
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<tr>
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<td>Xylanse (4000 U/kg diet)</td>
<td></td>
<td>Apparent Ileal 48.9→47 .6 (-3%)</td>
<td>Apparent Ileal 49.4→56 .3 (+14)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Phytase (500 U/kg diet) + Xylanse (4000 U/kg diet)</td>
<td></td>
<td>Apparent Ileal 48.9→54 .5 (+11%)</td>
<td>Apparent Ileal 49.4→61 .3 (+24%)</td>
</tr>
<tr>
<td>22.3</td>
<td>Sorghum, SBM</td>
<td>Phytase (500 U/kg diet)</td>
<td>72.7→74 .0 (+2%)</td>
<td></td>
<td>32</td>
</tr>
</tbody>
</table>

+, - represent decrease or increase, respectively.
Abbreviation used: DG: Daily gain; DFI: Daily feed intake, FCR: feed conversion ratio, SBM: soybean meal; ND: not different.
Abbreviation used: DG: Daily gain; DFI: Daily feed intake, FCR: feed conversion ratio, SBM: soybean meal; ND: not different.
1. (Beers and Jongbloed, 1992); 2. (Jongbloed et al., 1992); 3. (Lei et al., 1993a); 4. (Lei et al., 1993b); 5. (Adeola et al., 1995); 6. (Han et al., 1997); 7. (Harper et al., 1997); 8. (Kemme et al., 1997); 9. (Radcliffe et al., 1998); 10. (Kemme et al., 1999b); 11. (Kemme et al., 1999a); 12. (Stahl et al., 2000); 13. (Zhang et al., 2000); 14. (Sands et al., 2001); 15. (Traylor et al., 2001); 16. (Oryschak et al., 2002); 17 (McCann et al.2003); 18. (Selle et al., 2003); 19. (Cervantes et al., 2004); 20. (Johnston et al., 2004); 21. (Fan et al., 2005); 22. (Liao et al., 2005a); 23. (Liao et al., 2005b); 24. (Nitrayova et al., 2006); 25. (Oluks et al., 2007); 26. (Kim et al., 2008); 27. (Poulten et al., 2010); 28. (Bühler et al., 2011); 29. (Varley et al., 2010); 30. (Varley et al., 2011); 31. (Yáñez et al., 2011); 32. (Morales et al., 2012).

### 3.4.2. Background - Liquid feeding

In their review Missotten et al, (2010) defined liquid feeding as a feeding practice where liquid diet is prepared either from a mixture by by-products from the liquid food industry and traditional dry materials, or from dry raw materials mixed with water (feed mixed with water at a ratio of 1:1.5 to 1:4). If the time between mixing and feeding is too short for fermentation to occur, the term liquid feed or non-fermented liquid feed is used (Canibe and Jensen, 2003). However, if the time between mixing and feeding is sufficient for fermentation to occur or is long enough for steady state conditions for fermentation to be reached, the term fermented liquid feeding (FLF) is used (Missotten et al., 2010). Depending on presence of inocula, fermented liquid feeding is further classified to two types, spontaneous fermented liquid feeding (i.e. no inoculum is added) and inoculated fermented liquid feeding (water and feed mixture are inculcated with a culture of lactic acid bacteria) (Brooks et al., 2003; Missotten et al., 2010).

Missotten et al. (2010) summarised (Figure 3) the events that occur during the fermentation process into the following phases:

---

**Table:**

<table>
<thead>
<tr>
<th>Weight (kg)</th>
<th>Diet</th>
<th>Enzyme (U/kg diet)</th>
<th>Digestibility (%) response to phytase</th>
<th>Performance response</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Phytase (500 U/kg diet)</td>
<td>DM CP P Ca</td>
<td></td>
<td></td>
</tr>
<tr>
<td>37.1</td>
<td>Corn starch, DDGS (wheat and corn)</td>
<td>Phytase (500 U/kg diet)</td>
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<tr>
<td></td>
<td></td>
<td>Xylanse (4000 U/kg diet)</td>
<td></td>
<td>Apparent Ileal 48.9→47 .6 (-3%)</td>
<td>Apparent Ileal 49.4→56 .3 (+14)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Phytase (500 U/kg diet) + Xylanse (4000 U/kg diet)</td>
<td></td>
<td>Apparent Ileal 48.9→54 .5 (+11%)</td>
<td>Apparent Ileal 49.4→61 .3 (+24%)</td>
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<tr>
<td>22.3</td>
<td>Sorghum, SBM</td>
<td>Phytase (500 U/kg diet)</td>
<td>72.7→74 .0 (+2%)</td>
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<td>32</td>
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1- Initial Phase - the first phase of fermentation is characterized by low levels of lactic acid bacteria, yeast and lactic acid, high pH, and, high levels of enterobacteria (Canibe and Jensen, 2003). The initial phase has been further subdivided into:

a. Phase 1: in which high pH allows the proliferation of coliform bacteria (Brooks, 2008).

b. Phase 2: in which growth and fermentation by lactic acid bacteria inhibits pathogenic and spoilage organisms by the production of organic acids (particularly lactic acid) (Brooks, 2008).

2- Steady State - this phase is characterized by high levels of lactic acid bacteria (responsible for the antimicrobial effect), yeasts, and lactic acid, and low enterobacteria counts (Canibe and Jensen, 2003). The steady state phase attained at this point equates to phase 3 (Brooks, 2008).

![Figure 3 - Schematic representation of the microbial population and pH during the different phases in the fermentation of fermented liquid feeding (FLF). From Missotten et al. (2010); based on Canibe and Jensen (2003), and Brooks (2008).](image)

Water temperature influences the rate of changes that occur in soaked feed (Missotten et al., 2010). For example, Carlson and Poulsen, (2003) reported that soaking dry feed in 20°C water stimulated endogenous phytase activity leading to degradation of 17-79% of the total phytate in the diet within the first 8 hours. The same result was achieved within 2 hours when the water temperature increased to 30°C. Increasing the water temperature to 38°C increased the growth of lactic acid bacteria and thus reduced the feed to a pH of 4.7 after 12 hours of incubation. A temperature of 30°C is preferable because it allows a fast production of lactic acid and therefore rapid inhibition of enteropathogens (Brooks et al., 2003). Manipulation of temperature and pH allows us to optimise conditions for the application of enzymes to feeds as will be discussed in the next section.

Increasing water temperature before soaking feed could be a suitable means for optimizing nutritional quality of soaked/fermented feed for pigs. Using solar energy (an
environmentally friendly energy source) to heat water at temperature close 30°C could have an added value in Australian areas where sunlight is abundant.

3.4.3. Protease

Proteases have been added to swine diets regularly for many years as part of an enzyme mixture containing xylanases, glucanases, pectinases, amylases, and other activities (Simbaya et al., 1996; Cowieson and Adeola, 2005). Protease has received less attention from nutritionists compared to the other enzymes used in swine diets due to the interactions with the digestive architecture of the host, with other supplemental enzymes and with dietary proteins (Adeola and Cowieson, 2011). Saarelainen et al. (1993) and Saleh et al. (2004) have reported that the hydrolytic activity of carbohydrases may be limited or the carbohydrate itself may be digested in the presence of protease. Different proteases have been reported to produce different responses in swine due to compatibility with endogenous proteases. This may also be due to modification of dietary proteins such as in soya bean (Adeola and Cowieson, 2011). Thus, the application of protease enzymes is beyond the scope of this report.

3.4.4. Phytase

Phytases are a group of enzymes that have the ability to convert insoluble phytic acid that is present in many feeds (mainly grains and oilseeds) into orthophosphate and inositol phosphates. Generally, phytases are classified as 3- and 6-phytase on the basis of the site of action on the phytic acid molecule of initial dephosphorylation (Adeola and Cowieson, 2011). The difference between the previous two types is also based on their origin source. The 3-phytases are of microbial origin and start hydrolysis at the carbon 3 atom of the inositol ring, while, 6-phytases are of plant origin and start phosphate cleavage at the carbon 6 atom of the inositol ring (Dvorakova, 1998).

Phytase has the capacity to hydrolyse dietary phytate, the mixed salt of phytic acid (myo-inositol hexaphosphate; IP6) to liberate six P moieties and inositol in the porcine gastrointestinal tract (Selle and Ravindran, 2008). However, only a proportion of phytate-bound P is released because phytase does not degrade phytate completely (Kemme et al., 2006) and because endogenous phytase activity generated by the small intestinal mucosa is insufficient to dephosphorylate phytate effectively (Selle and Ravindran, 2008). From the large amount of research conducted so far phytase in mixtures of nonspecific phosphatases was capable of hydrolysing 75% of P presents in phytate (as shown in table 1). This suggests there is a place for further improvement.

Phytate is a reactive, and extremely influential compound with physiological effects far beyond a reduction in P digestibility (Selle and Ravindran, 2008). Recently, Adeola and Cowieson (2011) reviewed the influence of phytate on other nutrients inside the animal body. In their review, they reported that phytate also influences protein and mineral digestibility and absorption via different proposed mechanisms.

Phytase application in swine feed at different growth and production stages has been investigated intensively during the past 20 years. Phytase improves growth and enhances P and Ca utilization, but positive effects on the metabolism of other nutrients are not always observed (table 1). Different approaches have been adopted to enhance the effectiveness of phytase such as changing phytase dosage level relative to dietary phytate, level of different minerals in diets (mainly Ca and P) or the addition of other enzymes (such as glucanase and xylanase). However, there were conflicting opinions that are reflected in the inconsistent outcomes of some studies (some examples are shown in Table 1). The inconsistent outcomes reported in most studies relates to variation in dietary phytate concentration, the source of phytate, animal age and species, mineral concentrations in the diet, protein level in diet, dietary pH, thermal treatment, the ratio between protein level and dietary phytate, the ratio between minerals, vitamin D concentration, selected
ingredients, phytase source, and level of addition of phytase (Selle and Ravindran, 2008; Adeola and Cowieson, 2011).

Several mechanisms by which phytase may improve the utilization of metabolizable energy (ME) have been summarized by Adeola and Cowieson (2011), including improved solubility of dietary nutrients and other complexes, improved solubility of cofactors (e.g. Ca or Zn) for digestive enzymes, reduced endogenous energy flow, improved capacity for active transport of nutrients from the gut associated with Na, reduced integrity of fibrous complexes (in which phytate may be implicit), and direct inhibition of digestive enzymes (or their activation) by phytate. However, there is no generally established mechanism to explain the effect of phytase on energy digestibility.

Selle and Ravindran (2008) summarized factors that influence the response to dietary phytase in pig diets as follows:

1- Phytase enhancement of protein digestibility is positively correlated to phytate level in the diet and more importantly to phytate: protein ratio (positively correlated). Adeola and Cowieson (2011) reviewed the influence of protein on phytase activity and suggested that a phytate to protein ratio of 0.05:1 is critical. If the ration is lower protein: protein aggregation can take place thereby reducing protein digestibility under the acidic conditions within the stomach. They also suggested that in most commercially produced formulated diets, the actual ratio is marginally less than this, and has not been taken into consideration when formulating the diet.

2- Ingredients included in pigs diet. For example, the hydrolysis rate of phytate is higher in soya bean than in rapeseed meal. This suggests that selecting ingredients based on hydrolysis rate, although they may be more expensive, may result in better pig growth performance after phytase inclusion and may justify their inclusion in diets.

3- Heat treatment of feed, such as pelleting, can reduce phytase activity although some commercial brands claim to have heat resistance. It is worth mentioning that feed material has some phytase activity and the activity can also be reduced after heat treatment like pelleting. Providing diets in mash form without pelleting could be beneficial for maximising phytase activity. Particle size distribution may also play a role in determining the effectiveness of phytase, with large particles limiting access of the enzyme to substrate which has been reported with amylase digestion of starch in milled grain (Al-Rabadi et al., 2009).

4- The presence of cations like Zn$^{2+}$, Fe$^{2+}$, Mn$^{2+}$, Ca$^{2+}$, Mg$^{2+}$ can reduce phytase activity at pH 6-7 (the pH range typically found in the small intestine) and affect nutrient absorption. Their negative effect on phytase activity is arranged in descending order (i.e. highest enzyme inhibition by Zn and lowest by Mg). It is worth noting that zinc oxide is extensively used in pig diets to control the growth of pathogenic bacteria.

5- The presence of Ca and inorganic P and their relatively high ratio in pig diets has a negative effect on phytase activity. Ca and P have high acid binding affinities and may increase gut pH (inhibit the solubilisation of phytate). In addition, the presence of inorganic P may reduce catalytic activity of phytase. Reducing both levels of Ca and P in the diet as well as reducing Ca:P ratio below 1.1:1 can reduce their negative impact on phytase activity.

6- Limited retention time in the pig stomach, with a relatively short time resulting in lower substrate digestion. This factor was not discussed in many articles and may be related to our inability to manipulate stomach retention time. The presence of pepsin, which reduces phytase activity.

7- Recently Adeola and Cowieson (2011) suggested that the key solution to reduce antinutritional effects of phytate is to dephosphorylate IP6 as soon as possible in
the proximal gastrointestinal tract to lower the molecular weight esters of IP. However, they did not directly identify a technique that could be used to achieve this outcome. Their solution is based on the release P from IP6, causing a decrease in IP6 concentration and thus reducing the net antinutritional effect caused by the extra phosphoric effect which limits mineral, amino acid, vitamin, and energy metabolism and ultimately animal health, and efficiency. Based in their review, they suggested that lower phosphate content esters (IP2 and IP1) exert a lower antinutritional effect. The esters have a reduced capacity to chelate divalent cations and thus their solubility in the small intestine will be improved. This allows greater access for the endogenous phytase/phosphatase enzymes. They concluded that the primary responsibility for exogenous microbial phytase is not so much to dephosphorylate IP6 into inositol and free phosphate but to minimize the entry of IP6, IP5, IP4, and IP3 into the duodenum.

3.4.5. Carbohydrates (NSP enzymes)
The main function of NSP (non starch polysaccharide) enzymes is to hydrolyse carbohydrate structures that pigs cannot digest. The influence of carbohydrates on swine performance has been reviewed recently and the responses to NSP enzyme addition were not consistent (Liu and Baidoo, 1997; Adeola and Cowieson, 2011). Variable responses have been attributed to differences in the type and quantity of cereal grains used, the age of the animal, the extent of deficiency of limiting nutrients and the extent to which the enzyme increased digestible nutrient content (Liu and Baidoo, 1997; Adeola and Cowieson, 2011). However, it seems that swine age was the most influential factor that affects swine response to NSP enzymes.

3.4.5.1. Synergistic effect of NSP enzymes with phytase
Another extra optimization step is to include both enzymes (xylanase or glucanase depending on feed ingredient used in diet) to exert a synergistic effect on substrate with phytase. Parkkonen et al. (1997) observed that xylanase increases the permeability of the aleurone layer of wheat, which is the site of phytic acid storage. Some studies (Kim, 2003; Kim et al., 2005a) showed that there is no synergistic effect between NSP enzymes and phytase in the pig stomach as phytase activity occurs first. Phytase is mainly active at low gastric pH’s (pH range from 2-5.5) whereas xylanase and glucanase are active under only slightly acidic condition (pH 4-7 and pH 3.5-6.5, respectively). However, the synergistic effect of both enzyme types (NSP enzyme and phytase) has been reported in poultry in which the anatomical compartmentalisation of their digestive system facilitates the actions of both NSP enzymes ad phytase: ideally NSP enzymes/phytase are active in the crop (pH=4-5), phytase is active in the stomach and NSP enzymes play a dominant role in the small intestine.

Thus, for successful feeding strategies with NSP enzymes and phytase, the action of NSP enzymes has to start before or with phytase to ensure maximum performance. This will allow for the breakdown of cell walls that encapsulate protein and starch (figure 4) and for the elimination of the negative impact of phytate on digestive enzymes once the feed enters the small intestine (Sharma et al., 1978; Singh and Kirkorian, 1982).

3.4.5.2. Constraints
The feed has to be offered in mash form, although the industry may be ill-prepared with feeding infrastructure to do so. This technology is most likely to be cost-effective, although the rate of feed flow in any system to sustain peak intakes needs to be considered carefully. In contrast, pelleting has many advantages over mash feed such as cost of transportation, flow ability in silos, cost of transportation, level of moisture in feed (more water in pellet which cause more profit to feed mills), reduces feed waste and also kills pathogens.
3.5. **Nutrient synchrony**

Increasing nitrogen retention and reducing its loss can ensure maximum protein deposition and thus growth in growing animals. Protein is known to have a high water holding capacity and thus animals will gain more weight when more protein is retained. To achieve this it is important that dietary amino acids, glucose and fat are absorbed simultaneously. In a study conducted in pigs (50 kg), where dietary starch and protein dominant meals were provided 8 hours apart, protein retention decreased by 10% when compared with pigs fed identical meals: there was no effect on fat retention (van den Borne, 2006). Asynchronous nutrient supplies result from either the different timing of carbohydrate and protein dominant meals (Barja et al., 1972) as shown above, from differences in the kinetics of digestion and absorption of feed ingredients (Englyst et al., 2003) or from an imbalance in the nutrient supply in a diet. Although fat is an energy dense constituent, its effect on nutrient synchrony is low because of its low inclusion rate in diets: it is important however to ensure high durability of processed pellets. Asynchronous absorption of glucose and amino acids by animals can decrease metabolizable energy delivery and may increase amino acid oxidation (van den Borne et al., 2007).

Three possible mechanisms for the increased amino acid oxidation with decreasing nutrient synchrony have been suggested (van den Borne et al., 2007).

- Firstly, insulin secretion should be in synchrony with the post-absorptive supply of amino acids to increase the retention of dietary amino acids and inhibit gluconeogenesis (Barthel and Schmoll, 2003). Glycemic and insulimemic responses are significantly correlated ($r = 0.94$) (Wolever et al., 2006). Thus, higher protein retention in diet with high starch digestion rate have been attributed to the stimulation of the release of insulin that acts on cells throughout the body to stimulate uptake, retention, and storage of amino acids (Rooyackers and Nair, 1997).

- Secondly, the presence of dietary carbohydrates may affect amino acid metabolism in the intestinal tissues with concurrent implications for the kinetics of amino acid availability to other tissues (Mariotti et al., 2000).
Thirdly, amino acids may be used to provide adenosine triphosphate (ATP) for maintenance and for protein deposition or for gluconeogenesis in the absence of glucose of dietary origin (van den Borne et al., 2007). The reduction in energy delivery associated with a decrease in starch digestion may reduce net energy and minimize the chance of glucose having a sparing effect on amino acid oxidation (van den Borne et al., 2007).

Weurding et al. (2003) reported that glucose should be available along the digestive tract; diets containing starch that is relatively resistant to digestion and is therefore available as an energy substrate in the lower small intestine to supply glucose, will spare amino acids from being oxidized. Thus the variable solubility of carbohydrate within a diet will assist in promoting amino acid absorption to increase protein synthesis by up to 10%. In effect this phenomenon is achieving the same outcome as the synchronous protein/energy diet reported by van den Borne (2006).

More recently the effect of different level of starch digestion rate (three levels: high, medium and low) and two levels of protein digestion rate (high and low) on level of protein retention have been evaluated in grower pigs (Drew et al., 2012). They concluded that the rate of starch digestion was more important for protein retention, with highly soluble starch sources increasing protein retention compared to slowly digested starch sources. Al-Rabadi et al. (2009) reported that there is a large variation in digestion rates for different size particles within a single milled grain sample. The rate of digestion may vary by an order of magnitude between the smallest and largest particle for each of milled barley and sorghum. However starch sources with different rate of digestion yielded similar glucose levels at the distal part of small intestine when grower pigs were fed mixed protein and starch diets (Drew et al., 2012).

Diet formulation based on weight distribution of particle size, rather than average particle size, may be a better method for specifying feeds for animal growth, as it provides the possibility of more effective nutrient synchrony between glucose and amino acids, by matching the digestion rates of starch and protein nutrient sources (van den Borne et al., 2007). As previously mentioned, there is a general trend that diets with a smaller average particle size also have a lower geometric standard deviation. These diets have been reported to have a higher metabolisable energy and nitrogen retention in lactating sows (Wondra et al., 1995c) and in growing pigs (Oryschak et al., 2002). It is possible that more efficient animal growth could be achieved through the choice of appropriate particle size distributions, as different particle sizes provide a wide range of starch fractional digestion rates (Al-Rabadi et al., 2009). Recently, comparison of in vitro starch digestibility showed that the extent of starch digestion of the non-fractionated material could be predicted from the weighted digestibility of each particle size fraction for both barley and sorghum, at different incubation times (Al-Rabadi et al., 2012). In addition, different particle size ranges have different starch compositions and thus they contribute differently to the rate of glucose absorption along the digestive system (Al-Rabadi et al., 2009; Al-Rabadi, 2011).

The mode of feeding animals will also alter these protein and energy fluxes. In commercial operations animals are most often fed ad libitum for practical reasons. With interval or meal feeding, insulin sensitivity and therefore metabolic responsiveness of animals is retained (Scrimgeour et al. 2008). This results in an improved efficiency of feed conversion when compared to the ad libitum fed controls, in which insulin resistance becomes an important limitation to amino acid utilisation. Thus the processing of feeds needs to be adjusted to the method of feeding animals. This relationship has been seldom explored in the pig feed industry.
4. Research opportunities

There is opportunity for the Australian pig industry to improve the efficiency of pig feed manufacture and/or utilisation by pigs of whole or individual components of cereal grains and pulses by evaluating and adopting novel feed processing technologies, or by the modification of currently used feed technologies. This could include:

- Introducing new technologies and optimising existing technology, to maximize the utilisation of nutrients in grains (wheat, triticale and sorghum) and pulses (e.g. peas, faba bean and lupines) in order to improve the growth performance of pigs.
- Examining the significance of anti-nutritional factors when fractionation technologies are applied to milled grains. This may include separating fractions rich in anti-nutritional factors affecting pigs for use in other applications, or treating fractions to inactivate or reduce the concentration of anti-nutritional compounds.
- Evaluating the effects of the form in which the diets are fed (mash or pellet or extrudate or expanded whole grains) on carbohydrate solubility and digestibility and their impact on growth performance.
- Examining the relationship between these feed variables and mode of feeding animals ad libitum or in distinct meals to achieve optimum feed conversion efficiencies and maintain insulin sensitivity.

4.1. Introduction

Starch in cereal grains is the most abundant energy source for most domestic production animals (Svihus et al., 2005). However, the availability of starch in cereals inside the animal body is not complete. Under Australian conditions, different in vivo pig digestibility studies have revealed that 1-5 MJ/kg dry matter (DM) is not utilized (Black et al., 2009), and this is a significant economic issue for the pork industry. Incomplete starch utilisation has been attributed to many factors including source and starch structure, other grain constituents such as protein and fibre, the presence of anti-nutritional factors, animal factors such as age and particle size.

Several strategies have been adopted to maximize utilization of cereals and legumes by pigs, including liquid feed, reduction in particle size, low and mild hydro-thermal processing (such as pelleting, expanding, and steam flaking) (Svihus et al., 2005) and use of specific enzymes. Although thermal processing of grains improved growth rates and efficiency in gain in pigs, this improvement was small and differences in processing conditions resulted in varied responses in the pig.

The concepts being developed are intended to improve the feed conversion ratio in pigs, making better use of a range of conventional grain sources (cereals such as barley, triticale and sorghum; pulses such as peas. These concepts have to be developed with the methods used for practical feeding in mind.

The primary impact on the Australian pork industry will be by developing cost-effective processing technology to increase the FCR which will reduce the cost of production and therefore improve the long term economic viability of Australia pig farms. There will be secondary impacts related to reduce the ecological impact of pig-farming by improving grain utilisation.

4.2. Opportunity 1: Modifying grain milling and particle segregation

4.2.1. Background

Previous in vitro starch digestibility experiments shows that particle size is an important factor that affects the digestibility of starch (Al-Rabadi et al., 2009; Pork CRC annual report, 2010 ). In barley and sorghum, in vitro trials showed that the starch in large
Feed intake trials (sponsored by Pork CRC) were conducted to evaluate the effect of milling barley and sorghum, then separating the large grain fragments using a seed cleaner machine, then re-grinding the large fragments to reduce their size in order to maximize energy delivery to pigs. This novel alternative to grinding all of the grain to smaller size was shown to improve animal growth performance and improve Herd Feed Conversion (HFC) at different growth stages (weaner and grower stages) without producing large amounts of dust and fines (Al-Rabadi et al., unpublished data)).

Visual examination of faecal samples (Figure) for pigs fed grain-based diets (after regrinding large particles) has shown incomplete starch digestion due to poor separation of the large particles by the seed cleaner machine. This is may be due to the fact that effective segregation of coarse particles with a seed cleaner, and regrinding the coarse fraction was not optimized for grains. For example, more than 30% (by weight) of a reground coarse fraction (after re-milling barley using 3.2 mm screen size) retained on sieve size greater than 1 mm were present. In sorghum, more than 55% (by weight) of a reground coarse fraction (after re-milling barley using 3.2 mm screen size) was retained on a sieve size greater than 0.5mm. While innovative use of large particle separation and re-milling improved feed conversion, the presence of an undigested grain fraction in faecal samples suggests there is room for further improvement by ensuring an efficient segregation and milling process.

Figure 5 - The presence of undigested grain fragments in the faeces of pigs fed a diet of ground barley. The large fragments had been separated and re-milled.

The hammer mill has been reported to produce a wide range of particle sizes compared to the roller mill (Douglas et al., 1990). During roller milling each grain passes through the mill independently of surrounding grains (Campbell et al., 2001): for that reason, the breakage patterns for each grain depends mainly on the interaction between the grain the roller mill design and operation conditions (Campbell and Webb, 2000). Roller mills have at least two pairs of rolls, often accompanied by two or three pairs, that usually crush the grain as it passes between rollers (Laurinen et al., 2000). Reducing geometric standard deviation has been achieved by using three high-rollers in mills with decreasing trend (in terms of decreasing the distance between the subsequent paired rolls) when the objective was to reduce average particle size (Healy et al., 1994a). Alternatively, further reduction of geometric standard deviation has been reported when corn grains are firstly ground with a roller mill and then milled using a hammer mill (Healy et al., 1994a) (Wondra et al., 1995a). Adjustment of operating conditions within the mill can also affect particle size distribution. In corn and by using the same mill, reducing hammer mill screen size from 9.6 mm to 1.2 mm has resulted in a linear reduction in particle geometric standard deviation (Wondra et al., 1995a; Wondra et al., 1995c). When the hammer mill screen size was
plotted against geometric standard deviation, each 1 mm reduction in milling screen size resulted in a 0.09 reduction in geometric standard deviation ($R^2=0.82$, $n=7$). Use of multiple stages of grinding with a roller mill has been reported to reduce geometric standard deviation. Roller mills have been reported to modify geometric standard deviation (increase or decrease) when a series of test grindings is performed on a double pair roller mill (Svihus et al., 2004). This approach helps in defining the relationship between roll distances and particle distribution, and the roll distances which yield a particular geometric mean diameter (Rodgers et al., 2012).

4.2.2 Methodology

Combining both mill types (hammer mill and roller mill) in sequence can provide an alternative approach to reduce the coarse fraction of particles without generating extra fines. In theory, a hammer mill must first grind whole grains which then passes to a roller mill which breaks down the coarse fraction by adjusting the distance between the two rolls without generating extra fines (depending on grain type). Hopefully, the fine fractions generated by the hammer mill will pass through the two rolls without being exposed to further crushing. This approach is illustrated in Figure 6. The distance between the two rollers will be adjusted based on grain type and hardness. Due to possible access to ground material after crushing, the distance between rollers can be modified to achieve desired particle size and its distribution. Air suction can also help to avoid fine particles reaching rollers. Although this processing approach is in use, there has been little or no scientific evaluation of the approach. *In vitro* digestibility of starch for a segregated fraction will be investigated and estimated for each grain type after different milling operation conditions as described previously (Al-Rabadi et al., 2009).

![Diagram of multi-stage milling process for grains.](image)

*Figure 6 - Multi-stage milling process for grains.*

The results of our previous study showed that the *in vitro* digestibility for different sized fractions were additive in their effects, as there was no difference between the predicted *in vitro* digestibility from the weighted summation of sieved fractions and the same
measurements for non-fractionated control treatments (Al-Rabadi et al., 2012). Hopefully, a balance between nutritive value of milled grains (i.e. starch digestibility) and cost of processing (production capacity and electricity consumption) will be achieved to minimize production cost of optimum milled grains.

4.3. Opportunity 2: Steam pelleting of the coarse fraction of milled feeds

4.3.1. Background

Steam pelleting is the most widely used pig feed processing method in Australia. Steam pelleting have been reported to have many advantages (other than related to the improvement in diet nutritive value) and offering pellets rather mash feed to pigs can contribute positively to their performance. Behnke (1994) summarized the advantages of pelleting not related to nutrition as the following:

- Decreased feed wastage
- Reduced selective feeding
- Decreased ingredient segregation
- Less time and energy expended for prehension
- Destruction of pathogenic organisms
- Improved palatability

The presence of water is a prerequisite to induce gelatinization. Lund (1984) reported that a ratio of 0.3:1.0 (water : starch) is needed to induce starch gelatinization. However, in pelleting processes, far less than 30% water can be used (Sauer et al., 1990; Thomas et al., 1998). In commercial feed mills and during steam pelleting process, usually mash feed is directly heated by adding steam (up to 5-6% of mash weight). Water contents higher than 5-6% can result in a mash that cannot be effectively forced through the die, and can cause blockage and slippage between the rollers and the die, that increases the required energy for consumption (Thomas et al., 1998). This may suggest that it is difficult to achieve complete starch gelatinization during the pellet processing (Gilpin et al., 2002). In addition, a previous study showed that small grain fragments have a higher water holding capacity compared to larger grain fragments (Al-Rabadi et al., 2012). In practice, Svihus et al. (2005) reported that steam conditioning and pelleting resulted in gelatinization of only between 1% and 20% of the starch present.

This may suggest that small particles (which have a higher digestibility when present in raw form) have a higher possibility of starch gelatinization due to its greater exposure to steam: small particles have a higher surface area per unit mass. Inducing starch gelatinization by increasing level of steam addition (with or without adding surfactant) and exposure intensity for the coarse fraction size by reducing competition from small particles could be a successful and novel approach to enhance overall nutritive value of a pellet.

The most significant change in pelleting technology over the last 10-15 years has been the lengthening of conditioning time. There has been a move away from the use of high steam pressure and short time conditioning for 15-20 seconds to larger volume lower steam pressure conditioning for 90-120 sec. The major advantage is an increase in both pellet quality and through-put. These changes however involve capital expenditure on an upgrade to conditioning equipment and increased capacity for steam generation (John Spragg, personal communication).

The challenge remains to recombine the small particle fraction with the processed coarse particle fraction. It is also important to determine if the better quality pellets produced at lower temperatures translate to better pig growth performance.
4.3.2. Methodology

This approach is basically based on inducing starch gelatinization by increasing the level of steam addition (with or without adding surfactant) and by enhancing exposure of the coarse fraction size only to steam after being segregated using a seed cleaning machine. Hopefully, this approach will reduce competition between small and coarse particles on steam in favour of coarse particles as is the case with conventional technology. This could be a successful and a novel approach to enhance overall nutritive value of pellets by treating coarse fraction separately with steam. This approach most likely suits grains that have high starch content in the coarse fraction such as barley. To overcome the problem of the pelleting process at the die, the coarse fraction exposed to steam will be mixed with the dry fine fraction.

We propose that this could be achieved using a large size paddle mixer to mix the steam-exposed coarse grain fraction and fine fraction plus other ingredients. Mixing the wet fraction with non wet fractions could be a problem; however, careful redesigning of the paddle mixer can solve this issue. For example, the wet coarse fraction, which should not be very sticky and coagulated, could enter the paddle mixer from different inlet points distributed along the paddle mixer to reduce mixing time with the fine fractions. Oil is sprayed in relatively high amounts in the processing of fish feed and the mixer equipment used in this process might provide a template for mixing wet with dry fractions here. Feed additives such as pellet binders can be used to enhance pellet durability if durability is compromised. This is summarized in Figure 7.

Figure 7 - Diagrammatic representation of methodology required for Opportunity 2.

The dry fine fraction should absorb excess water present on the surface of the wet coarse fraction (after being exposed to heat) without increasing energy consumption by the die or causing any blockage. The level of steam addition will depend on yield percentage of the coarse fraction and water holding capacities of both fine and coarse fractions. Tools used to characterize starch gelatinization properties (such as RVA and DSC) will be used to optimize processing conditions (level of steam addition, presence of surfactant and mixing time). If the pelleting process is successful, *in vitro* digestibility studies will be conducted before conducting experiments *in vivo* to evaluate the effectiveness on our proposed approach.

4.4. Opportunity 3: Extrusion of large pulse or grain fragments

4.4.1. Background

Several strategies have been adopted to maximize utilization of cereals by pigs after milling such as applying low, mild and high thermal processing (such as pelleting, expanding, and steam flaking) to the coarse grain component. Although improved growth rates and efficiency in gain in pigs have been achieved, this improvement was small and
the pig production response varied due to the processing variables (Choct et al., 2004), type of cereals (Medel et al., 2004) and the stage of animal growth (Choct et al., 2004).

There are many ways in which particle size can affect the rate and extent of water penetration, and thus gelatinization of starch within grain fragments. The physical structure of the grain can play a role, particularly in the coarse fraction. This fraction basically consists of half or whole grains, with the seed coat covering much of the grain fragment surface. As it is difficult for water molecules to penetrate the seed coat, water penetration into the coarse grain fragments may be significantly slowed. Furthermore, with the increase in particle size, the surface area to volume ratio is lower, which may also reduce the rate of water penetration into the coarse fractions (Addo et al., 2006; Hsu, 1983).

Water absorption into coarse fractions has been reported previously to be less than for finer fractions, resulting in lower levels of starch gelatinization after extrusion (Garber et al., 1997). In addition, the tendency of the coarse particles to absorb water more slowly is thought to contribute to a higher gelatinization temperature (Onwulata and Konstance, 2006). Pre-conditioning of coarse particles of corn before extrusion has been reported previously to improve starch gelatinization (i.e. degree of cook), to of the extent found with fine particles (Mathew et al., 1999). Even under less severe heat treatments, such as steam pelleting, the duration of pre-conditioning has been reported to be highly correlated to the extent of starch gelatinization (Gilpin et al., 2002). Furthermore, coarse particles have a reduced contact area with the extruder barrel than fine particles, causing them to be less affected by temperature (Onwulata and Konstance, 2006), due to the limitations of heat transfer. However, despite all these considerations, the fractional digestion rates for all (ground) extruded materials were at least five times greater than for any non-extruded grain fractions when starch digestibility was examined in vitro (Al-Rabadi et al., 2011a). Extrusion of only the coarse fraction may justify using a relatively expensive extrusion process in piglet feed before and after weaning.

4.4.2. Methodology

This proposed approach is based on optimization of previous study conducted by Al-Rabadi et al. (2011) where the extrusion process for coarse particles is conducted without a preconditioning step. After the extrusion process, scanning electron micrograph showed the remains of the intact coarse fraction. In addition, viscosity profiles showed starch gelatinization was incomplete. The current proposed approach will use the same operation variables in the previous study with the addition of a preconditioning step for the coarse fraction (after being segregated by seed cleaning machine). The raw fine fraction and coarse extruded fraction will be mixed using the technology identified above in opportunity 2.

However if the fine fraction is pelleted and coarse fraction extruded, their combination will provide a unique feed with added value which will justify the additional cost of production. The value of these processes would need to be determined by laboratory analysis (viscosity and in vitro digestibility analysis) of the finished product. Based on the outcome of laboratory analysis, an experiment conducted in vivo will be conducted. Sorghum grains will not be used due to the reduction of their protein digestibility when exposed to wet cooking. Alternatively, sorghum will be processed by whole grain expansion (popping or dry heat processing) to avoid this effect. Whole sorghum grain expansion will be discussed in the next section.

4.5. Opportunity 4: Whole grain expansion of sorghum

4.5.1. Background

When valuating sorghum, there was incomplete in vitro starch digestion of <0.1 mm fragments after 24 hours of incubation partly due to the presence of a protein matrix (Al-
Rabadi et al., 2011b). Rupturing the sorghum microstructure via whole grain expansion or popping could open the endosperm and protein matrix structure and thus increase nutrient availability from sorghum without the requirement for milling. Popping has been reported as an explosive process that can induce cell wall fragmentation and thus improve the accessibility of starch reserves of the endosperm to digestive enzymes (Parker et al., 1999; Correia et al., 2010). Micrographs showed that popping sorghum grain changed the starch granules into thin lattices of interconnecting sheets, however protein bodies remained (Harbers, 1975) (Figure 8). Unlike wet cooking, popping sorghum is reported not to reduce protein digestibility (Parker et al, 1999). Wet cooking of sorghum results in the formation of sulphydryl-disulphide interchanges that make the grain less digestible (Weaver et al., 1998). Recent studies have shown that water plays an important role in these deleterious effects of cooking sorghum (Correia et al., 2010).

![Figure 8 - The microstructure of popped sorghum grain (Harbers 1975).](image)

**4.5.2. Methodology**

This proposed approach is based on inducing starch gelatinization in sorghum by reducing protein digestibility that is associated with wet cooking. Australian local varieties of sorghum will be popped by using a hot air pop corn making machine. Sorghum varieties with high popping capabilities will be further analysed for hydrothermal (i.e. gelatinization) priorities and in vitro starch and protein digestibility. Due to high specific volume (low bulk density of popped sorghum), popped grains will be milled before running any analyses.

**4.6. Opportunity 5: Maintaining metabolic efficiency through appropriate feeding**

**4.6.1. Background**

The dissociation of glucose and insulin status demonstrated in *ad libitum*-fed grower pigs by Scrimgeour et al (2008) was associated with increase in feed:gain relative to the same pigs fed in distinct meals. The loss of entrainment of insulin status with feeding pattern is likely to alter the efficiency of amino acid absorption, transport and incorporation into protein. The impact of processing of grain in different ways and the associated kinetics of starch degradation and glucose accumulation will determine the level of insulin sensitivity and therefore metabolic efficiency in growing animals. It will also be associated with the accumulation of complex carbohydrates in the mucous lining of the gastrointestinal tract. Once the processing of each grain is determined through measurement of feed:gain, it will be important to benchmark the procedure by assessing insulin sensitivity in animals fed
each type of processed grain. The feed product resulting in the highest sensitivity will most likely induce the most efficient protein synthesis since maximum amino acid uptake will coincide with the greatest sensitivity of cells to glucose uptake also. Since insulin is also a vasoregulatory hormone this sensitivity will also coincide with a greater supply of these key nutrients to target tissues.

4.6.2. Methodology

Piglets fed processed products that have been shown to generate excellent feed:gain ratios when fed ad libitum will then be fed for 7 days at 90% of this amount as 2 meals 8 hours apart will be subjected to an oral glucose tolerance test after a 12 hour fast. Three blood samples collected through ear vein catheters will be collected over 60 minutes to determine the insulin response to the bolus glucose dose.

A rigid protocol will be established to determine which processed grain product will provide the most effective insulin response in animals fed ad libitum or in distinct meals. This will assist the industry in deciding which processing methodology is best for each grain type. An alternative and less interventional approach is to collect a single blood sample immediately before a feed and then 2 hours after. The pre-post feeding change in insulin status will provide an indirect estimate of insulin sensitivity. Blood glucose and alpha amino nitrogen could be measured also to provide an indirect assessment of tissue sensitivity.

4.7. Opportunity 6: Maximising Phytase Activity

4.7.1. Background

The main idea of this treatment protocol is to provide a special degradation chamber to optimize phytase activity for use on farm. Generally, the use of liquid medium creates many more opportunities for using exogenous enzymes and, if there is sufficient benefit to cost, enzyme activity can be improved by adjusting temperature, pH and treatment time (Brooks et al., 2001).

Water can be mixed with HCl / acidifiers / inocula to achieve the target pH (between 4 and 5). Caution will be required not to disturb electrolyte balance in pig body when using HCl (Mahan et al., 1996). After achieving the target pH, phytase can be added to the diet (Fraction A and Fraction B combined) and mixed frequently. Directly before feeding, premixes and additives can be added to the diet in plastic containers and mixed to avoid fermentation of additives, especially synthetic amino acids and vitamins used typically in pig diets. As a safety precaution, the feed pH should be measured prior to feeding.

The combination of the following factors will maximise the release of organic P and enhance dietary protein and energy release. Premixes could be added directly before it is fed to pigs:

- Optimizing pH (by fermentation, or by adding HCl for rapid pH reduction)
- Soaking (dry feed mixed with water at the identified ratio)
- Removing cations from premixes (e.g. Zn, Ca) at the time of phytase addition
- Reducing pepsin at the time of adding phytase,
- Using the optimum ratio of both Ca:P and phytate:protein and with the help endophytase in the grain.

4.7.2. Methodology

A possible approach is to find a feeding strategy at farm level that maximises phytase activity to eliminate the antinutritional effect of phytate. This approach is based on a combination of actions that ensure maximum degradation of phytate before the ration is fed to pigs (Figure 9).
The proposed feeding strategy at farm level to enhance phytase enzyme activity. (Fractions A and B should be mixed directly before feeding).

The principle of this approach can be summarized in the following three actions:

1) Optimize conditions for phytate degradation, through the adjustment of pH, decrease in pepsin activity and minimising the presence of minerals mainly cations.

2) Facilitate phytase activity by water soaking of grain and adding other enzymes (such as NSP enzymes) that attack cell walls to eliminate cell wall physical barriers. In a recent study in Denmark, Blaabjerg et al. (2010) showed that soaking feed ingredients (not heat treated and heat treated) for up to 24 hours resulted in a significant reduction of 55-88% in IP-6.

3) Re-evaluation of diet formulation by taking into consideration optimum Ca: P ratio (reduce ratio to 1.1:1) and increasing phytate: protein ratio (higher than 0.05:1) before the addition of phytase. To achieve this without compromising nutrient content and thus pig performance, formulated diets must be divided into two fractions using feed formulation software:
   a. Fraction A - will be formulated to optimize Ca:P and phytate:protein ratios for phytate degradation. This fraction is expected to be the major fraction derived from cereal as cereals contain low protein levels.
   b. Fraction B - will comprise the remaining feed ingredients required to complete the diet. This is expected to be composed mainly of protein rich ingredients.

Both feed fractions will be soaked in water separately and then mixed. Finally and after ensuring maximum presence of IP2 and IP1, positively charged mineral premixes are added before feeding directly to pigs. Figure 9 provides a proposed feeding strategy at farm level to enhance phytase enzyme activity.

Addition of liquid feed containing lactic acid bacteria (Lactobacillus plantarum and Pediococcus 308 spp.) to inhibit growth of spoilage bacteria and enhance palatability can and ultimately pig health (Missotten et al., 2010).

4.8. Integration of Research

The research opportunities outlined above reflect the influence of a number of major factors in controlling feed conversion efficiency. While it is necessary to break the research opportunities into individual spheres of research, drawing on one or two aspects, they can also be thought as being inter-connected with multiple approaches to solve the ultimate objective of improving feed conversion. Based on the research objectives outlined above, a schematic showing the inter-relationships is given in Figure 10. All possible inter-relationships are not shown on the schematic, as in many instances the proposed strategy will involve processes that fall under the “Main Processing Categories” heading (e.g. Opportunity 6: Maximising phytase activity).

The preferred research strategy builds on the previous experience of Dr Ghaid Al-Rabadi in improving grain feed conversion efficiency. It is therefore proposed that the following approach be used:

- Manipulation of particle size distribution (Opportunity 1)
- Thermal processing of grains (Opportunities 2, 3, and 4)
- Maximising phosphorus availability (Opportunity 6)
- Using feeding strategies to manipulate metabolic efficiency (Opportunity 5)

The research will primarily involve in vitro evaluation of the impact of processing steps, with in vivo trials restricted to the most promising opportunities.
4.8.1. Costing of research opportunities

Capital investment is required for installation of additional milling and grain conveying equipment even if it is only the coarse particles that are being ground prior to processing in the hammer mill. The following costings incorporate a depreciation spread over a 20 year life expectancy of installed equipment. The costs of installation are best estimates and require more detailed investigation based on individual site installation costs. Within the costing the following assumptions apply:

- The cost of installation is spread across the volume of grain processed over 20 years.
- Typical production rate 20 tonnes/hour
- Grain processing annual volume 40,000 tonnes for a “typical” 50,000 tonne pig feed mill.
- Annual running time 2,000 hours = 38 hours/week.
4.8.1.1. Opportunity 1 - Modifying grain milling and particle segregation

The estimated costs are split into two components.

**Depreciation Cost**

Configuring a roller mill after grinders is not a normal practice for a mill. A roller mill will therefore cost approximately $0.5 million. This assumes there is sufficient space to install a roller mill and the mill does not require a major rebuild of its grinding area.

$0.5 million spread over 20 years = $25,000/year = a depreciation cost of $0.63 /tonne.

**Operating Cost**

There will be an additional cost in roller mill operation as all grain is processed through the hammer mill as is currently practiced. The power load on the roller mill will be less than that required for milling whole grain and is anticipated to be in the order $1-2/tonne for the component requiring this additional processing.

4.8.1.2. Opportunity 2 - Steam pelleting

**Depreciation Cost**

Installation of grain separators to allow removal of fine particles can be achieved using lower cost sieving equipment. Under this opportunity the pelleted coarser particles are to be recombined with the fine non conditioned fine particles, with this occurring before the pellet die to prevent blockage of the die and before entering the cooler. The method for recombining the fine particles with the steam conditioned coarser feed fraction would require pelleting line redesign and engineering.

At this stage it is uncertain how the processing changes would function and what the relative costs would be to implement. In existing pelleting lines the formed pellets exiting the die drop directly into the cooler.

Further work is required to better define the potential cost of this research opportunity.

4.8.1.3. Opportunity 3 - Extrusion of coarse pulse or grain fragments

After initial milling outlined in opportunity 1, the process of extrusion of the coarse component may incur a capital cost of more than $2 million depending on the throughput of the mill and the proportion of particles that requires processing. This would need to be depreciated over 20 years.

$2.0 million spread over 20 years = $100,000/year = a depreciation cost of $2.52 /tonne using the assumptions for throughput outlined above.

The cost of recombination of the extruded component and raw fine particles awaits the design of appropriate equipment.

4.8.1.4. Opportunity 4 - Whole grain expansion of sorghum

This facility may require a grain feed bin and conveyers to and from the grain expansion equipment. The capital cost of whole grain expansion equipment (likely to be more than $1 million) would need to be depreciated over 20 years as above. The economics of this investment would need to be calculated on throughput which at this stage is hypothetical, since further developmental work is required before this can be calculated.

4.8.1.5. Opportunity 5 - Maintaining metabolic efficiency through appropriate feeding

The cost of experimentation of this nature would depend on the ability to design a feeder that would deliver meals at distinct intervals at the one time at multiple points so that the dominant pigs in any group do not dominate the feeder.
A prototype feeder may cost $20,000 to develop and initial experimentation may cost an additional $50,000.

4.8.1.6. Opportunity 6 - Maximising phytase activity

Phytase treatment costs approximately $2 per tonne of feed.

As alternatives the cost of steeping will be approximately $40/tonne. If the soaking required is a spray of water this will cost $2 per tonne. However this cost would be saved as no phytase would be needed after soaking.

Further processing would be the same as above. Again developmental work is required here.

Figure 10 - Hierarchy of relationship in the processing, formulation and feeding for pigs. Due to space limitations the examples and opportunities are not intended to be an exhaustive list. Note of Abbreviation: NSP, Non-starch polysaccharide.
4.9. Prioritising the research opportunities

Research priorities is based on pigs growing stage:

4.9.1. Finisher pigs

The argument for determining which feeding/processing strategy to use should be based on the ability to enhance animal growth performance (FCR) and minimize feeding production cost in part by minimizing the cost of feed processing. It is clear that increasing the number of processing steps can increase feeding costs mainly by decreasing the production capacity of feed mills especially when thermal input/treatment of feeds is required. Because feed intake of finishers pigs is higher than any other production stage, feed mills spend more time in processing finisher feed which makes feed production capacity more critical at this stage. In addition, capital investment is required to install hydrothermal equipment which makes processing finisher feed more expensive. Based the literature, it is clear that particle size is the most influential factor on grain digestibility. Thus, eliminating the coarse fraction (without producing extra fines) of milled grains should be the main approach while avoiding the use of any thermal energy input to minimize any additional cost. Modifying grain milling and particle segregation at the same time (opportunity 1) has the ability to enhance animal growth performance (FCR) with minimal additional feeding production cost, although there is an additional cost for capital equipment for a roller mill if it is not available. In addition, opportunity 1 performed at the feed mill, can be integrated very well with feeding strategies adapted at the farm level (maximizing phytase activity via fermented liquid feeding and reformulating pig feed, opportunity 6) to provide further improvement in nutritional value of grains. From a practical point of view, there may also be a need for significant capital investment including the reconfiguration of a mill to accommodate the alternative strategies suggested herein. Previous work sponsored by the Pork CRC and conducted at the University of Queensland showed that separation of the coarse fraction using a seed cleaner machine was not efficient at separating the coarse fraction, although significant improvement in FCR was achieved after further milling of the coarse fraction. Furthermore, only slight improvement in FCR was achieved when milled coarse fraction was further steam pelletized. We still believe that there is room for further improvement. The added value of this approach is that it modifies grain milling without producing extra fines. We suggest that this approach will provide more control over particle size with greater productivity from the feed mill. In contrast opportunities 2 and 3 will not achieve this.

Although no quantitative economic comparison for opportunity 1 relative to opportunities 2 and 3 is provided, it is clear that a lower capital investment is required for the former with less processing steps. Clearly particle size has more influence on animal growth performance than mild hydrothermal treatment of grain. The combination of opportunities 1 and 6 would seem to provide the most cost effective methodology for the improvement in feed conversion ratio.

Once the most effective processing combination is decided, it is highly likely that further efficiencies can be gained by altering feeding practices to sub-\textit{ad libitum} interval feeding. The experimental data collected to date show a significant 5-10\% improvement in feed conversion efficiency with single penned animals. The dynamics of group feeding and the development of multiple feeding point technology for group pens would need to be investigated using such a protocol.
4.9.2. Weaner pigs

Sorghum is considered to be the most difficult grain to digest due to its complex protein matrix and negative nutritional response to hydrothermal treatments. Whole grain expansion of sorghum grains selected for high popping yield (Opportunity 4) could be the most important priority to feed pigs at the weaning stage. Application of whole grain expansion can be justified by the high cost of weaner feed, the lack of a need for milling treatment, and the high palatability of popped sorghum. Whole sorghum expansion is clearly a superior technology involving a single easy processing step.

5. References


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6. Acknowledgements

David Henman, Rivalea Australia, Corowa, NSW and John Spragg (JCS Solutions) provided valuable advice on the costing of research opportunities.

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### 7. Appendix 1 - Notes

#### Table 7.1 - Cereal and pulse production (1000 t) in Australian states. 1

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<th></th>
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<th>New South Wales</th>
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<th>South Australia</th>
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<td>237</td>
<td>7</td>
<td>125</td>
<td>283</td>
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<td>1,945</td>
<td>146</td>
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<td>175</td>
<td>73</td>
<td>1</td>
<td>86</td>
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<td>Other grains</td>
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<td>101</td>
<td>69</td>
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<td>107</td>
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<td>7,585</td>
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1 Northern Territory and ACT produce less than 1,000 tonnes of these grains.
2 Agricultural Commodities, Australia, 2010-11, Australian Bureau of Statistics.
   www.abs.gov.au/ausstats/abs@.nsf/mf/7121.0
Table 0.2 Recent research reports or reviews of grain composition and digestibility.

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</table>
Grain | Brief summary | Reference
|---|---|---
| Wheat | *Triticum* sp. | Study reviews wheat composition and digestibility; summarises data from 26 studies containing 426 wheat samples | (Kim et al., 2005b)

* Paper previously summarised in table.

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Energy consumption</th>
<th>Particle size (mean ± std deviation)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hammer Mill</td>
<td>Swinging hammers rotating at high speed; screen size can be varied to control particle size</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roller Mill</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pin Mill</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multicracker</td>
<td>Maize 11.3 kJ/kg Soybeans 14.1 kJ/kg Wheat 10.4 kJ/kg</td>
<td>Maize 1.76 ± 0.84 mm Soybeans 2.10 ± 0.85 mm Wheat 2.08 ± 0.84 mm</td>
<td>(Thomas et al., 2012)</td>
</tr>
<tr>
<td>Processes</td>
<td>Temperature</td>
<td>Grain</td>
<td>Digestion</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------------</td>
<td>------------------</td>
<td>---------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Meal</td>
<td>-</td>
<td>Peas</td>
<td>Processing had no effect on digestibility of dry matter, organic matter or protein.</td>
</tr>
<tr>
<td>Cold pelleting</td>
<td>55°C at end of process</td>
<td>Soybean meal Tapioca</td>
<td>Fat 83.8% Fibre 66.7%</td>
</tr>
<tr>
<td>Steam pelleting</td>
<td>70°C</td>
<td></td>
<td>Fat 83.9% Fibre 60.3</td>
</tr>
<tr>
<td>Expander treatment</td>
<td>104°C</td>
<td></td>
<td>Fat 83.8% Fibre 59.0%</td>
</tr>
<tr>
<td>Expander-pelleting</td>
<td>Not reported</td>
<td></td>
<td>Fat 79.4% Fibre 54.2%</td>
</tr>
<tr>
<td>Meal</td>
<td>-</td>
<td>Same meal for both processes</td>
<td>Processing affected digestibility of dry matter, crude protein, and gross and digestible energy</td>
</tr>
<tr>
<td>Steam pelleting</td>
<td>Not reported</td>
<td></td>
<td>DG 446 g/d FCR 1.20 g:g</td>
</tr>
<tr>
<td>Mash</td>
<td>-</td>
<td>Same meal for both processes</td>
<td>No effect on digestibility of dry</td>
</tr>
</tbody>
</table>

(Note: a indicates a specific reference number.)
<table>
<thead>
<tr>
<th>Processes</th>
<th>Temperature</th>
<th>Grain</th>
<th>Digestion</th>
<th>Feed Conversion Ratio</th>
<th>Texture</th>
<th>Starch Gelatinisation</th>
<th>Power Consumption</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pellet</td>
<td>Steam conditioned at 35°C; pelleted (not temperature given)</td>
<td></td>
<td></td>
<td>DG 389 g/d</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>F:G 1.31 g:g</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Expanded pellet</td>
<td>Steam conditioned at 71°C; pelleted at 60°C</td>
<td></td>
<td></td>
<td>DG 264 g/d</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>F:G 1.49 g:g</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Mash</td>
<td>-</td>
<td>Same meal for all processes</td>
<td>No effect on digestibility of dry matter, energy or protein; higher fat digestibility</td>
<td>DG 217 g/d</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(Ohh et al., 2002)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>F:G 1.26 g:g</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Expanded pellet</td>
<td>Steam conditioned at 71°C; pelleted at 60°C</td>
<td></td>
<td></td>
<td>DG 185 g/d</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>F:G 1.10 g:g</td>
<td></td>
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</tr>
<tr>
<td>Expanded pellet crumble</td>
<td>Steam conditioned at 71°C; pelleted at 60°C; crumbled</td>
<td></td>
<td></td>
<td>DG 187 g/d</td>
<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>F:G 1.00 g:g</td>
<td></td>
<td></td>
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<td>-</td>
</tr>
<tr>
<td>Processes</td>
<td>Temperature</td>
<td>Grain</td>
<td>Digestion</td>
<td>Feed Conversion Ratio</td>
<td>Texture</td>
<td>Starch Gelatinisation</td>
<td>Power Consumption</td>
<td>Reference</td>
</tr>
<tr>
<td>-----------------</td>
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</tr>
<tr>
<td>Extrusion</td>
<td>Control</td>
<td>Blood plasma (BP) Whey protein concentrate (WPC) Fish meal (FM)</td>
<td>Extrusion temperature did not affect amino acid digestibility</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(Ohh et al., 2002)</td>
</tr>
<tr>
<td></td>
<td>100°C</td>
<td>Protein sources extruded with maize, then mixed with other ingredients</td>
<td>Extrusion temperature x protein source interaction affected digestibility of His, Lys, Phe, Thr and Val</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
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<tr>
<td></td>
<td>120°C</td>
<td></td>
<td>The temperature x protein source interaction was complicated, e.g. heat treatment of WPC increased His digestibility, but reduced Gly digestibility.</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td>140°C</td>
<td></td>
<td></td>
<td>-</td>
<td>-</td>
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<tr>
<td>Pellet</td>
<td>Maize</td>
<td></td>
<td></td>
<td>-</td>
<td>-</td>
<td>Durability 83.0%</td>
<td>31.0 kJ/kg</td>
<td>(Chae and Han, 1998)</td>
</tr>
<tr>
<td>Extrusion</td>
<td>Maize</td>
<td></td>
<td></td>
<td>-</td>
<td>-</td>
<td>96.6%</td>
<td>Pellet 31.3</td>
<td></td>
</tr>
<tr>
<td>Processes</td>
<td>Temperature</td>
<td>Grain</td>
<td>Digestion</td>
<td>Feed Conversion Ratio</td>
<td>Texture</td>
<td>Starch Gelatinisation</td>
<td>Power Consumption</td>
<td>Reference</td>
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</tr>
<tr>
<td>Pellet</td>
<td>Sorghum</td>
<td>-</td>
<td>-</td>
<td>83.7%</td>
<td>-</td>
<td>-</td>
<td>32.8 kJ/kg</td>
<td>(Chae and Han, 1998)</td>
</tr>
<tr>
<td>Extrusion</td>
<td>Sorghum</td>
<td>-</td>
<td>-</td>
<td>93.4%</td>
<td>-</td>
<td>-</td>
<td>37.4 kJ/kg</td>
<td>Expander 98.3 kJ/kg</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Overall 135.4 kJ/kg</td>
<td></td>
</tr>
<tr>
<td>No extrusion</td>
<td>Barley</td>
<td>Processing conditions no significant effect on pig performance. Extrusion temperature approached a significant effect (P = 0.0559) on DG.</td>
<td>DG 814 g/d F:G 2.27</td>
<td>-</td>
<td>-</td>
<td>(Chae and Han, 1998)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extrusion</td>
<td>No conditioning; 100°C</td>
<td>-</td>
<td></td>
<td>DG 840 g/d F:G 2.27</td>
<td>-</td>
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<tr>
<td>Extrusion</td>
<td>No conditioning; 150°C</td>
<td>-</td>
<td></td>
<td>DG 878 g/d F:G 2.26</td>
<td>-</td>
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<tr>
<td>Processes</td>
<td>Temperature</td>
<td>Grain</td>
<td>Digestion</td>
<td>Feed Conversion Ratio</td>
<td>Texture</td>
<td>Starch Gelatinisation</td>
<td>Power Consumption</td>
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</tr>
<tr>
<td>Extrusion</td>
<td>Conditioned; extruded at 100°C</td>
<td>-</td>
<td>DG 858 g/d F:G 2.24</td>
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<tr>
<td>Extrusion</td>
<td>Conditioned; extruded at 150°C</td>
<td>-</td>
<td>DG 879 g/d F:G 2.24</td>
<td>-</td>
<td>-</td>
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<td>-</td>
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</tr>
<tr>
<td>Milling</td>
<td>Coarse milled wheat</td>
<td>Wheat flour and rapeseed</td>
<td>Smaller particle size increases digestibility of dry matter, and energy, but did not affect digestibility of nitrogen and essential amino acids</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(Lahaye et al., 2008)</td>
</tr>
<tr>
<td>Milling</td>
<td>Fine milled wheat</td>
<td>Wheat flour and rapeseed</td>
<td>Low or high compression pressing did not affect digestibility of dry matter, energy, nitrogen and essential amino acids</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Milling and pressing</td>
<td>Fine milled wheat; conditioned at 84.6°C; low compression pressing</td>
<td>Wheat and rapeseed</td>
<td>Pellets had higher digestibility than meal from fine milled wheat for nitrogen and some essential amino acids</td>
<td>-</td>
<td>Durability 81.1%; Hardness 1.43 MPa</td>
<td>-</td>
<td>46.1 kJ/kg</td>
<td></td>
</tr>
<tr>
<td>Processes</td>
<td>Temperature</td>
<td>Grain</td>
<td>Digestion</td>
<td>Feed Conversion Ratio</td>
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</tr>
<tr>
<td>Milling and pressing</td>
<td>Fine milled wheat; conditioned at 85.2°C; high compression pressing</td>
<td>Wheat and rapeseed</td>
<td>-</td>
<td>81.9% 1.99 MPa</td>
<td>-</td>
<td>-</td>
<td>72.4 kJ/kg</td>
<td></td>
</tr>
</tbody>
</table>

* Reported as % of the maximum electrical power consumed by the equipment