The effect of feed processing techniques on weanling piglet performance

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I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

Summary

Starch is the main component of cereal grains and is usually the primary energy source for pigs and poultry. Feed manufacturing can adopt several measures, including physical treatments such as milling or pelleting and other techniques, such as enzyme treatment, to disrupt cell structure. Grinding and pelleting are the most common food processing methods used for pigs. However, pelleting of complete balanced feeds is no longer such an economical proposition due to rising energy and equipment costs; therefore this cost has to be outweighed by an increased production efficiency. It has been known for many years that grinding is an essential prerequisite for the satisfactory blending of the ingredients of a multi-component food. Feed cost represents the major item in the cost of animal production. Without doubt, research and production efforts will continue to refine feed processing techniques to reduce the cost of feed and to increase the value of feed for a target animal. The possibilities for improvements in feed are endless; however the cost of each innovation must be carefully weighed against demonstrated improvements in animal performance.

***Experiment 1*:** The effect of feed processing techniques on weanling pig growth-performance
The effects of processing of the carbohydrate source and the feed on growth performance of commercial Landrace x Large White piglets (n=480) weaned at 28 ± 2 d were investigated. Two processing combinations of the carbohydrate source were used with 3 processing conditions of the diet in a 2 x 3 factorial design. The pigs were blocked by weight (7.196 ± 2.03 kg BW) and then allotted randomly to 1 of 6 dietary treatments. Ten pens of 8 piglets each were fed with each dietary treatment. The two main processing conditions of the carbohydrate source were raw or extruded maize and the 3 processing conditions of the diet was meal or pelleted or extruded. No carbohydrate processing x diet processing interactions were observed ($P > 0.05$) for ADG, ADFI or FCR. In this experiment, extrusion of the maize led to an significant decrease in FCR efficiency ($P < 0.05$) (1.57 vs. 1.42) when compared to a raw maize diet. Pelleting a diet had no significant effect ($P > 0.05$) on ADG but tended to decrease ADFI ($P < 0.07$) and significantly improve FCR efficiency (1.49 vs. 1.66) when compared to a meal diet. Extruding the whole diet did not have any significant ($P > 0.05$) effect on ADG but tended to decrease ADFI ($P < 0.07$) and gave an significant improvement in FCR when compared to a meal diet (1.34 vs. 1.66). This processing technique also gave a significant improvement ($P < 0.01$) in FCR when compared to a pelleted diet (1.34 vs. 1.49).

Experiment 2: The effect of pig feed processing conditions on pig metabolism parameters
The effects of processing of the carbohydrate source and the diet on certain metabolism and production parameters of commercial Landrace x Large White pigs (n=24) were investigated. Two processing combinations of the carbohydrate source were used with 3 processing combinations in a 2 x 3 factorial design. Six diets were formulated on an iso-nutrient basis (14.48 MJ/kg metabolizable energy (ME),

23.01 crude protein (CP), 1.092% lysine, 0.742% methionine and cystine and 0.271% tryptophan on a DM basis). The pigs were blocked by weight (26.02 ± 0.25 kg BW) and then allotted randomly to 1 of 6 dietary treatments. The carbohydrate source was raw or extruded maize and the diets was meal or pelleted or extruded. No carbohydrate processing x diet feed form interactions were observed ($P > 0.05$) for dry matter intake (DMI), dry matter digestible energy (DE), Nitrogen (N) or dry matter intake (DMI). In a metabolism and nitrogen (N) balance study, apparent N digestibility, digestible energy and metabolizable energy contents were found not to be significantly ($P > 0.05$) influenced by carbohydrate or diet processing.

Opsomming

Stysel is die hoof komponent in grane en is gewoonlik die primêre verskaffer van energie vir varke en pluimvee. Voermeulens kan verskeie metodes implementeer, insluitend fisiese behandeling soos bv. maal, verpilling en ensiem behandelings, om sel struktuur te verander. Maal en verpilling is die mees algemene prosessering metodes wat vir varkvoer gebruik word. Maar, verpilling van totaal geballanseerde voere is nie meer so ekonomies geregverdig nie as gevolg van stygende energie en masjinerie koste. Daarom moet die koste van voervervaardiging oorbrug word deur 'n verhoogde produksiedoeltreffendheid. Dit is al lankal bekend dat maal 'n voorvereiste is vir effektiewe vermenging van grondstowwe van 'n multi-komponent voer. Voerkoste verteenwoordig die hoof item van die koste van intesiewe diereproduksie. Voedingskudiges sal sonder twyfel voortgaan om voerprosessering te verfyn om so die koste van die rantsoen te verlaag en om die waarde van die rantsoen te verhoog vir die dier. Die moontlikhede is veelvuldig, maar die koste van elke ontwikkeling moet opgeweeg word teen verhoogde diereproduksie.

Eksperiment 1: Die effek van voerprosesserings-tegnieke op speenvark groei en produksie
'n Proef is uitgevoer om die prosesseringseffek van 'n koolhidraat bron en voer op die groei van Landras x Groot Wit speenvarke (n=480) wat gespeen is op 28 ± 2 d te bepaal. Twee prosesserings-kombinasies van die koolhidraat bron en drie prosesserings-kondisies van die dieet is in 'n 2 x 3 faktoriaal ontwerp uitgevoer. Die varkies is geblok volgens massa (oorspronklik 7.196 kg ± 2 kg) en toe ewekansig in 1 van 6 dieët behandelings ingedeel. Die proefdiëte is vir 10 hokke varkies gevoer, elke hok het 8 varkies in gehad. Die twee hoof prosesserings-kondisies van die koolhidraat bron was rou of gaar mielies en die drie prosesserings-kondisies van die dieët was meel of gaar of geëkstrueer. Geen koolhidraat prosesserings x dieët prosesserings interaksie van die dieët was opgemerk ($P > 0.05$) vir gemiddelde daaglikse toename (GDT), gemiddelde daaglikse voer inname (GDVI) of voer omset doeltreffendheid (VOD) nie. In die eksperiment was die VOD van die geëkstrueerde mielie dieët, statisties betekenisvol laer ($P < 0.05$) (1.57 vs.1.42) as die rou mielie dieët. Verpilling van die dieët het geen statisties betekenisvolle effek ($P > 0.05$) op GDVI gehad nie, maar die VOD was statisties betekenisvol ($P < 0.05$) beter (1.49 vs. 1.66) wanneer dit met die meel dieët vergelyk word. Ekstrusie van die dieët het geen statisties betekenisvolle effek op GDT en GDVI gehad nie, maar die VOD was statisties betekenisvol ($P < 0.05$) beter wanneer dit met die meel (1.34 vs. 1.66) en verpilde dieët (1.34 vs 1.49) vergelyk word.

Eksperiment 2: Die effek van voer prosessering op vark metabolisme parameters
'n Eksperiment is uitgevoer op Landras x Groot Wit bere (n=24) om die effek van prosessering van 'n koolhidraat bron en voer te bepaal. Twee prosesserings-kombinasies van die koolhidraat bron en drie prosesserings-kondisies van die dieët is in 'n 2 x 3 faktoriaal ontwerp uitgevoer. Ses diëte is geformuleer

op 'n iso-nutriënt basis (14.48 MJ/kg metaboliseerbare energie (ME), 23.01 ru-proteïen (RP), 1.092% lisien, 0.742% metionien and sistien en 0.271% tryptofaan op 'n droeë materiaal (DM) basis). Die varke is geblok volgens massa en ewekansig aan 1 van 6 diëte toegeken. Die koolhidraat bron was gaar of rou mielies en die diëte was meel, verpil of geëkstrueer. Geen koolhidraat-prosessering x dieet interaksie is opgemerk (P > 0.05) nie. In 'n metabolisme en stikstof (N) balans-studie is daar gevind dat DM verteerbaarheid, skynbare N verteerbaarheid, verteerbare energie (GE) en ME inhoud nie beduidend deur die behandelings beïnvloed word nie.

This thesis is dedicated to Louise- the one that completes me

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List of abbreviations

ANF's	=	Anti nutritional factors
ADFI	=	Average daily feed intake
ADG	=	Average daily gain
BW		Body weight
cm		centimeters
CP	=	Crude protein
d	=	Days
FCR	=	Feed conversion ratio
g		grams
GT	=	Gelatinization temperature
kg		kilograms
LAL	=	lysinoalanine
LAN	=	lanthionine
NSP	=	Non-starch polysaccharides
OM	=	Organic matter
TTAD	=	Total tract apparent digestibility

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General conclusions 4.1

The language and style used in this thesis are in accordance with the requirements of the South African Journal of Animal Science. This dissertation represents the compilation of manuscripts where each chapter is an individual entity and some repetitions between chapters have therefore been unavoidable.

Chapter1

Processing of piglet weaner diets

1. Introduction

Intensification of pig farming has led to shortening of the suckling period of piglets from 5-6 weeks to 3-4 weeks of age in order to maximize annual sow productivity (Partanen & Mroz, 1999) and decrease the risk of piglet disease infestation through the sow (Alexander, 1980). The separation from the sow changes the main energy source for the piglet because the milk fat and lactose of the sow's milk is replaced by plant carbohydrates (mainly starch) in the postweaning diet (Partridge & Gill, 1993). However, at these early ages the digestive system is immature (Lindemann *et al*., 1986, Aumaitre, 1995; Jensen, 1997) and leads to a post-weaning lag period. This post-weaning lag period is a result of a limited digestive and absorption capacity due to insufficient production of HCl, pancreatic enzymes and sudden changes in feed consistency and intake (Aumaitre *et al*. 1995; Cranwell, 1995; Owsley *et al*., 1986). A side effect of this is a higher risk of postweaning diarrhea, which causes retarded growth, increased mortality and extra medical costs (Jahn & Uecker, 1987; Aumaitre *et a*l. 1995). At this age the immunological status of a piglet is also low as passive immunity acquired through maternal colostrum is dramatically decreased and active immunity is only beginning to develop (Cranwell, 1995).

The fact that starch is stored in plants in a crystalline complex structure might also impair its digestion in piglets (Cunningham, 1995). The ability of young pigs to adapt to, and adequately digest, grain-soybean meal starter diets after weaning, is necessary for normal growth in the nursery and during the subsequent growing-finishing period. The ability, however, is questionable during the first 3 to 10 d post-weaning (Owsley *et al*., 1986). Kitts *et al*. (1956). Hudman *et al*. (1957) reported an increase in intestinal proteolytic activity from birth to weaning. However, Hartman *et al*. (1961) and Corring et al. (1978) reported an increase in proteolytic activity only starting at 3 weeks of age. Shields *et al*. (1980) and Efrid et al. (1982) reported that amylase production of the pancreas progressively increases until 10 weeks of age. The young pig should, therefore, be able to digest both starch and vegetable protein after weaning at 28 days (d). Performance (Meade *et a*l., 1965; Leibbrandt *et al*., 1975) and apparent nutrient digestibility (Owsley *et al*., 1986) measured during the week after weaning, however, demonstrated the pig's inability to adequately digest diets containing starch and vegetable protein during this period.

Starch is digested to dextrins by the alpha-amylases present in the upper gastro-intestinal tract, which are further hydrolyzed by brush border enzymes prior to absorption. Thus starch is potentially totally digestible in the small intestine (Graham, 1991).

According to Armstrong (1978) approximately 60-70% of the energy ingested by the weaned piglet is derived from carbohydrates, so processing of this portion of the diet is of major significance to the young animal's performance. Starch, the predominant carbohydrate in the diet is derived mainly from the cereal components and consists ordinarily of granular glucose units, amylose and amylopectin. The extrusion process causes expansion and gelatinization of the starch granules with an opening up of these complex molecular chains. Given optimum process conditions, extrusion has the potential to gelatinize high levels of starch in most feed raw materials (85-100%, Bjork & Asp, 1982; Asp & Bjorck, 1989). Although complete starch gelatinization at atmospheric pressure requires at least 30-40% moisture, many authors have shown that extrusion cooking produces a virtually complete starch gelatinization at low moisture content when the temperature exceeds 110-135 °C (Bjorck & Asp, 1989). The extruded starch has increased solubility and decreased viscosity, favoring availability to amylase and rapid absorption of resultant glucose in vivo.

The structure of starch can be modified by heat or by physical treatment, inducing a change in the crystalline structure or degree of gelatinization (Fadel *et al.*, 1988), thereby facilitating its enzymatic degradation (Holm & Björck, 1988; Osman *et al.*, 1990) which can improve ileal starch digestibility (Graham *et al.*, 1989). Heat treatment of cereals also partly solublizes the non-starch polysaccharides fraction (Fadel et al., 1988). The modification of starch granules depends on the treatment (Holm *et al.*, 1988) and the starch source (Farber & Gallant, 1976; Faulks & Bailey, 1990).

According to Patridge & Gill (2001) the implicit assumption is usually made that gelatinization of dietary starches in diets for young pigs is a desirable feature in view of their immature digestive physiology and enzyme complement at weaning (Kidder & Manners, 1978). However, reports from scientific literature on this aspect, tend to be equivocal (Aumaitre, 1989; Skoch *et al.*, 1983; Van der Poel *et al.* 1989, Vestergaard *et al.* 1990; van der Poel *et al*, 1990, Sauer *et al.* 1990; Hancock, 1992).

Factors such as different weaning ages and weights of pigs used, disease challenge, different processing conditions (both in terms of raw material grinding and subsequent heat treatment), digestibility measurements (e.g. whole tract rather than ileal) and the influence of other dietary raw materials all interact and confound the establishment of a consensus view.

In commercial practice diet formulation for the young pig from birth to 10 kg, almost invariably entails a degree of dietary insurance to cope with a range of different management systems and environmental and disease challenge which will be experienced by the newly-weaned animal. Correctly heat processed cereals are always likely to form an integral part of this nutritional management package.

The boundary line over this weight range, however, where gelatinization is desirable and economically justified is never likely to be clearly established in view of the tremendous variability in enzyme development of the young pig at this age (Kidder & Manners, 1978; De Passille *et al*, 1989).

One potentially detrimental effect of extrusion cooking of complete diets is the formation of amylose-lipid complexes. These complexes are fairly resistant to alpha-amylase *in vitro*, however studies *in vivo* in the rat indicate that they are completely digested and absorbed, albeit at a slightly lower rate than free amylose (Bjorck & Asp, 1982).

2. Digestion in the weaner piglet

2.1 The weaning process- gut function and health

In an ideal world of pig production, weaning would be a gradual process rather than an abrupt event in the young animal's life. Unfortunately the constraints imposed by management systems (e.g. financial, nutritional and environmental) cause it to be a sudden occurrence that can result in poor health and performance in the immediate post-weaning period.

Various explanations and hypothesis have been forwarded to account for the variable growth and loss of health experienced by many piglets at weaning. Some have been summarized as follows (Partridge & Gill, 2001):

1. Insufficient digestive enzymes for new food substrates;
2. reduced adsorptive capacity due to changes in villus structure;
3. poorly developed gastric secretions;
4. removal of beneficial factors present in sow's milk (e.g. natural antibacterial immunoglobulins);
5. inadequate feed intake;
6. form of post-weaning diet offered, dry meal/pellet ;
7. environmental stresses.

Sow's milk contains important protective maternal antibodies, which are lost to the piglet at weaning. The major immunoglobulin component of sow's milk is IgA (Husband & Bennel, 1980) and between 3 and 4 weeks of age the suckling piglet would receive about 1.6 g IgA/day (Svedsen & Brown, 1973). Unlike colostrum antibodies, IgA and other milk immunoglobulins are not absorbed from the gut and thus form a continuous defense along the lumen against infectious organisms to which the sow has developed resistance (Kidder, 1982). This protection is essential while the piglet's own production of IgA remains undeveloped, that is from birth to about 6 weeks of age (Svedson & Brown, 1973).

The literature therefore suggests that piglets weaned at 3 and 4 weeks of age lose valuable protection of maternal antibodies at the time when their own immature immune system cannot resist a significant disease challenge.

Furthermore susceptibility to disease may be increased since the immune status of the piglet is compromised by an immunosuppressive reaction to weaning (Coenen & Kruse, 1986).

2.2 Changes in digestive enzymes and gut morphology of weaned piglets

Once the piglet has eaten feed, the feed move through various sections of the digestive tract (Figure 1). In the mouth, small amounts of alpha-amylase are secreted with the mucus on to the feed and the feed moves into the esophagus and into the stomach. From the stomach the feed moves through the small intestine (duodenum, jejenum and ileum) to the large intestine (colon and rectum) after which the undigested feed is excreted as faeces (Argenzio *et al.*, 1975).

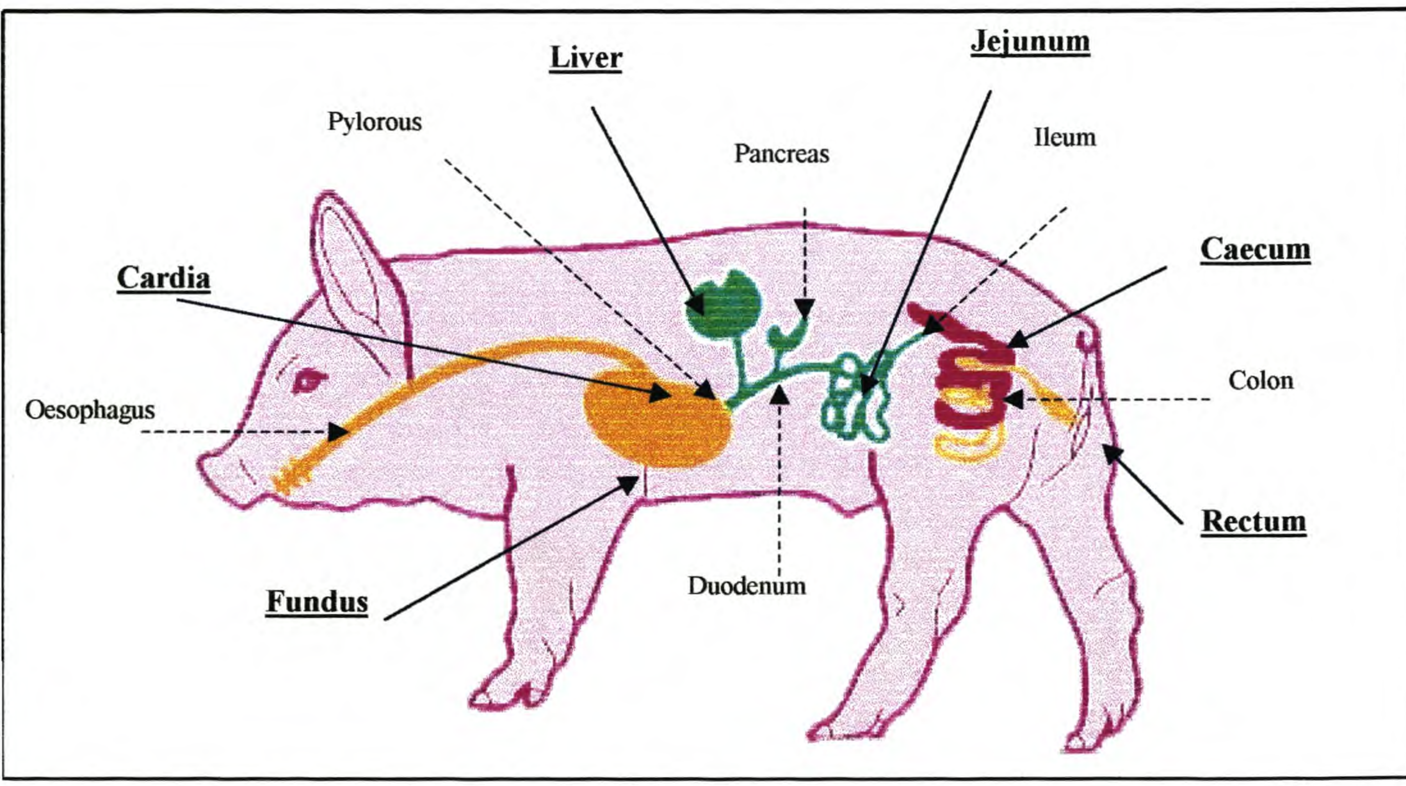

Figure 1 Physiology of the digestive tract of the weaner piglet (Gaubert, 2000).

The cardia and pylorous sphincters control the passage of food through the stomach. The inner surfaces of the cardia and the pylorous contain a variety of secretory cells, which collectively secrete gastric juices. A number of factors can influence the stimulation of the glands to secrete gastric juices (e.g. presence of food in the stomach). Gastric juice contains mainly water, inorganic salts, mucus, hydrochloric acid and pepsinogen. Hydrochloric acid activates pepsinogen converting it into the proteolytic enzyme by removing a low molecular weight polypeptide from the precursor molecule. Pepsin preferentially attacks those peptide bonds adjacent to amino acids (phenylalaine, tryptophan and tyrosine) but have also a significant action on linkages involving the dicarboxylic acids, glutamic and aspartic. The products of protein digestion in the stomach are mainly polypeptides of variable chain length and a few amino acids (Gaubert, 2000).

Four secretions enter the small intestine: duodenal, bile, pancreatic juice and succus entericus. The duodenal glands produce an alkaline secretion, which enters the duodenum through ducts situated between the villi. This secretion acts as a lubricant and protects the duodenal wall from the hydrochloric acid entering the stomach. Bile is secreted by the liver and passes into the duodenum through the bile duct. It contains the sodium and potassium salts of bile acid, mainly glycoholic and tauocholic, the pigment biliverin and bilibulin, cholestrol and mucin. The bile salts play an important role in digestion by activating pancreatic lipase and emulsifying fats. The pancreatic juice is secreted by the pancreas, a gland that lies in the duodenal loop and opens into the duodenum through the pancreatic duct. A number of factors induce the pancreas to secrete its juice into the duodenum. When acids enter the duodenum, the hormone secretin is liberated from the epithelium of the small intestine into the blood. When it reaches the pancreatic circulation, it stimulates the pancreatic cells to secrete a watery fluid with a high concentration of bicarbonate ions. Cholecystokinin (pancreozymin), a hormone is liberated from the mucosa when peptides and other digestive products reach the duodenum (Gaubert, 2000).

Cholecystokinin stimulates the secretion into the pancreatic juice of pro-enzymes and enzymes such as trypsinogen, chymotrypsinogen, procarboxypepsidase, proclastase, alpha-amylase, lipase, and lecithinases. Inactive zymomogen and trypsinogen is converted to the active trypsin by enterokinase (an enzyme liberated from the duodenal mucosa). Trypsin also converts chymotrypsinogen into the active enzyme chymotrypsin as well as pro-carboxypeptidase into carboxypeptidase (Gaubert, 2000).

All these enzymes attack peptide bonds splitting off terminal amino acids. The break down of fats is achieved by pancreatic lipase. This enzyme does not completely hydrolyze the triglycerides and the action stops at the monoglyceride stage (Gaubert, 2000).

Dietary fats leave the stomach in the form of large globules, which are difficult to rapidly hydrolyze. Fat hydrolysis is helped by emulsification, which is brought about by the reaction of bile salts. Succus entericus is produced in the crypts of Lieberkühn, the tubular depression between the villi. This secretion contains enzymes associated with the hydrolysis of disaccharide's (Gaubert, 2000).

Several studies have shown a consistent depression in level of pancreatic and intestinal enzyme secretion in the newly-weaned piglet (Kidder & Manners, 1980; Shields *et al.*, 1980; Hampson & Kidder, 1986; Lindeman *et al.*, 1986). Some observations, however, would have been negatively influenced by poor or variable feed intake in the pre-weaning and immediate post-weaning period. The technique of gavage feeding (gastric intubation) has allowed the effects of continuous supplies of dietary substrate on enzyme induction to be more critically examined (Kelly *et al.*, 1990; 1991a,b).

Such studies indicated that high levels of creep feed intake could induce marked increase in specific and total enzyme activities at weaning (Kelly *et al.*, 1990). In the post-weaning period high feed intakes (via gastric intubation) also stimulates gut development and enzyme levels in the small intestine. It appears that the small intestine of the newly weaned animal still has sparse capacity in terms of enzyme complement, to deal with cereal-based weaner diets (Kelly *et al.*, 1991b). Creep feed intake of piglets weaned at 3 to 4 weeks of age is notoriously variable both within and between litters. Factors such as weaning age, sow milk output (i.e. drive of the litter to eat), palatability and digestibility of the creep feed offered, wet or dry feeding form (i.e. meal or pellets) and access to the creep (e.g. floor fed or in hoppers) are all likely to influence the quantities consumed and thereby the degree of induction of digestive enzymes.

One consistent effect on the digestive physiology in the immediate post-weaning period is the change in villus morphology, from long slender villi characteristic of the suckling animal to leaf-shaped villi with varying degrees of atrophy (Miller *et al.*, 1986a; Cera *et al.*, 1988). Villus height is often halved and crypt depth doubled in the newly weaned pig, a situation which results in immature enterocytes reaching the villus tip where they show a reduced capacity to express enzyme activity (Miller *et al.*, 1986). Continuous supply of dietary substrate via gavage feeding can reduce, but does not completely prevent, these changes in villus height and crypt depth occurring (Kelly *et al.*, 1991a).

3 Structure of cereal grains

Grains develop from the ovule of their flowers after fertilization and are enclosed in two scale-like glumes, the lemma and palea. In barley, the glumes fuse with the ovary during development of the grain, forming the husk or hull; thus barley is a covered kernel and the same is true for oats, although with the latter grain the glumes are not fused to the kernel but only firmly adhered to it. In wheat and rye the lemma and palea are loose and when the grain is threshed they separate from the kernel, forming chaff and leaving the grain as a naked kernel. Maize and sorghum are also naked kernels. The anatomical structure of all grains is generally the same and the various components are detailed in Figure 2.

The starchy endosperm comprises of discrete microscopic starch granules held closely with protein filling the intergranular spaces. The physical appearance of the granule is a characteristic of the cereal. The 'horny" or "waxy" endosperm consists almost entirely of amylopectin (Greenwood, 1970). Flint maize have a high content of horny endosperm while the dent maize, so called because the floury endosperm in the region of the crown contracts in such maize during maturation giving rise to a small indentation, contain a greater proportion of floury endosperm. In milo the endosperm contains a relative greater proportion of horny endosperm relative to the floury type and the outer layer of the endosperm are formed from dense proteinaceous cells (Lawrence, 1967).

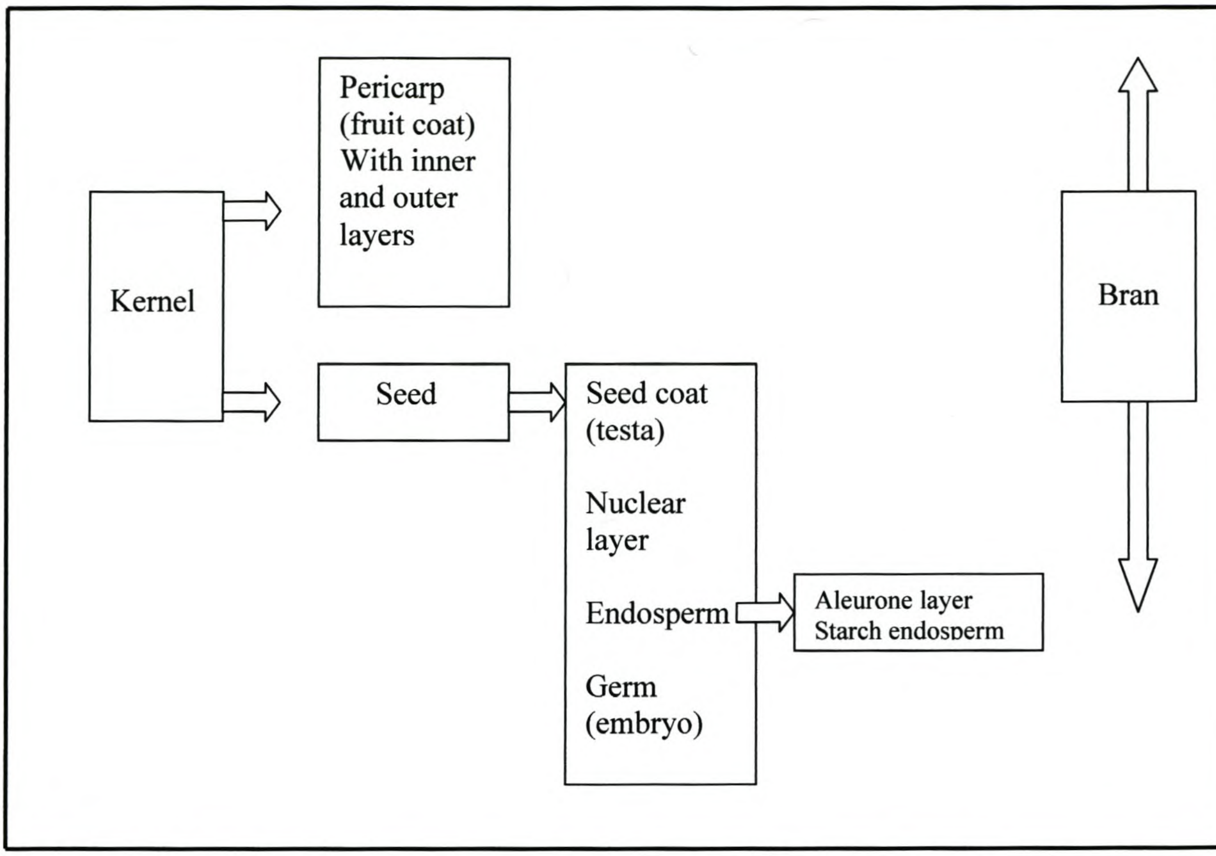

Figure 2 Outline of the various components of a cereal grain (Adapted from Lawrence, 1967).

4. Carbohydrates

4.1 Classification

Carbohydrates can be classified according to their molecular size into low molecular weight (mono-, and oligosaccharides) and as high molecular weight (polysaccharides) according to the number of individual monosaccharides from which the carbohydrates are built (Figure 3).

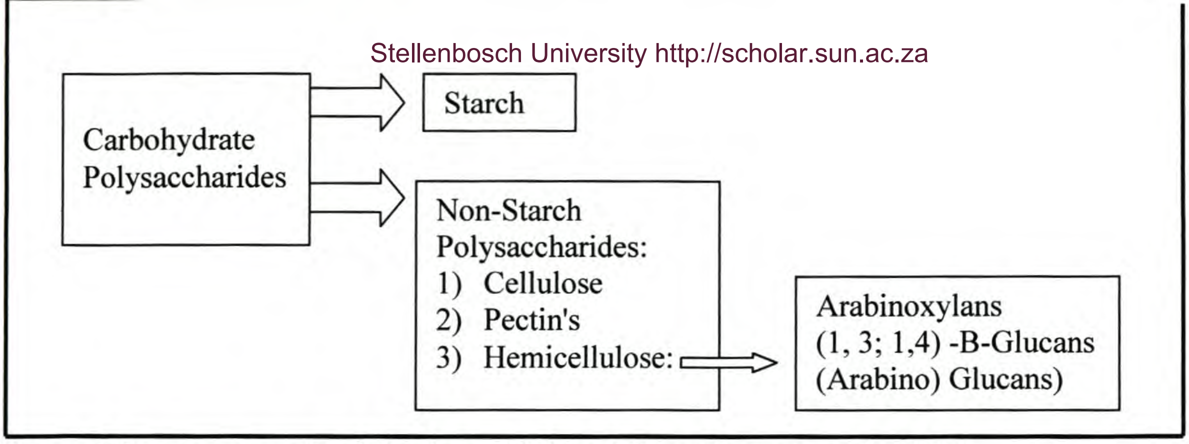

Figure 3 Components of carbohydrates (Adapted from Voragen *et al.*, 1995).

4.1.1 Monosaccharides

Monosaccharides can be classified on the basis of the number of carbon atoms. In food and feed raw materials, pentoses (five carbon atoms) and hexoses (six carbon atoms) are commonly present. Monosaccharides differ in the chiral position of the different hydroxyl groups and the position of the carbonyl group (aldehyde or keto). All monosaccharides are readily soluble in water and are present in a cyclic form (Voragen *et al.*, 1995).

4.1.2 Polysaccharides

From a chemical point of view polysaccharides could be classified on the basis of the constituent monosaccharides composition, but in practice various classification criteria are used, like monosaccharides composition, glycosidic linkage type, morphological appearance or solubility of the polysaccharide. A general classification of polysaccharides is the division into starch and non-starch polysaccharides (Voragen *et al.*, 1995) (Figure 3).

4.1.2.1 Non-starch polysaccharides (NSP)

Non-starch polysaccharides (NSP) can be identified as those polymeric carbohydrates, which are different in composition and structure (glycosidic linkage type) from amylose and amylopectin. These polysaccharides can be located intracellularly (e.g. fructans, mannans) or extracellularly (e.g. exudates) but the majority of the non-starch polysaccharides originate from the plant cell wall (e.g. arabinoxylans, cellulose, mannans). The latter are integral parts of cell wall structures together with proteins and often with lignin. In general, these complexes are not readily accessible to enzymes and not degraded by the digestive enzymes of mononogastric animals. In the colon of mononogastric animals they are fermented to free fatty acids which are subsequently absorbed. Based on their solubility in different solvents, NSP can be classified into pectins (soluble in hot aqueous solutions of chelating agents or weak acids), hemicellulose (soluble in alkali) and cellulose (only soluble in concentrated acids). Whereas the cellulose fraction comprises of only one polymer, a Beta-1,4 linked glucose polymer, both the pectin and the hemicellulose fraction comprise various different polysaccharides either chemically interlinked or not.

Depending on the source of feed raw material the monosaccharide composition of the non-starch polysaccharide can differ greatly. In by-products of the fruit industry pectin is the most abundant group of molecules whereas in cereal (by-) products arabinoxylans (hemicelluloses) and cellulose are predominant. The properties (e.g. solubility, viscosity, water-binding capacity) of the non-starch polysaccharides strongly depend on their structure and large differences exist between the pectin and hemicellulose fraction from different origins. Therefore, characterization and quantification of non-starch polysaccharides in terms of hemicellulose, pectin and cellulose, or even into the commonly used classes neutral-detergent and acid detergent fiber (Van Soest, 1976), is not sufficient for understanding the behavior of these components in raw material processing.

4.1.2.2 Resistant starch

In both native and processed material resistant starch could be present. Resistant starch can be formed by recrystallization of solubilized amylose. In addition, native starch with a so-called Beta-type crystallization pattern and starch granules embedded in a cell wall matrix, are also not digested in the upper part of the digestive tract. Resistant starch can therefore be defined as that part of the total starch present which cannot be digested in the upper part of the digestive tract and is fermented in the colon as dietary fiber (Voragen *et al*. 1995).

4.1.2.3 Starch

The storage of polysaccharides is essentially an alpha-D-(1,4)-linked glucan with alpha-D-(1,6) linked branch points and comprises a mixture of amylose and amylopectin. Amylose, a linear, thread-like molecule consists of straight chains of glucose units linked between carbons 1 and 4 while amylopectin, a molecule containing many branches, is made up of much shorter chains of 1-4 linked glucose units, all but one joined through a 1-6 linked to another chain, i.e. amylopectin is a branched polymer. The glucose units have a glucopyronose structure.

Amylose has a degree of polymeration of 1,000 to 2,000 D-glucose units; the length of a unit chain in polymeration is 19-26 D-glucose units (Greenwood, 1970) although the whole molecule is one of the largest found in nature. While the proportion of amylose to amylopectin is primarily under genetic control, another factor affecting this ratio is the maturity of the plant; as the maturity increases, so does the amylose content (Greenwood, 1970). Table 1 gives the proportion of amylose in whole granular starches from a number of cereals.

Table 1 The amylose content and gelatinization temperature range of whole granular cereal starches (Armstrong, 1978).

Cereal	Amylose % in starch	Gelatinization temperature range (°C)
Barley	22	59-64
Maize	28	62-72
Oats	27	-
Wheat	26	65-67
Sorghum	25	67-77

5. Starch

5.1 Structure

All starch granules show a layer or shell structure. If each layer has an uniform thickness, the granule is concentric with the hilum, the nucleus around which successive layers of starch are built up, in the center. If starch deposition is more extensive in one direction the hilum will be in an eccentric position. On the basis of X-ray studies, and possession by the starch granule of the property of birefringe, it is known that the granule contains crystalline regions extending radially from the center and dispersed in a more abundant, amorphous network. In the highly ordered crystalline regions, called crystallites, numbers of parallel polymers chains are held close, one to another, by numerous secondary bond forces in the form of hydrogen bonds.

The more abundant amorphous regions comprise a network of randomly distributed polymer chains loosely held to other chains by hydrogen bonding, when they are in sufficiently close proximity. By reason of the fact that starch, which contains little amylose, still possesses areas of crystallinity, it is supposed that glucose polymer chains in amylopectin are responsible for crystalline formation. Some of the branching areas of particular amylopectin molecules, which may be involved in crystalline structures, extend into one or more amorphous regions and thus contribute to the interlinking within the granule. It will be appreciated that association between molecules is much weaker in the amorphous regions than in the crystalline regions (Armstrong, 1978).

Seib (1971) visualizes a maize starch granule in terms of steel rods (crystallites) of various lengths arranged individually in space so that the ends of their long axis coincide with radii of the sphere. The rods are fixed in position by springs randomly welded between adjacent rods; such springs representing randomly distributed polymer chains in the amorphous region.

Starch granules normally contain between 10-17% moisture, the exact amount depending on atmospheric conditions. The first 8-11% is considered to be water crystallization since dehydrated starch is amorphous and heat is liberated when the starch is rehydrated (Armstrong, 1978). Greenwood (1970) subdivides starches into two groups on the basis of their origin in organs that retain a high water content (starches in tubers, bulbs etc.) or in which less water is available and water content decreases during ripening. The last-mentioned group includes the cereal starches and as a result of the drying process submicroscopic cracks and cavities develop in the granule. Such points of access to the inner parts of the granule may contribute to facilitating the penetration within the granule of the large sized starch degrading enzymes, which can then attack the polymers both within and on the periphery of the granule.

Amorphous, solid substances such as glass and plastics are termed isotropic since, with the completely random distribution of molecules, their optical properties are the same in all directions. The starch granule is anisotropic due to the presence of crystalline regions in the predominantly amorphous mass and this apical anisotropy results in the phenomenon termed double refraction or birefringe. When starch granules are viewed through a microscope using polarized light, two zones of light extinction occur in the form of a dark interference or Maltese cross. The central point of interaction in the cross is the hilum. Birefringe is lost when crystallinity is destroyed. These crystallites are relative resistant to chemical and enzymatic attack. In contrast, the gel phase (amorphous regions) is less dense and more susceptible to chemical and enzymatic modifications and absorbs water more readily at a temperature below the gelatinization temperature (Zobel, 1988).

5.2 Gelatinization of starch

Due to the association of molecules in the granule, starch is insoluble in cold water despite the fact that it contains many hydroxyl groups and is therefore hydrophilic. As the water is heated, small volumes of water are absorbed and swelling starts to occur. In early stages birefringe is retained and the process of swelling is reversible. However, when a certain temperature is reached, the gelatinization temperature, crystallinity of the granule is destroyed, i.e. birefringe is lost and the swelling becomes irreversible.

This change is associated with the rapture of the secondary hydrogen bonds that hold the polymer chains together in the crystallines and results in complete destruction of the ordered arrangement. Since it is not possible to re-establish the molecular arrangement possessed in the original granule, the process is completely irreversible. Gelatinization temperature (GT) can thus be defined as the temperature of water at which starch granules placed in it lose their polarization cross, i.e. lose the property of birefringe.

Since granule size, differences in degree of association between molecules in amorphous regions and other factors affect temperature of gelatinization, there is not one gelatinization temperature but a range of 8-10 °C over which loss of birefringe occurs (Zobel, 1988). Some values for the temperatures are given in Table 1. From that it can be seen that barley has the lowest GT range and sorghum has a slightly higher value than maize.

According to Hauck *et al*. (1994) gelatinization improves starch digestion in two ways:

- It enhances the ability of starches to absorb large quantities of water and this leads to improved digestibility.
- It leads to the destruction of the outer cell wall components as well as ordered crystalline structures within starch granules which increases the susceptibility of the starch breakdown by amylase.

If starch is over-cooked, soluble amylose leaks out. On slow cooling there is a gradual alignment of the glucose chains into tightly bound bundles of glucose molecules. Those bind together and a re-establishment of hydrogen bonds may occur. The process is essentially irreversible (Greenwood, 1970) and it is extremely difficult to re-dissolve retrograded amylose. The retrogradation of starch (formation of beta-amylose and crystallized amylopectin) may decrease the ability of enzymes (amylases) to break down the linkages of starch and convert it into more soluble carbohydrates, including glucose (Hoseney, 1986). Therefore, although gelatinization of starch will increase the digestibility of carbohydrates, retrogradation will decrease digestibility of starch in the small intestine (Honktrakul *et al*., 1998).

6. Reactivity of Food components

6.1 Reactivity of Carbohydrates

During (moist) heat treatment the reducing sugars can take part in caramelization and Maillard reactions, resulting in flavour changes and loss of nutritional value. As a result of thermo-mechanical treatments part of the NSP can be solubilized from the cell wall matrix through degradation or losing of physical binding forces.

This can contribute to the viscosity of the chymous (e.g. arabinoxylans) or open up the cell wall structures for release of nutrients. As mentioned before, upon moist treatment starch granules can gelatinize (hydrate) and become more digestible. However, depending on the conditions, resistant starch can be formed which is not digestible by monogastric animals (Voragen *et al*., 1995).

6.2 Reactivity of proteinaceous material

The presence of the essential amino acid lysine, can take part in the Maillard reaction, due to the presence of the free amino group. By heat-treatment at alkaline conditions essential amino acids present in proteins can be cross linked and upon hydrolysis of the proteins, unusual compounds like lysinoalanine (LAL) and lanthionine (LAN) are formed, which can not be digested. Also, under these conditions formation of non-nutritive D-amino acids from the naturally occurring L-configuration can take place. Heating proteins at neutral pH in (semi) dry conditions can result in the formation of iso-peptide bonds (cross-linking). It may be obvious that in addition to those reactions which cause a direct lower nutritional quality the cross-linking reactions may significantly change the protein structure as well as the total feed matrix structure by which the nutritional quality can also change.

The above mentioned reactions cause a change in the chemical structure of the amino acids, peptides and/or proteins. For the proteins this can lead to denaturation. However, denaturation of proteins can also take place at elevated temperatures without these reactions occurring. The proteins will denaturate and can aggregate, by which their solubility generally decreases and their digestibility increases. Bio-active proteins like enzymes, lectins and trypsin inhibitors will be inactivated. Due to denaturation hydrophobic interactions can take place and thiol groups may be exposed for interaction (Voragen *et al*., 1995). Table 2 gives an overview of some of the reaction of carbohydrates.

Table 2 Reactivity of some food components (Voragen *et al*., 1995).

Carbohydrates	**Proteinaceous material**
Maillard reaction	Maillard reaction
Caramelization	LAL/LAN formation
Solubilization	Deamination
Resistant starch formation	Denaturation

6.3 Maillard reaction

For the carbohydrate components one of the most important reactions is the Maillard reaction in which many constituents of raw materials can participate and which affects many quality attributes. Reactions between reducing sugars and free amino groups from amino acids, peptides and proteins prevail, but oxidized vitamin C is also very active with reducing compounds formed by oxidation of lipids and polyphenols. The scheme proposed by Hodge in 1953 (Figure 4) to describe the many reaction pathways of the Maillard reactions is still considered the most satisfactory representation. Figure 5 (O'Brien & Labuza, 1994) gives a simplified overview of Maillard reaction pathways.

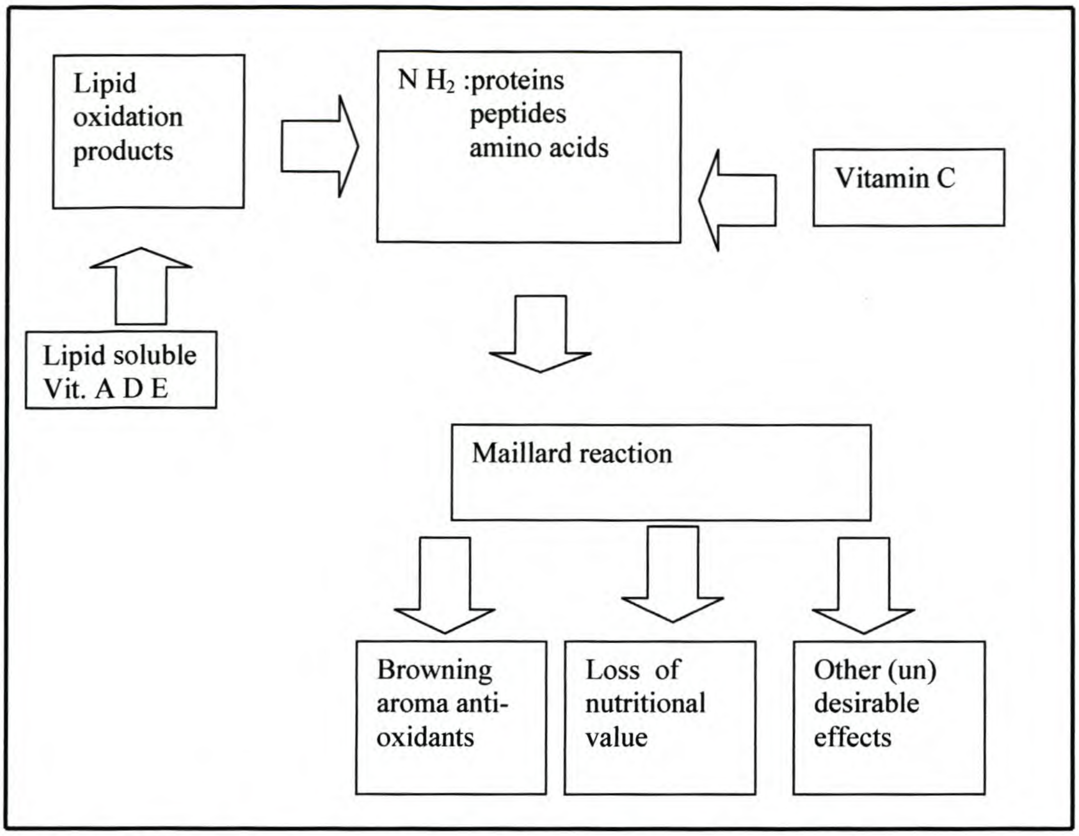

Figure 4 Constituents taking part in the Maillard reaction (Adapted from Hodge, 1953)

Three stages are distinguished (Figure 5): An initial stage, an intermediate stage and an end stage. In the initial stage a nucleophilic addition of the amino group of an amino compound to the electrophilic carbonyl groups of a reducing sugar or another carbonyl takes place and a glycosamine is formed. This is still a reversible reaction, which is followed by a re-arrangement of the glycosamine to so called Amadori (aminoketose), or Heyns (aginose) compounds. In the intermediate stage Amadori and Heyns compounds are further degraded by a myriad of very complex reactions.

Depending on the conditions three main routes may be followed; one route starts with 1-2 enolisation followed by elimination of water and the amino group giving, among others, 3-deoxysons (reactive dicarbonyls), furfural or hydroxymethylfurmural (HMF). The presence of these latter compounds in a food is often used as an indicator of heat damage. These reactions particularly take place at pH less than 3. Another route, favored by a pH greater than 7, begins with 2-3 enolisation, followed by deamination and the formation of 1-deoxyosons which subsequently fragment into many small, volatile flavor compounds. Many of these fragmentation products have strong reducing carbonyl groups, which engage in new reactions with amino compounds. In products with a high content of amino acids and treated at high temperatures (> 120°C) amino acids react with dicarbonyl compounds by the Streker degradation mechanism (O'Brien & Labuza, 1994).

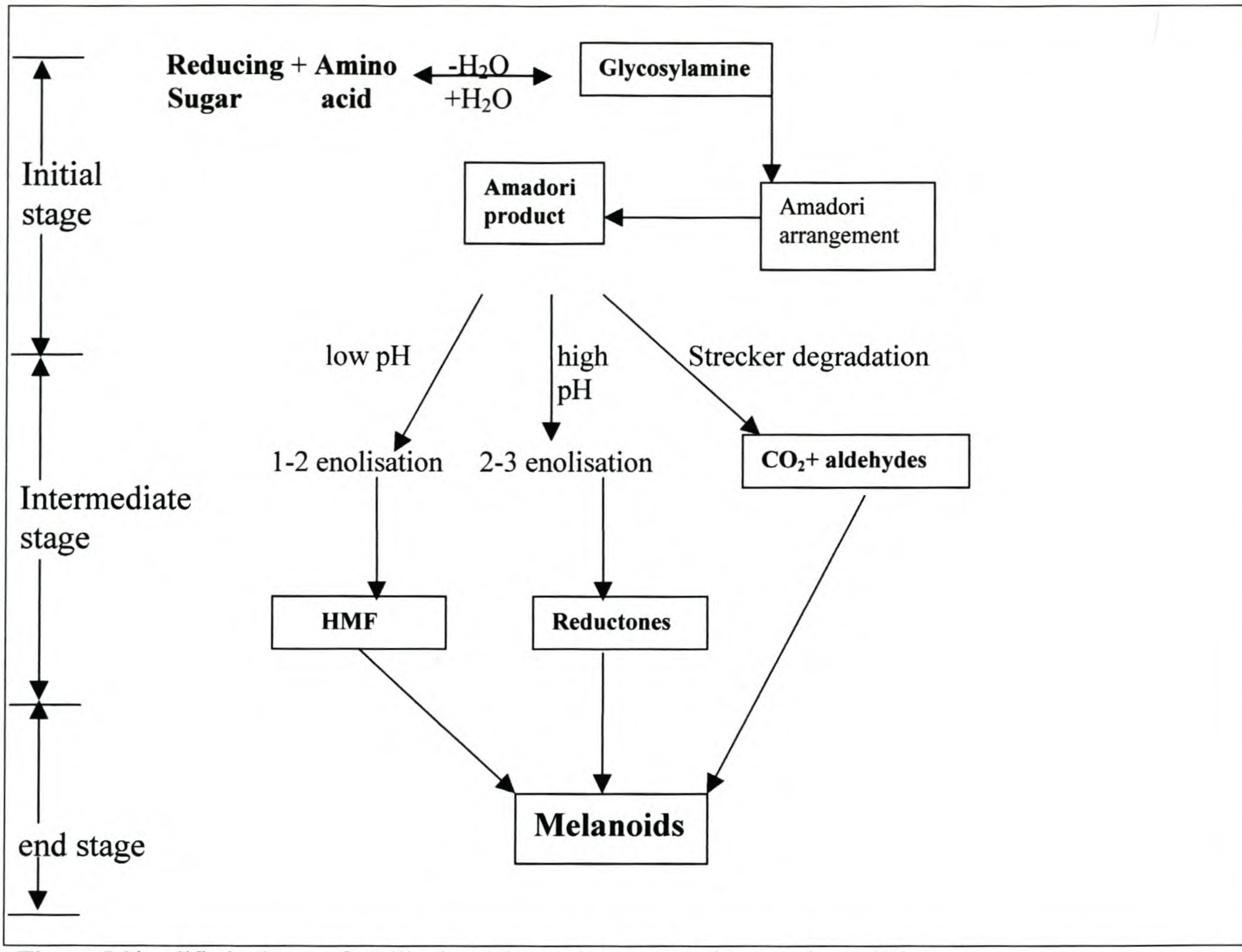

Figure 5 Simplified scheme of Maillard reaction pathways (O'Brien & Labuza, 1994).

After transamination and decarboxylation ,CO_2 and aldehydes are formed next to pyrazines, oxazoles and, from S-containing amino acids, thiazoles. The changes taking place in this stage are not yet visible; in model systems measuring the increase in absorbency at 420 nm follows these changes. In the end stage many of the reaction products formed in the preceding reactions condense and polymerize to high molecular, brown complexes called melanoidins. Amino groups are strongly involved in these reactions, which is noticeable from the fact that in this stage a strong reduction in available (essential) amino acids is observed.

6.3.1 Factors and conditions determining the Maillard reaction

To be reactive in the Maillard reaction sugars need an aldehyde or keto group. Sugars are not reactive and sucrose is reactive only after hydrolysis to glucose and fructose. In general, pentoses are more reactive than hexoses, aldoses more than ketoses and monosaccharides more than di- and oligosaccharides. Dehydro-ascorbic acid is a derivate of L-Gulonic acid and is very reactive.

The reactivity of amino compounds depends on the concentration of free amino groups. Amides are therefore more reactive than amino acids and basic amino acids more than neutral amino acids. Neutral amino acids are in general more reactive than acidic and polar amino acids. The influence of temperature on the Maillard reaction is very complex. With increasing temperature the velocity increases and the reaction route also changes. At low temperature (< 60°C) Amadori compounds are formed and there is hardly any browning. At temperatures averaging ±100 °C, Strecker degradation and melanoindin formation prevails. The type of reaction taking place is also influenced by pH and moisture content of the product.

The Maillard reaction is minimal in the pH range 3-4. Lower pHs can cause formation of reducing sugars and amino acids by hydrolysis (sucrose) and thus promote Maillard reactions. The Maillard reaction increases to an optimum at pH of 1, at higher pH values Maillard reactions decrease. The Maillard reaction can be limited by operating in a pH range of 3-4, at a low moisture content, by keeping the process temperatures as low as possible or by carrying out high temperature treatments in a very short time. Another way to minimize the Maillard reaction is to remove or lower the concentrations of reactants, for instance by fermentation of reducing sugars (Voragen, 1995). Complex starter diets containing high quality dairy products or specialty sources in diets are especially susceptible to the formation of the Maillard reaction during high temperature in feed processing. This may lead to decreased availability of nutrients to the animal and hence reduced performance (Honktrakul *et al*., 1988).

6.4 Protein denaturation

Thermo-mechanical treatments are often used to increase the nutritional value of proteins by inactivation of antinutritional factors (ANF's) and protein denaturation. Inactivation of ANF's alone is not sufficient to explain the increase in protein digestibility, which was obtained after thermo-mechanical treatments (Marsman *et al*., 1993; Liener, 1994). This suggests that denaturation of storage proteins is also an important process in thermo-mechanical treatments. Protein denaturation can be defined as any change in the conformation of a protein that does not involve the breaking of peptide bonds.

Most proteins undergo structural unfolding followed by aggregation when subjected to moisture or heat or shear. Unfolding is usually a reversible process and if the thermo-mechanical treatment is stopped before aggregation begins, the protein can return to its native conformation. If more heat or shear is added non-covalent interaction like hydrophobic and electrostatic interactions, which contribute to the stabilization of the three-dimensional structure, will be broken, resulting in irreversible protein denaturation. Thermo mechanical treatment may also result in the breaking of covalent bonds such as disulphide bonds. During denaturation hydrophobic groups are uncovered in a decreased solubility of the protein in aqueous solutions (O'Brien & Labuza, 1994).

If the mechanical energy is high enough during processing, protein denaturation can be followed by association and dissociation reactions. Association and dissociation reactions can also be followed by breaking or formation of some covalent bonds e.g. hydrolysis of peptide bonds, modification of amino side chains (lysinoalanine or Maillard) and the formation of new covalent isopeptide cross-links. Upon cooling large protein complexes can be formed by inter- and intra-molecular interactions (O'Brien & Labuza, 1994).

7. Cereal Processing

7.1 Techniques applied in cereal processing

Starch is the main component of cereal grains and is usually the primary energy source for pigs and poultry (Graham, 1991). Feed manufacturing can adopt several measures, including physical treatments such as milling or pelleting and other techniques, such as enzyme treatment, to disrupt cell structure (Graham *et al.*, 1989). Grinding and pelleting are the most common food processing methods used for pigs. However, pelleting of complete balanced feeds is no longer such an economical proposition due to rising energy and equipment costs (Skoch *et al.*, 1983), therefore this cost has to be outweighed by an increased production efficiency (Krider & Carrol, 1971). It has been known for many years that grinding is an essential prerequisite for the satisfactory blending of the ingredients of a multi-component food (Armstrong, 1978). Feed cost represents the major item in the cost of animal production. Without doubt, efforts will continue to refine feed processing techniques to reduce the cost of feed and to increase the value of feed for a target animal. The possibilities for improvements in feed are endless; however the cost of each innovation must be carefully weighed against demonstrated improvements in animal performance (Ensminger, 1985; Behnke, 1996).

Cereals can be processed in two ways. Firstly they can be processed in the "cold" state, i.e. without the application of any form of heat. Secondly, they can be processed by various heating and pressure methods (Lawrence, 1978). Processing in the "cold" state involves hammer milling, crimping, plate milling and rolling or crushing. Processing by the application of heat involves expansion, extrusion, cubing, flaking and a recent innovation, micronization. In addition, to the "cold" processing category, it is important to differentiate between the effects of the above-mentioned techniques on moist and dried grain.

Within the "hot" processing category, the effects of pressure as applied in extrusion, expansion and cubing processes in particular is another variant which has to be considered in terms of effects on resultant pig performance. In addition to the effect on digestibility and pig performance there is now considerable evidence to indicate that cereal processing may play an important part in affecting pig health.

Accordingly the possibility of a correlation existing between these two different aspects of pig production cannot be discounted. Some possible ways in which processing techniques may affect both performance and health are represented in Figure 6.

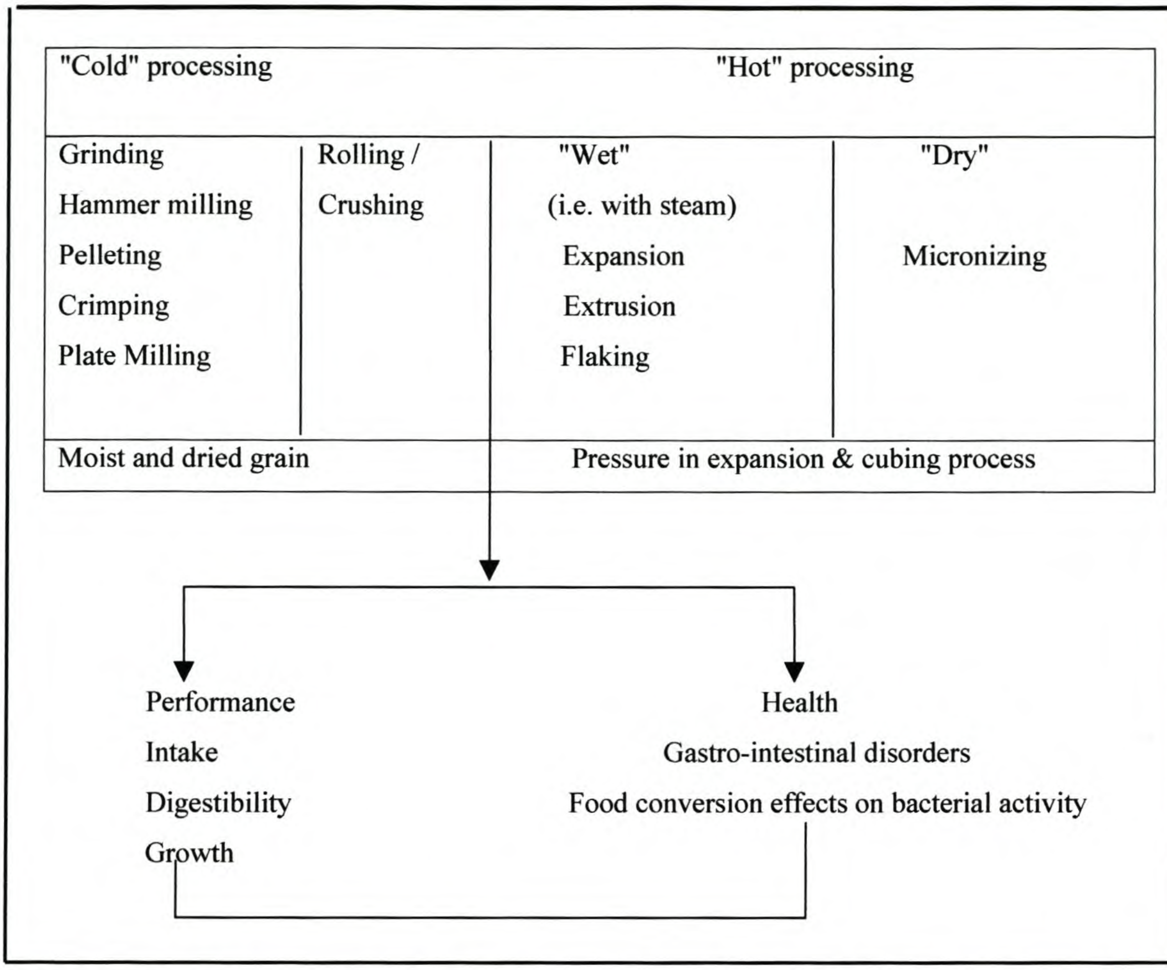

Figure 6 Possible variations in cereal processing and their relationship to pig performance and health (Lawrence, 1978)

The conditions during the processes determine the reactivity of the various chemical entities contained in the material, the type of reactions and the extent to which they will occur. The major parameters characterizing the process are temperature, moisture content, or more correctly water activity (A_W), residence time and shear. The ranges given in Table 3 for each parameter should be seen only as indications. The effect of the process is also influenced by parameters determined by feedstock used, and process conditions like pH and pO_2. The thermo-mechanical processes are often applied in order to achieve certain specific goals as gelatinization of starch, inactivation of endogenous enzymes and trypsin inhibitors, drying or product shaping.

The moisture content during the reactions is often low or intermediate, being unfavorable for most of the reactions to occur (Voragen *et al.*, 1995).

Table 3 Thermo-mechanical treatments (processes) in the animal feed industry (Voragen, 1995).

Process	Temp. (°C)	Moisture content[3]	Resistance time	Shear
Toasting[1]	100-140	low	minutes	-
Drying[1]	>100	medium	minutes	-
Steam flaking	~100	medium	minutes	+
Steam explosion[1]	140-210	medium	seconds	++
Grinding[1,2]	~20	low	seconds	++
Granulation	50-95	medium	minutes	-
Pelleting[2]	60-100	low	seconds	+
Expansion[2]	80-140	medium	seconds	+
Extrusion[2]	90-140	medium	seconds	++

[1] used as pretreatment; [2] used as main process; [3] low< 18%; medium: 18-30%

7.2 "Cold" Processing Methods

7.2.1 Grinding / Rolling

The following grinding/rolling effects on pig performance will be looked at:

- Intake
- Digestibility, growth and efficiency of food conversion ratio
- Gastro-intestinal disorders

7.2.1.1 Effect on intake

According to Lawrence (1978) there is some evidence to suggest that total intake (under *ad-libitum* feeding systems) or level of intake (under restricted feeding regimes) can be affected by the processing of the cereal component of the diet. Under *ad-libitum* feeding systems, there is an indication that dried whole barley is eaten less readily than barley, which has been ground or rolled (Haugse *et al.*, 1966). Coarsely ground maize (Maxwell *et al.*, 1970) and oats (Crampton & Bell, 1946) are eaten less readily than in the cases where, grinding has produced finer particle sizes. For maize, support for these findings is to be found in the work of Clawson (1962). For sorghum the effects of particle size on intake would appear to be less clearly defined. Wheat, perhaps, presents the greatest difficulty in terms of processing. If too finely ground, it tends to become pasty and clogs in the pig's mouth. Cunha (1957) has suggested that wheat grains should be fed whole to overcome this problem whilst Mayrose (1965) implied that coarse grinding or rolling is likely to give the best palatability. There would appear, however, to be no published work that can substantiate these claims under *ad-libitum* feeding systems.

With *ad-libitum* feeding, which is perhaps used to a greater degree than restricted feeding in this country, the importance of cereal processing is reflected in the extent to which the animal copes with the diet as well as the speed in which the diet is eaten. In the case of whole dried barley grains it was observed that the barley was being eaten much more slowly than barley grains in rolled or ground form (Lawrence, 1970a). Furthermore in the case of wheat, it has been observed that with dried grains pigs preferred the rolled to either the coarsely crimped or ground forms (Lawrence, 1967a). With barley, sorghum and maize, however, the results from experiments using these three cereals in either crimped or ground forms, suggests that both is equally acceptable (Lawrence, 1967b).

With moist (undried) grains there is some evidence to suggest that in the case of barley, the voluntary intake of dry matter may be reduced compared with that obtained for conventionally dried grains (Perez & Preston, 1971). In this case, the moist grain was plate-milled before being offered and the experiment did not include a comparison of other forms of processing of moist cereals. In fact, apart from milling, rolling is in some cases an alternative, which can be used for processing moist barley. There is no published evidence to indicate which of these methods is best in terms of palatability. With maize, the work of Young (1970) indicates that, as with barley at high moisture content, as apposed to dried grain, dry matter intakes may be significantly reduced. In terms of different processing methods, Young (1970) found no significant difference between whole, rolled or ground forms of the moist grain fed to pigs.

7.2.1.2 Effect on digestibility, growth and efficiency of food conversion

The pig appears to be a poor masticator of food with a few exceptions (Frape *et al.* 1968, with barley). The evidence available suggests that whole grains are most poorly digested and give an inferior performance, compared with those which have been rolled or ground to varying degrees of fineness (e.g Young, 1970 with maize and Haugse *et al*, 1966 and Lawrence, 1970b with barley). Such inferior results are largely a reflection of a high percentage of cereals grains passing through the digestive tract intact. In terms of smaller differences in particle size, for example coarse grinding compared with more conventional grinding used, it is probable that differences in the same direction, though of smaller magnitude, will be obtained (Clawson, 1962; Lawrence, 1967a and Pickett *et al.* 1969, with maize and Lawrence, 1967b with sorghum and barley).

7.2.1.3 Effect on gastro-intestinal disorders

According to Lawrence (1978), there is considerable evidence available, implying the existence of a casual relationship between cereal particle size and the incidence of ulceration of the oesophgeal region of the stomach. Nearly all of the research on this subject has been conducted in the U.S.A. The available evidence strongly suggests that with maize based diets, the finer the grinding, the greater the frequency of occurrence of ulcers in the oesophgeal region (Mahan *et al.*, 1965; Pickett *et al.*, 1969).

Other work indicates that sorghum, wheat and barley may be implicated in gastro-intestinal disorders to a greater (Riker *et al*., 1966) or lesser (Reese *et al*., 1966) extent. Some types of fibrous materials, for example, oats or oat hulls, may have an ameliorating effect in this context (e.g. Riker *et al*., 1967). Such a protective effect may only be manifested if the oats grain, is too finely ground (Maxwell *et al*., 1966).

It has been postulated that the ulceration may be caused by the texture of the diet influencing pepsin and /or acid secretion (Maxwell *et al*., 1967, 1970; Reimann *et al*., 1968). Many of these studies have reported that the stomach contents of pigs fed the potential ulcerogenic diets are very fluid. Maxwell *et al*. (1970) suggests that the ulceration may be partially a result of the pepsin secreted and that the acid is transported very easily within the stomach, to the relatively unprotected oesophageal region, because of the fluid nature of the digesta. Kidder & Manners (1978) have suggested a further hypothesis on this matter. They reported that the ulceration might be due to duodenal regurgitation. The consequent contact of the regurgitated material with the unprotected oesophageal region of the stomach causes the ulcerative condition. If this is in fact the case, then it would seem reasonable to suppose that the fluid digesta could have a major part to play in affecting both regurgitation itself and the mixing which ensues in the stomach after regurgitation has taken place. Effects on the pH changes at the pyloric /fundic junction of the stomach of different sized barley particles have also been noted by Lawrence (1970a). In this case the coarser particles tended to give more acid conditions. Also in this case the digesta in the stomach was much less fluid than in the case where the finer particles had been fed.

The rate of passage through the gut was also effected by the processing treatment, the coarser particles tending to pass through the gut more quickly than did those of a finer nature (Lawrence 1970a). Thus the coarser particles gave poorer digestibility and growth, had a quicker rate of passage through the gut and induced a more acid environment in the pyloric/fundic region of the stomach. However, the relative large rolled particles, gave atypical results in context, in that they passed through the gut more quickly than the finer ground particles and yet gave similar or slightly better digestibility and growth.

7.3 "Hot" processing methods

Whilst the application of heat and /or pressure to cereals may alter their external physical characteristics, the primary aim of such processes is to modify the structure of the cereal starches through the process of gelatinization. In the natural state starch is insoluble in cold water but on heating the granules swell, rupture and pass into a state of colloidal dispersion.

It is possible that such gelatinization is caused by the heat and moisture weakening the H-bonds through which the starch molecules are orientated in the original structure, this weakening occurring along both concentric and radial lines. The ultimate result of this breakdown of the starch granule structure is an almost formless sac and consequently leaching out of parts of the starch.

The degree of gelatinization achieved will depend on the process used and can be assessed by various methods, which depend on in vitro measures of enzymatic digestion. The ultimate aim of such procedures is to provide the animal with starch, which is more readily available to in vivo enzyme attack, therein providing the animal with a more readily available supply of energy (Lawrence, 1978). The following "hot processing" techniques applied in the industry and the influence on pig performance will be looked at:

- Extrusion
- Expansion
- Pelleting
- Flaking
- Micronizing

7.3.1 Extrusion

The food extruder has been described as a low moisture, continuos-flow reactor capable of processing biopolymers and ingredient mixes at relatively high temperatures under high pressures and shear forces at a relatively low moisture content. Harper (1981), Mercier (1975) and Bjorck *et al*. (1985) reported that extrusion of ground corn increased starch gelatinization, which improved the flavour and palatability for weaning pigs. The extrusion process also improves the utilization of alternative grains (e.g. sorghum and barley) or by-product ingredients (bran or middlings) to a greater extent than corn (Honktrakul *et al*., 1998). Noland *et al*. (1976) found that extrusion processing improved the energy and N digestibility of grain sorghum. Honktrakul *et al*. (1998) (Table 4) compared three treatments with each other: (1) pelleted only, (2) corn that was moist-extruded and then the complete diet pelleted (extruded) and (3) the complete diet was expanded and then pelleted (extruded). Honktrakul *et al*. (1998) also showed an increase in growth performance in segregated early-weaned pigs when only the corn portion of the diet, in both simple and complex nursery formulations was expanded, as compared to expanding complete diets. Honktrakul *et al*. (1998) showed decreased ADG (average daily gain) and FCR (feed conversion ratio) when they expanded the complete diet for segregated early-weaned pigs, but improved ADG and FCR ratio when they extruded only the corn portion of the diet.

Herkelman *et al*. (1990) reported that extrusion of corn did not improve utilization of N or lysine, but extruded corn had a greater digestible energy value than corn for 20 kg pigs. Mercier & Feillet (1975), Bhattacharya & Hanna (1987) and Van der Poel (1989) found that extrusion improved the digestibility of starch in cereal grains. Previous studies have reported no beneficial effect of extrusion processing on the growth performance of pigs fed corn- or grain sorghum-based diets (Noland *et al*., 1976; Herkelman *et al*. 1990; Richert *et al*., 1992). In a trial performed by Sauer *et al*. (1990), it was found that ADG and FCR were significantly better ($P < 0.05$) with the extruded diet than with the pelleted diet.

Table 4 Literature comparisons between Meal, Pelleted and Extruded diets fed to weanling pigs.

Parameter	**Age**	**Raw meal**	**Raw pelleted**	**Extruded pelleted**	**Extruded maize diet Pelleted**	**Extruded maize Re-extruded Pelleted**	**References**
Daily Gain (Kg)	14-21	0.180^{a}	0.200^{b}				Jensen *et al.*, 1965
	-	0.370^{a}	0.360^{a}				Skoch *et al.*, 1983
	21		0.356^{a}	0.386^{b}	0.375^{ab}		Sauer *et al.*, 1990
	12		0.227^{a}	0.222^{a}		0.259^{b}	Honktrakul *et al.*, 1998
	28-35	0.363^{a}	0.413^{b}				Laitat *et al.*, 1999
	23	0.396a	0.423^{b}				Medel *et al.*, 1999
	22	0.210^{a}	0.253^{a}			0.154^{b}	Johnston *et al.*, 1999
Daily feed intake (Kg)	14-21	0.370^{a}	0.320^{a}				Jensen *et al.*, 1965
	-	0.730^{a}	0.740^{a}				Skoch *et al.*, 1983
	21		0.625^{a}	0.648^{b}	0.656^{ab}		Sauer *et al.*, 1990
	12		0.249^{ab}	0.268^{ac}		0.259^{ab}	Honktrakul *et al.*, 1998
	28-35	0.752^{a}	0.729^{b}				Laitat *et al.*, 1999
	23	-	-				Medel *et al.*, 1999
	22	0.236^{a}	0.201^{b}			0.186^{b}	Johnston *et al.*, 1999
FC Ratio (Kg feed) (Kg gain)	14-21	1.63^{a}	1.49^{b}				Jensen *et al.*, 1965
	-	1.97^{a}	2.06^{a}				Skoch *et al.*, 1983
	21		1.75^{a}	1.65^{b}	1.75^{a}		Sauer *et al.*, 1990
	12		0.91^{b}	0.83^{a}		1.00^{b}	Honktrakul *et al.*, 1998
	28-35		1.64^{a}		1.54^{b}		Laitat *et al.*, 1999
	23	1.25^{a}	1.18^{b}				Medel *et al.*, 1999
	22	0.89^{a}	1.26^{a}			0.83^{b}	Johnston *et al.*, 1999

[abc] Values within a row, with the same superscripts are not significantly different .

ADG and FCR ratios were improved by 8% and 6%, respectively (Table 4). However, Johnston *et al.*, (1999) (Table 4) found no significant difference ($P > 0.05$) between meal treatments (raw, pelleted or expanded). They postulated that the lack of growth response was mainly due to the very low performance of the pigs fed the extruded treatments rather than a lack of response by pigs fed the standard pellets.

Pigs fed the extruded treatments had a 39% decrease ($P < 0.001$) in rate of gain, a decrease of 21% in efficiency of gain ($P < 0.05$) when compaired to pigs fed the standard conditioned diet (control). Pigs fed the standard pellet had the highest efficiency, a 41% increase over the meal control. The pelleted extruded diet had the lowest efficiency of gain. This would be in agreement with Traylor *et al.* (1997) who showed that phase 2 nursery pigs fed extruded complex diets tended to have a lower rate of gain. One possible explanation for the variation in response to extrusion processing could be the type of extruder (moist vs. dry, single vs. twin) and (or) extruder conditions (e.g., moisture, temperature, and pressure) (Honktrakul *et a*l. 1998).

Aumaitre (1989) observed that processed maize caused more diarrhea than raw maize diets, and hypothesized that processing might cause higher rates of feed intake during the first days after weaning (21 d), a situation that could induce overloading of the digestive tract and consequently diarrhoea. This hypothesis is in agreement with Medel *et al.* (1999) (Table 4) that observed a lack in performance during the first 2 weeks period of their experiment. Skoch *et al.* (1983) (Table 4) reported a similar growth rate but improved feed efficiency in heavier pigs (15.5 kg) fed extruded maize and wheat middlings-based diets compaired to those fed a control diet. Moreira *et al.* (1994, 1995) compared raw with extruded or precooked maize in different blends. They found no improvements in feed efficiency but a decrease in growth rate when precooked maize was used. On the contrary, Van der Poel *et al.* (1990) reported that processing of maize improved feed efficiency in 21 d old piglets between 14 and 35 d after weaning; but not during the first 14 d or during the whole trial. Medel *et al.* (1999) reported that total tract apparent digestibility of OM (organic matter) was improved with processed maize- and barley-based diets. Aumaitre (1976) also found significant improvements of 3-4% in TTAD (Total tract apparent digestibility) of OM and CP (crude protein) due to processing of barley and maize. In addition Sauer *et al.* (1990) reported differences in TTAD of DM (dry matter), energy and CP when wheat and barley-based diets was extruded or extruded and pelleted. Den Hartog *et al.* (1988) reported that TTAD did not differ between diets containing either 60% extruded or 60% raw maize, whereas the ileal digestibility of dry matter and nitrogen free extract was significantly higher for the extruded maize-based diets. Van der Poel *et al.* (1989) also found differences due to maize processing (extruded, micronized or pressure-cooked) in nitrogen free extract TTAD. In a subsequent study, Van der Poel *et al.* (1990) only found differences in ileal digestibility of organic matter and nitrogen free extracted TTAD.

Vestergaard *et al.* (1990) compared extrusion, steaming, steaming under pressure, roller heating, and micronization of barley in 21 d old weaned piglets. They used a wide range of starch gelatinization and concluded that this trait was not correlated. Table 5 poses potential advantages and disadvantages of extrusion and expansion of young pig diets.

Table 5 Potential advantages and disadvantages of extrusion and expansion of young pig diets (Partridge & Gill, 2001)

Factor	**Advantage**	**Disadvantage**
Protein	Denaturation, reduction of anti-nutritional factors	Protein: Possible destruction of amino acids; Maillard reaction-complexing of reducing sugars and free amino acids.
Starch	Gelatinization, deactivation of naturally occurring alpha amylase inhibitors in raw cereals	Formation of amylose-fatty acid complexes.
Fats and oils	Releasing of encapsulated oil from raw materials. Inactivation of lipolytic enzymes.	Oxidation of lipids and flavour components.
Fiber	Increasing the proportion of soluble non-starch polysaccharides at the expense of insolubles.	Not applicable.
Vitamins	Not applicable.	Potential loss of vitamin activity, especially: A, K, C, B1 and Folic acid.
Minerals	Not applicable.	Possible phytates complexing with Zn, Mg. Destruction of natural phytase.
Feed hygiene	Reducing levels of bacteria, moulds, fungi and aflatoxins.	Not applicable.
Feed additives	Extruded feeds can provide an adsorbent kernel for coatings e.g. oils, flavours, heat stable vitamins, enzymes, probiotics and syrups etc.	Loss of some feed additives if processed in excess. e.g. some enzymes and antibiotics.
Palatability	Improved 'mouth feel', texture	Development of undesirable flavours, reaction products.

7.3.2 Expansion

This process is used to a greater extent in the U.S.A. The process usually involves the softening of ground grain by steam heating and the forcing of this material through a steel tube by an auger so as to increase heat (on average up to 100°C) and pressure until the material is eventually forced through the cone-shaped holes in the expander head. On passing through these holes there is a sudden release of pressure and the escaping steam expands (gelatinizes) the grain. The product is then dried and ground into a meal.

There is little evidence to suggest whether or not such material is preferred to ordinary ground meal when offered on an *ad-libitum* basis. From the point of view of pig performance there is little evidence to suggest that growth and food conversion efficiency are improved (Lawrence, 1978).

According to Lawrence (1978) most experiments report depressions in performance from feeding expanded grain, particularly where the cereal under investigation is maize (Riker *et al.*, 1964,1967; Nuwer *et al.*, 1967). It is possible that such results may be correlated with the fact that expanded grain would appear to be a pre-disposing factor to gastric ulceration. Between the various cereal grains there is evidence that gelatinized maize and sorghum are implicated to a greater extent than gelatinized wheat and barley (Riker *et al.*, 1967). However, it would appear that the resultant particle size of the expanded material might, ultimately, be of the greatest importance (Nuwer *et al.*, 1967). Nuwer *et al.* (1964) postulated that the ulcerogenic properties of expanded grain may be due to the excessive heat of the expansion process altering the chemical make-up of the endosperm and/or producing toxic substances within it. Nuwer *et al.* (1967) has strongly suggested that the ulcerogenic activity is in fact to be found in the grain endosperm and bran and not in the germ.

O'Doherty *et al.* (2000) fed growing-finishing pigs the following diets: raw pellets, expander processed pellets, raw meal and expander processed meal. Pelleting of diets increased the organic matter ($P < 0.05$), protein ($P < 0.01$), energy ($P < 0.01$) and ash ($P < 0.01$) digestibility as well as the digestible energy (DE) content of the diets ($P < 0.01$). Expander processing had no effect on the organic matter, protein and energy digestibility of the diets. Expansion had no effect on the DE content of the pelleted diets. However, expansion increased the DE content of the meal diet ($P < 0.05$). Both pelleting and expansion of the diets decreased growth rate during the grower and finisher period. Pelleting of the diets improved FCR during the grower and finisher period ($P < 0.05$), while expander processing had no effect on FCR.

Peisker (1994) reported that the expansion of complete diets for 35 d old nursery pigs containing wheat bran improved the average daily gain of the pigs by 10% while expanding only the wheat portion of the diet resulted in an improvement of 24%. Traylor *et al.* (1997) suggested that benefits of expander technology shown in simple diets might not be seen in complex diets for the same age of pig. One of the benefits of expander technology is an increase in pellet quality (Traylor *et al.*, 1997).

7.3.3 Pelleting

In the pelleting process the cereal (or complete diet) is subjected to pressure being forced through the die of the pelleting machine. The friction of this process causes a rise in temperature and the cereal is, therefore, exposed to a form of dry heat. In almost all pelleting processes the cereal is passed through a steam chamber before it is forced through the die. In such cases the cereal is therefore subjected to " wet" as well as "dry" heat (Lawrence, 1978).

Since its introduction in the 1930's pelleting has become an important process in the feed industry. Pelleting diets can affect animal performance in a variety of ways. The following is a partial list of pelleting attributes that might contribute to improved performance (Behnke, 1994):

1) decreased feed wastage ;
2) reduced selective feeding;
3) decreased ingredient segregation;
4) less time and energy expended for prehension;
5) destruction of pathogenic organisms;
6) thermal modification of starch and protein;
7) improved palatability.

In addition, pelleting allows the use of a wider variety of ingredients without excessive changes in the physical properties of the diet. This often will allow diet costs to be reduced with little or no effect on performance (Behnke, 1996).

Lewis et al. (1955) reported a definite preference by early-weaned pigs for pellets over meal when given a choice. Jensen *et al*. (1955) showed that pelleting affected choice of diets when creep-fed pigs had access to several different diets. Braude *et al*. (1960) reported that pelleting resulted in increased consumption of creep feed. Hanke *et al*. (1972) obtained an improvement ($P < 0.05$) in feed efficiency by pelleting a corn soybean meal diet.

Baird (1973) showed that pelleting of a corn-soybean meal diet improved ADG and feed conversion (7.8%) while reducing feed intake, but this result differs from the findings of Skoch *et al*. (1983) (Table 6). Skoch *et al*. (1983) found that pelleting did not have any significant effect on ADG, ADFI or FCR Jensen & Becker (1965), Laitat *et al*. (1999) and Johnson *et al*. (1999) observed a significant ($P < 0.05$) decrease in ADFI but a non-significant ($P < 0.05$) increase in ADG (Table 6).

FCR Jensen & Becker (1965) concluded that enzymatic digestion of their samples revealed that pelleting rendered the starch fraction of corn more susceptible to enzyme action. It is suggested by Wondra *et al*. (1995) that the forces in the pelleting process that gelatinize starch could also disrupt the structure of the particles, making them more accessible for digestive enzymes, thus explaining the improved nutrient digestibility. Jensen & Becker (1965) (Table 6) reported that early-weaned pigs fed pelleted diets, whole or in part gained 13.8% more per unit of feed than did pigs fed mash diets. Feed efficiency was increased by 10.3% over that with the mash treatment when the grain portion of the diet was pelleted and reground before being mixed in the diet (Jensen & Becker, 1965).

Table 6 Comparisons between meal and pelleted diets fed to weanling pigs.

Parameter	Age of piglets (days)	Meal	Pellet	Reference
Daily gain (kg)	14-21	0.18^{a}	0.20^{b}	Jensen & Bekker, 1965 ($P < 0.01$)
	-	0.370^{a}	0.360^{b}	Skoch *et al*., 1983 ($P < 0.05$)
	28-35	0.363^{a}	0.413^{b}	Laitat *et al*., 1999 ($P < 0.05$)
Daily feed intake (kg)	14-21	0.370^{a}	0.320^{a}	Jensen & Bekker, 1965 ($P < 0.01$)
	-	0.730^{a}	0.740^{a}	Skoch *et al*., 1983 ($P < 0.05$)
	28-35	0.752^{a}	0.729^{b}	Laitat *et al*., 1999 ($P < 0.05$)
Feed conversion (kg feed)/ (kg gain)	14-21	1.63^{a}	1.49^{b}	Jensen & Bekker, 1965 ($P < 0.01$)
	-	1.97^{a}	2.06^{a}	Skoch *et al*., 1983 ($P <0.05$)
	28-35	1.64^{a}	1.54^{b}	Laitat *et al*., 1999 ($P < 0.05$)

^{ab} Value within a row, with the same superscripts are not significantly different.

Laitat *et al*. (1999) (Table 6) found that piglets fed pelleted diets rather than meal had a significant greater ADG and a significantly lower feed conversion ratio. Skoch *et al*. (1983) (Table 6) observed no significant improvement in ADG, feed intake or FCR when they pelleted the diets of weanling pigs. The protein digestibility with a pelleted diet was, however, significantly lower.

In growing pigs, Conrad (1959) summarized the results from 10 experiments in which barley was compared in a meal ration and in a pelleted ration. Pelleting rations containing barley increased gains 14% and resulted in a 15% feed saving. Gorril *et al*. (1960a,b,c) and Seerley *et al*. (1962a,b) have shown that pelleting improves utilization of certain diets by growing-finishing swine. Comparisons of meal and pellets for rations containing corn have not provided differences quite as great as those obtained for pelleting of rations containing barley. Becker (1966) showed approximately a 10% feed-efficiency advantage for pelleting maize-based swine rations, for both the growing and finishing phase.

Jensen (1966) summarized the effects of pelleting for swine under a wide variety of conditions. A summary of 30 comparisons covering 12 years (1953-1964) showed that on the average, pigs consuming pelleted feed gained weight 6% faster and required 5% less feed per kg of gain. According to Hanke *et al*. (1972), Harris *et al*. (1979), Tribble *et al*. (1979), Skoch *et al*. (1983), Walker *et al*. (1989) and Wondra *et al*., (1994), pelleting grower-finishing diets result in an increase of 3-5% in ADG and 7-10% in FCR.

7.3.4 Flaking

The flaking process may vary according to a number of factors but generally it is a process which has been applied most frequently to maize grain. In the U.S.A., the process most frequently used for flaking cereals (particularly maize) is that in which the cereal is first cracked and then has its moisture content raised to approximately 20% by soaking in water (over a period of 1-2 d) before being cooked in a steam chamber, then passing through heavy flaking rollers and dried back to approximately 14% moisture. One alternative to this is the raising of the moisture content and cooking of the grain simultaneously in a steam chamber, then the material is treated in a similar manner to that for the process described above. In the case of maize a further modification in the flaking process can be done by removing the germ and only subjecting the germless fraction to the flaking procedure. The flaking process is one which is relatively expensive to operate and largely because of this the cost of flaked cereals is usually appreciably higher than that of cereals in a raw or ground form. Usually flaked cereals are included in pig diets at fairly low levels, often to keep the diet "open" and to give it some texture and from the point of view of nutritive value their contribution is therefore fairly small (Lawrence, 1978).

7.3.5 Micronizing

Micronizing is a new method, which is still mainly used on an experimental basis. In this process a gas/ air mixture is used to heat a china clay ceramic, to a predetermined temperature. This causes the surface of the ceramic to produce a luminous red glow known as "Bright Line Spectra" and this radiates the electromagnetic spectrum in the infrared invisible band. The material to be processed is passed beneath the ceramics and absorbs radiation produced between the wavelengths 2 and 6 microns. It is thought that the selective absorption of the infrared rays by the material causes it to become irradiated. This in turn causes the molecules of the material to vibrate in accordance with the resonance of their own wavelength and frequency, resulting in rapid internal heating and a rise in vapour pressure. The rapid heat increase and rise in water vapour pressure affects the starch and proteins in the grains causing them to swell, fracture and gelatinize. After this the grains are rolled (flaked) and cooled. This process has the advantage of being very quick and continuous. For example the dwell time for irradiation need not be any longer than 50 seconds in some cases. Many factors will, however, affect this time and this is only given to indicate the speed of throughput, which can be achieved under certain conditions.

8 Weaner piglet feeding in South-Africa

Since the 1990's pig production in South-Africa have followed the global trend of higher production efficiency. Farmers increased their sow herds and started to use A.I., all-in-all-out systems and decreased the weaning age in order to increase production efficiency. There are a number of feed-mills and farmers that started to use extruded/expanded grains in early-weaned piglet feeding. Soya-heat-treatment (extrusion/expansion) is a common practice to decrease the anti-nutritional factors encapsulated in the soybean. But the use of heat treated maize ("pop-maize") in early-weaned piglets is a new concept. A number of feed-mills and farmers have also investigated and invested large amounts of time and money in the use of extruders/expanders. However, no literature could be found where meal, pelleted and extruded diets have been compared to the extent that is described in this thesis. Without doubt, efforts will continue to refine feed processing techniques to reduce the cost of feed and to increase the value of feed for a target animal. The possibilities for improvements in feed are endless; however the cost of each innovation must be carefully weighed against demonstrated improvements in animal performance. Therefore, the objective of this experiment is to investigate the effects of various processing conditions (heat treatment and feed form) of maize-based diets on weaned piglet's performance and to determine if the additional processing results in additional financial gain.

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Chapter 2

The influence of feed processing on piglet weaner performance

The influence of feed processing on piglet weaner performance

Abstract

The effects of processing of the carbohydrate source and the feed on growth performance of commercial Landrace x Large White piglets (n=480) weaned at 28 ± 2 d were investigated. Two processing combinations of the carbohydrate source were used with 3 processing conditions of the diet in a 2 x 3 factorial design. The pigs were blocked by weight (7.196 ± 2.03 kg BW) and then allotted randomly to 1 of 6 dietary treatments. Ten pens of 8 piglets each were fed with each dietary treatment. The two main processing conditions of the carbohydrate source were raw or extruded maize and the 3 processing conditions of the diet was meal or pelleted or extruded. No carbohydrate processing x diet processing interactions were observed ($P > 0.05$) for ADG, ADFI or FCR. In this experiment, extrusion of the maize led to an significant decrease in FCR efficiency ($P < 0.05$) (1.57 vs. 1.42) when compared to a raw maize diet. Pelleting a diet had no significant effect ($P > 0.05$) on ADG but tended to decrease ADFI ($P < 0.07$) and significantly improve FCR efficiency (1.49 vs. 1.66) when compared to a meal diet. Extruding the whole diet did not have any significant ($P > 0.05$) effect on ADG but tended to decrease ADFI ($P < 0.07$) and gave an significant improvement in FCR when compared to a meal diet (1.34 vs. 1.66). This processing technique also gave a significant improvement ($P < 0.01$) in FCR when compared to a pelleted diet (1.34 vs. 1.49).

Key Words: Weaned piglets, Raw, Extruded, Meal, Pelleting

Introduction

Intensification of pig farming has led to the shortening of the suckling period of piglets from 5-6 weeks to 3-4 weeks of age in order to maximize annual sow productivity (Partanen & Mroz, 1999) and decrease the risk of piglet disease infestation through the sow (Alexander *et al.*, 1980). The separation from the sow changes the main energy source for the piglet from the milk fat and lactose of the sow's milk to plant carbohydrates (mainly starch) in the postweaning diet (Partridge & Gill, 1993). However, at these early ages the digestive system is immature (1986, Aumaitre *et al.*, 1995; Jensen *et al.*, 1997) and the piglets cannot utilize the plant carbohydrates which leads to a post-weaning lag period. The fact that starch is stored in plants in a crystalline complex structure might also impair its digestion in piglets (Cunningham, 1959). The ability of young pigs to adapt to, and adequately digest grain-soybean meal starter diets after weaning, is necessary for normal growth in the nursery and during the subsequent growing-finishing period. The ability, however, is questionable during the first 3 to 10 days (d) post-weaning (Owsley *et al*., 1986a). Hudman *et al*. (1957) reported an increase in intestinal proteolytic activity from birth to weaning. However, Hartman *et al*. (1961) and Corring *et al*. (1978) reported an increase in proteolytic activity only starting at 3 weeks of age. Shields *et al*. (1980) and Efrid *et al*. (1982) reported that amylase production of the pancreas progressively increases until 10 weeks of age. The young pig should, therefore, be able to digest both starch and vegetable protein after weaning at 28 d. Performance (Meade *et al*., 1965) and apparent nutrient digestibility (Owsley *et al*., 1986b) measured during the week after weaning, however, demonstrated the pig's inability to adequately digest diets containing starch and vegetable protein during this period.

Starch is digested to dextrins by the alpha-amylases present in the upper gastro-intestinal tract, which are further hydrolyzed by brush border enzymes prior to absorption. Thus starch is potentially totally digestible in the small intestine (Graham, 1991). Approximately 60-70% of the energy ingested by the weaned piglet is derived from carbohydrates, so processing of this portion of the diet is of major significance to the young animal's performance. Starch, the predominant carbohydrate in the diet is derived mainly from the cereal components and consists ordinarily of granular glucose units, amylose and amylopectin (Armstrong, 1978).

The extrusion process causes expansion and gelatinization of the starch granules with an opening up of these complex molecular chains. Given optimum process conditions, extrusion has the potential to gelatinize high levels of starch in most feed raw materials (85-100%, Bjork & Asp, 1982). The extruded starch has increased solubility and decreased viscosity, favoring availability to amylase and rapid absorption of resultant glucose *in vivo*.

According to Patridge & Gill (2001) the implicit assumption is usually made that gelatinization of dietary starches in diets for young pigs is a desirable feature in view of their immature digestive physiology and enzyme complement at weaning (Kidder & Manners, 1978). However, reports from scientific literature on this aspect, tend to be equivocal (Aumaitre, 1976; Skoch *et al*., 1983; Van der Poel *et al*. 1989, Vestergaard *et al*. 1990; Van der Poel *et al*, 1990, Sauer *et al*. 1990). Factors such as different weaning ages and weights of pigs used, disease challenge, different processing conditions (both in terms of raw material grinding and subsequent heat treatment), digestibility measurements (e.g. whole tract rather than ileal) and the influence of other dietary raw materials all interact and confound the establishment of a consensus view.

Cereals are ground prior to mixing to decrease segregation and mixing problems, to facilitate further processes such as extrusion or pelleting and to increase their surface area for improved rate of digestion. Extensive grinding requires more energy; however, even small improvements in feed efficiency will often justify the added cost (Ensminger, 1985). Grinding and pelleting are the most common food processing methods used for pigs. However, pelleting of complete balanced feed is no longer such an economical proposition due to rising energy and equipment costs (Skoch et al., 1983); therefore this cost has to be outweighed by an increased production efficiency (Krider & Carrol, 1971).

Hanke *et al.* (1972) and Baird (1973) showed that pelleting of a corn-soybean meal diet improved ADG (average daily gain) and feed conversion efficiency significantly. Jensen & Becker (1965); Laitat *et al.* (1999); Johnston et al. (1999) observed a significant decrease in ADFI (average daily feed intake) but a non-significant increase in ADG. This differs from the findings of Skoch *et al.* (1983) who found that pelleting did not have any significant effect on ADG, ADFI or FCR (feed conversion ratio). Honktrakul *et al.* (1998) showed an increase in growth performance in segregated early-weaned pigs when only the corn portion of the diet was extruded. They further showed decreased ADG and FCR when they expanded the complete diet. Medel *et al.* (1999) found larger rates of gelatinization in extruded than in micronized cereals and concluded that heat processing of maize improves daily gain and feed efficiency of early weaned pigs and recommended the use of processed cereals in piglet weaner diets.

However, Aumaitre (1976) observed that processed maize caused more diarrhea incidences than raw maize diets, and hypothesized that processing might cause higher rates of feed intake during the first days after weaning (21d). This is a situation that could induce overloading of the digestive tract and consequently diarrhea. Moreira *et al.* (1994, 1995) found no improvements in feed efficiency but a decrease in growth rate when precooked maize was fed to weanling pigs (28 d).

According to Lawrence (1978), most trials report depressions in performance from feeding expanded grain, particularly where the cereal under investigation is maize (e.g. Riker *et al.*, 1964; Riker *et al*, 1967; Nuwer *et al.*, 1967). It is possible that such results may be correlated with the fact that expanded grain would appear to be a predisposing factor to gastric ulceration. *Nuwer et al.* (1964) postulated that the ulcerogenic properties of expanded grain might be due to the excessive heat of the expansion process altering the chemical make-up of the endosperm and/or producing toxic substances within it. O'Doherty, *et al*. (2000) found that pelleting of growing-finishing pigs, increased organic matter, protein, energy and ash digestibility as well as the digestible energy (DE) content of the diets. However, expander processing had no effect on the organic matter, protein and energy digestibility of the diets. Expansion also had no effect on the DE content of the pelleted diets, although, expansion increased the DE content of the meal diet. Both pelleting and expansion of the diets decreased growth rate during the grower and finisher period.

As noted, the effect of heat treatment of carbohydrates and diet feed form on weaner performance is highly contradictory. Therefore, the objective of this experiment was to investigate the effects of various processing conditions (heat treatment and feed form) of maize-based diets on weaned piglet's performance and to try elucidate this issue.

Materials and methods

Commercial Landrace x Large White piglets (n=480) weaned at 28 ± 2 d (mean weight = 7.196 ± 2.03 kg) were used to study the effects of processing of the carbohydrate source and the feed of the diet on growth performance. The pigs were blocked by weight and allotted randomly to one of six dietary treatments. Ten pens of eight pigs per pen were fed each dietary treatment. Treatments were arranged in a 2 X 3 factorial design with the main effects being processing of the carbohydrate source and feed. (Table 1).

Table 1: Dietary treatments fed to the weaner piglets.

Treatments	**1**	**2**	**3**	**4**	**5**	**6**
Maize	Raw	Raw	Raw	Extruded	Extruded	Extruded
Diet	Meal	Pelleted	Extruded	Meal	Pelleted	Extruded

Pigs were housed in an environmentally controlled nursery with 1.2 x 2.4 m pens and were allowed ad libitum access to water and feed. Temperature was maintained at 21 °C. Pigs and feed were weighed on days 28, 42, and 62 to calculate ADG (Average daily gain), ADFI (Average daily feed intake), and FCR ratio (Feed conversion ratio) (kg feed/kg gain). The trial was divided into two phases. Phase 1 (Table 2) diets contained 50.30% maize as a carbohydrate source and phase 2 (28-43 d) diets contained 44.01% maize as a carbohydrate source (42-62 d). Diets were formulated to contain 1.389% (phase 1) and 1.092% (phase 2) available lysine (NRC, 1994). The lysine was calculated from the NRC (NRC, 1994) values for the various feedstuffs using the chemically analyzed values as basis. All other amino acids were above the suggested minimum levels based on ratios relative to lysine (NRC, 1994). The amounts of synthetic lysine, methionine, limestone and monocalcium phosphate (21% P) added were adjusted to meet or exceed intended amino acid levels and NRC (1994) recommendations for Ca and P.

In this study, the carbohydrate source (maize) was extruded through a Multinetz SP 2000 single-screw extruder (Multinetz, NZ) and ground and mixed into the diets, which were then pelleted in a pellet mill (Simon-Barron California Hyflo 67) equipped with a 2.4-mm die or extruded. The extruder conditions were as follows: 138 °C barrel jacket temperature at the 3[rd] head, 21.09 kg/cm^2 of internal pressure at the die, 2.27 kg/min production rate, and approximately 100 °C exit temperature.

Due to differences in weaning weight, the latter was used in the statistical analysis as a co-variant and all other data (ADG, ADFI and FCR) were adjusted according. Differences between treatment means during the production trial were analyzed by two-way analysis of variance with processing of the carbohydrate source and processing of the diet as main factors (Statgraphics, 1991). All statistical procedures are as described by Snedecor and Cochran (1980).

Table 2: Composition of experimental diets (A-G) (as-fed basis) fed to the weaner pigs (± 28 d)

Ingredients (%)	**Phase 1 (28-42 d)[a]**	**Phase 2(42-62 d)[a]**
Maize	50.30	44.10
Whey powder	5.80	2.00
Wheat bran	0.00	15.00
Soybean 47	11.78	21.78
Soybean full fat	12.00	8.00
Fish meal 65	5.00	5.00
Oil-Sunflower	1.00	1.91
DL Methionine	0.23	1.90
Limestone	1.55	0.00
L-Lysine HCl	0.49	0.00
Monocalsium phosphate	0.65	0.00
Salt	0.03	0.05
Threonine synthetic	0.16	0.00
Ecolac 10 [b]	10.00	0.00
Vitacid [c]	1.00	0.00
Vit + min premix [d]	0.00	0.25
Antioxidant [e]	0.75	0.75

	Phase 1 (28-42 d)[a]	Phase 2(42-62 d)[a]
Nutrient Composition (%)		
Dry Matter	89.26	88.95
Fat	7.11	6.58
Crude fiber	2.58	4.13
ME (MJ/kg)	13.97	13.80
Protein	17.25	23.01
Lysine	1.389	1.092
Methionine	0.608	0.365
Ca (Total)	1.200	1.000
P (Avail.)	0.361	0.276
Na	0.180	0.115
Cl	0.260	0.180

[a] Diets were either fed as meal (control), pellet, extruded, meal (maize portion extruded), pellet (maize portion extruded) or extruded (maize portion extruded).

[b]Ecolac 10 provided 19.36 % CP, 6.63 % Fiber, 2.58% Cellulose, 1.5% Lysine, 0.57 % Methionine, 0.98 % Threonine, 0.25 % Tryptophane, 0.80 % Ca and 0.70% P.

[c]Vitacid provided a combination of propionic and formic acid. [i] Premix provided the following to one metric ton of complete diet: 11.025 IU vitamin A, 1.103 IU vitamin D3, 44 IU vitamin E, 4.4 mg meadione (medadione sodium bisulfite), 8.3 mg riboflavin, 29 mg d-pantothenic acid, 50 mg niacin and 166 mg choline chloride.

[d]provided the following (mg/kg of complete diet): 12 mg Mn, 165 mg Zn, 16 mg Cu, 0.3 mg I, and 0.3 Se.

[e] Bioret 20 was added at 750 g/ton.

Results and discussion

The effect of processing the carbohydrate source on the production data of piglets are presented in Table 3, (Phase 1) and Table 4 (Phase 2). The effect of processing of the diet on the production data of piglets are presented in Table 5, (Phase 1) and Table 6 (Phase 2). These values are the mean of ten replicates consisting of eight piglets per replicate.

In this investigation from weaning (28 d) to 42 d (Table 3), there was no significant difference in ADG or ADFI ($P < 0.05$) between raw maize diet or an extruded maize diet. However, extrusion of the maize led to an significant decrease in FCR efficiency ($P < 0.05$) (1.57 vs. 1.42) when compared to a raw maize diet. These results agree with the findings of Lindemann *et al.* (1986); Herkelman *et al.* (1990); Noland *et al.* (1976); Moreira *et al.* (1994, 1995) and Richert *et al.* (1992) who found no beneficial effect of extrusion processing on the growth performance or FCR of pigs fed corn- or grain sorghum-based diets.

Table 3 The effect of carbohydrate processing on production data of piglets during phase 1.

Maize treatment	**Weaning weight (±28 d)**	**Weaning weight* (±28 d)**	**Finishing weight* (42 d)**	**ADG (kg)**	**ADFI (kg)**	**FCR (kg feed)/ (kg gain)**
Raw	6.93[a]	7.19 [a]	10.48 a	0.22 [a]	0.30 [a]	1.42 [a]
Extruded	7.62[b]	7.19 [a]	9.96 b	0.19 [a]	0.31[a]	1.57 [b]
SE	0.16	2.03	0.16	0.10	0.01	0.44
P	0.001	0.99	0.42	0.11	0.90	0.03

* Weight adjusted corrected differences in initial weaning weight

[abc] Values in the same column with different superscripts differ (P< 0.05).

Table 4 The effect of carbohydrate processing on production data of piglets during phase 2.

Maize treatment	**Starting weight* (42 d)**	**Finishing weight* (62 d)**	**ADG (kg)**	**ADFI (kg)**	**FCR (kg feed)/ (kg gain)**
Raw	10.03 [a]	17.08	0.34 [a]	0.57 [a]	1.71 [a]
Extruded	10.41 [a]	17.79	0.38 [a]	0.67 [b]	1.78 [a]
SE	0.25	0.31	0.02	0.02	0.05
P	0.30	0.13	0.09	0.01	0.30

* Weight adjusted corrected differences in initial weaning weight

[ab] Values in the same column with different superscripts differ (P< 0.05).

Lindemann *et al.* (1986) found that treatment of maize by extrusion had no effect on production traits of piglets weaned at 36 d. According to Lindemann *et al.* (1986), the piglets have sufficient pancreatic and gastric enzyme activity to digest raw starch one week after weaning. Den Hartog *et al.* (1988) concluded that only very young piglets or when nutritional diarrhea exists, the use of treated maize may have advantages.

From 42 d to 62 d (Table 4), there was no significant difference (P > 0.05) in ADG, ADFI or FCR when a raw maize diet is compared with extruded maize diet. These results agree with previous studies that have reported no beneficial effect of extrusion processing on the growth performance of pigs fed corn- or grain sorghum-based diets (Noland *et al.*, 1976; Herkelman *et al.* 1990; Richert *et al.*, 1992). According to Lawrence (1978), most trials report depressions in performance from feeding expanded grain, particularly where the cereal under investigation is maize (e.g. Riker *et al.*, 1964; Riker *et al*, 1967; Nuwer *et al.*, 1967). It is possible that such results may be correlated with the fact that extruded grain would appear to be a predisposing factor to gastric ulceration. Nuwer *et al.* (1964) postulated that the ulcerogenic properties of expanded grain might be due to the excessive heat of the expansion process altering the chemical make-up of the endosperm and/or producing toxic substances within it.

Table 5 The effect of feed form on production data of piglets during phase 1.

Diet feed form	Weaning weight (±28 d)	Weaning weight* (±28 d)	Finishing weight* (42 d)	ADG (kg)	ADFI (kg)	FCR (kg feed)/ (kg gain)
Meal	7.72 [a]	7.19 [a]	10.04 [a]	0.21 [a]	0.33 [a]	1.66 [a]
Pellet	7.10 [b]	7.19 [a]	10.13 [a]	0.19 [a]	0.29 [a]	1.49 [b]
Extruded	6.99 [b]	7.19 [a]	10.60 [a]	0.23 [a]	0.29 [a]	1.34 [c]
SE	0.20	2.03	0.19	0.13	0.01	0.05
P	0.04	0.99	0.06	0.11	0.07	0.01

* Weight adjusted corrected differences in initial weaning weight

[abc] Values in the same column with different superscripts differ ($P < 0.05$).

From weaning (28 d) to 42 d (Table 5), pelleting a diet had no significant effect ($P > 0.05$) on ADG but tended to decrease ADFI ($P < 0.07$) and significantly improve FCR efficiency (1.49 vs. 1.66) when compared to a meal diet. These results are in agreement with Jensen & Becker (1965), Laitat *et al.* (1999) and Johnson *et al.* (1999). Baird (1973) showed that pelleting of a corn-soybean meal diet improved FCR while reducing feed intake. However, Skoch *et al.* (1983), found that pelleting did not have any significant effect on ADG, ADFI or FCR. Jensen & Becker (1965) concluded that enzymatic digestion of their samples revealed that pelleting rendered the starch fraction of corn more susceptible to enzyme action. Hanke *et al.* (1972), Baird (1973) and Wondra *et al.* (1995) attributed the improved performance with pelleting to an increase in nutrient digestibility and decreased feed wastage.

Extruding the whole diet did not have any significant ($P > 0.05$) effect on ADG (Table 5), but tended to decrease ADFI ($P < 0.07$) and gave an significant improvement in FCR when compared to a meal diet (1.34 vs. 1.66). This processing technique also gave a significant improvement ($P < 0.01$) in FCR when compared to a pelleted diet (1.34 vs. 1.49).

Table 6 The effect of feed form on production data of piglets during phase 2.

Diet feed form	Starting weight* (42 d)	Finishing weight* (62 d)	ADG (kg)	ADFI (kg)	FCR (kg feed)/ (kg gain)
Meal	9.97 [a]	17.63 [ab]	0.37 [ab]	0.64 [a]	1.75 [ab]
Pellet	10.45 [a]	18.11 [b]	0.39 [b]	0.63 [a]	1.61 [b]
Extruded	10.24 [a]	16.57 [c]	0.32 [c]	0.59 [a]	1.88 [a]
SE	0.31	0.38	0.02	0.02	0.05
P	0.56	0.03	0.03	0.44	0.01

* Weight adjusted corrected differences in initial weaning weight

[abc] Values in the same column with different superscripts differ ($P< 0.05$).

These results agree with the results of Sauer *et al*. (1990) and Johnson *et al*. (1999 a). Johnson *et al*. (1999a) fed an extruded diet to pigs weaned at 22 d (6.4 kg) and compared the results with those of pigs fed a pelleted diet. A significant reduction in ADFI and a decreased ADG ($P < 0.05$) was observed with the extruded diet. Sauer *et al*. (1990) also fed extruded diets to pigs weaned at 21 d (5.65 kg) and compared the results to pigs fed the same raw pelleted diet. Extrusion of the whole diet, as compared to pelleting the whole diet, improved ($P < 0.05$) ADG by 8% and FCR by 6%. One could postulate that the improvements in performance could be explained by that the extrusion process improves the palatability of the diet and provides a higher quality pellet (Patridge & Gill, 2001).

From 42 d to 62 d (Table 6), extruding the whole diet resulted in a significant ($P <0.03$) decrease in ADG (0.32 vs. 0.39) and FCR efficiency (1.88 vs. 1.61) when compared to a pelleted diet. These results agree with the results of Lawrence (1973) with 32 d old and Den Hartog *et al*. (1988) with 42 d old pigs as well as Johnson *et al*. (1999) who observed a reduction of 4% in ADG, 8% in ADFI and 4% in FCR with the whole extruded diet compared to a pelleted diet. These results may be explained by the chemical change called retrogradation of starch (Hoseney, 1986). The retrogradation of starch (formation of beta-amylose and crystalline amylopectin) may decrease the ability of enzymes (amylases) to break down the linkages of starch and convert it into more soluble carbohydrates, including glucose. Therefore, although gelatinization of starch will increase the digestibility of carbohydrates, retrogradation will decrease digestibility of starch in the small intestine. One might also postulate that the extrusion process might damage valuable vitamins and minerals (Patridge & Gill, 2001). Pipa and Frank (1989) reported the loss of vitamin A, vitamin E, and thiamin in pig feed that were expanded at 120 °C. Therefore, further research is warranted to evaluate extruder feed processing in association with weaner piglet diets.

Conclusion

Extrusion of the maize leads to depressions in performance and a reduction of 9.55% in FCR efficiency. It would thus appear that the excessive heat during the extrusion process alters the chemical make-up of the endosperm and/or produces toxic substances within it. Pelleting a diet improves FCR by 10% when compared to a meal diet. It could be postulated that the improvement in performance could attribute to an increase in nutrient digestibility and decreased feed wastage. Extrusion of a diet improves FCR by 19% when compared to meal diet. Therefore, extrusion of the diet improves FCR by 9% when compared to a pelleted diet. It is thus recommended that feedmills or farmers use pelleting of piglet weaner diets and compare the improvement in performance due to extrusion up against the additional cost of extrusion.

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Chapter 3

The effect of pig feed processing conditions on pig metabolism parameters

The effect of pig feed processing conditions on pig metabolism and production parameters

Abstract

The effects of processing of the carbohydrate source and the diet on certain metabolism and production parameters of commercial Landrace x Large White pigs (n=24) were investigated. Two processing combinations of the carbohydrate source were used with 3 processing combinations in a 2 x 3 factorial design. Six diets were formulated on an iso-nutrient basis (14.48 MJ/kg metabolizable energy (ME), 23.01 crude protein (CP), 1.092% lysine, 0.742% methionine and cystine and 0.271% tryptophan on a DM basis). The pigs were blocked by weight (26.02 ± 0.25 kg BW) and then allotted randomly to 1 of 6 dietary treatments. The carbohydrate source was raw or extruded maize and the diets was meal or pelleted or extruded. No carbohydrate processing x diet feed form interactions were observed ($P > 0.05$) for dry matter intake (DMI), dry matter digestible energy (DE), Nitrogen (N) or dry matter intake (DMI). In a metabolism and nitrogen (N) balance study, apparent N digestibility, digestible energy and metabolizable energy contents were found not to be significantly ($P > 0.05$) influenced by carbohydrate or diet processing.

Key Words: Pigs, Carbohydrate, Raw, Extruded, Meal, Pelleting, Extruded

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Introduction

Grain are normally ground prior to mixing to decrease segregation and mixing problems, further processes such as extrusion or pelleting are used to increase its surface area for improved rate of digestion. Extensive grinding requires more energy; however, even small improvements in feed efficiency will often justify the added cost (Ensminger, 1985). Grinding and pelleting are the most common food processing methods used for pigs. However, pelleting of formula foods is no longer such an economical proposition due to rising energy and equipment costs (Skoch *et al.*, 1983), therefore this cost has to be outweighed by an increased production efficiency (Krider & Carrol, 1971). Starch is the main component of cereal grains and is usually the primary energy source for pigs and poultry. Starch is digested by the alpha-amylases to dextrins present in the upper gastro-intestinal tract, which are further hydrolyzed by brush border enzymes prior to absorption.

Starch is potentially totally digestible in the small intestine (Graham, 1991). Feed manufacturing can adopt several measures, including physical treatments such as milling or pelleting and other techniques, such as enzyme treatment, to disrupt cell structure (Graham *et al.*, 1989). This induces a change in the crystalline structure or degree of gelatinization (Moreira, 1995), thereby facilitating its enzymatic degradation (Holm & Björck, 1988; Osman *et al.*, 1990) and can improve ileal starch digestibility (Graham et al., 1989). The modification of starch granules depends on the treatment (Holm & Björck, 1988) and the starch source (Farber & Gallant, 1976; Faulks & Bailey, 1990).

The forces in the pelleting process that gelatinize starch disrupt the structure of maize particles, making them more accessible for digestive enzymes, thus explaining the improved DM and N digestibility's observed (Wondra *et al.*, 1995). Hanke *et al.* (1972), Baird (1973) and Wondra *et al.* (1995) attributed the improved performance with pelleting to increased nutrient digestibility and decreased feed wastage, making the feed more palatable. However, improved palatability would be inconsistent with the decreased average daily feed intake (ADFI) observed for pigs fed pelleted diets. Thus, researchers have tended to attribute improvements in performance to decreased feed wastage and increased nutrient digestibility with pelleted diets (Wondra *et al.*, 1995). It also appears that the nutritional effects of pelleting are variable and depend on the age of the animal, diet composition and feed processing conditions (Van der Poel *et al.*, 1989).

Heat processing has been used for years to improve the nutritive value of raw material (O'Doherty *et al.*, 2000). Besides the inactivation of nutritional compounds, especially in legume seeds, heat processing may cause cell rapture, transform cell structures and influence the solubility of fiber components (Van der Poel *et al.*, 1989 & Camire *et al.*, 1990). Extrusion processing has been another recent initiative designed to improve the quality of livestock diets (Van der Poel *et al.*, 1989).

It is thought that the extrusion processing may alter the physiochemical properties of most feeds and may improve the physical and hygienic quality of diets, resulting in improved animal performance (Van der Poel *et al.*, 1989). Sauer *et al.* (1990) reported differences in total tract apparent digestibility (TTAD) of DM, energy and CP when wheat and barley-based diets was extruded or extruded and pelleted. Den Hartog *et al.* (1988) reported that TTAD did not differ between diets containing either 60% extruded or 60% raw maize. Van der Poel *et al.* (1989) also found differences due to maize processing (extruded, micronized or pressure-cooked) in nitrogen-free extract TTAD. In a subsequent study, Van der Poel *et al.* (1990) found only differences in ileal digestibility of organic matter and nitrogen free extract. No correlation between starch gelatinization and digestibility traits was observed.

In a grower-finisher pig experiment O'Doherty *et al.* (2000) found that expander processing had no effect on the organic matter (OM), energy, or protein digestibility. Laurinen *et al.* (1998) reported similar effects with only minor effects on digestibility, excluding that of ether extract.

Vestergaard *et al.* (1990) compared extrusion, steaming, steaming under pressure, roller heating, and micronization of barley in 21 d old weaned piglets. They used a wide range of starch gelatinization levels and concluded that gelatinization was not correlated with performance. With the performance of piglets (weaned at 23 d) Medel *et al.* (1999) also found larger rates of gelatinization in extruded than in micronized cereals, but no differences were detected in performance or digestibility values. Medel *et al.* (1999) concluded that heat processing of maize improves daily gain and feed efficiency of early weaned pigs and they recommended the use of processed cereals in piglet weaner diets.

Improvement of performance or digestibility due to cereal processing has been reported (Aumaitre, 1976; Skoch *et al.*, 1983), whereas slight or no benefits at all were found by others (Van der Poel *et al.*, 1989; Vestergaard *et al.*, 1990). The literatures referring to the effect of starch processing on the performance of growing pigs has thus been very contradictory.

The objective of this experiment was to investigate the effects of various processing conditions (heat treatment and feed form) of maize based diets on grower pig digestibility values and to determine if the degree of starch gelatinization could be related with the values.

Material and Methods

Commercial Landrace x Large White pigs (n=24) were used to study the effects of processing of the carbohydrate source and the diet feed form on certain metabolism and production parameters. Two processing combinations of the carbohydrate source were used with 3 processing combinations of the diet in a 2 x 3 factorial design. Six diets were formulated on an iso-nutrient basis (14.48 MJ/kg metabolizable energy (ME), 23.01 crude protein (CP), 1.092% lysine, 0.742% methionine and cystine and 0.271% tryptophan all on a DM basis). The pigs were blocked by weight and then allotted randomly to 1 of 6 dietary treatments. The diets and their nutrient composition are presented in Table 1 and 2.

The six diets were compared with each other in a metabolism trial. Twenty-four boars with a mean live mass of 26.2 (±0.25 SE) kg were used as experimental animals. Each diet was fed to four pigs. Pigs were subjected to a 15 d trial period consisting of a 10 d adaptation period and a 5 d collection period, during which faeces were collected. Pigs had free access to water at all times. Pigs were fed at 11% of metabolic mass ($W^{0.75}$) and received the feed in two equal portions at 8:00 and 13:00 daily. Representative samples from the respective diets were chemically analyzed for dry matter (DM), nitrogen (N) and fiber by standard AOAC methods (Association of Official Analytical Chemists, 1975). Gross energy determination on diet and faeces samples were carried out on a CP 400 adiabatic bomb calorimeter (Gallenkamp, Crawley). Procedures followed in collection and analysis of faeces samples are described in detail by Kemm & Ras (1971).

The maize was first ground through a hammer mill (2.5 mm screen) and then split into two fractions. The first fraction was incorporated untreated and the other fraction of maize were extruded through a Multinetz SP 2000 single-screw extruder (Multinetz, NZ) and re-ground (2.5 mm screen) and mixed into the diets, which were either fed in a meal form or pelleted in a pellet mill (Simon-Barron California Hyflo 67) equipped with a 2.4 -mm die, or extruded. The extruder conditions were as follows: 138 °C barrel jacket temperature at the 3rd head, 21.09 kg/cm^2 of internal pressure at the die, 2.27 kg/min production rate, and approximately 100 °C exit temperature. The different processing conditions produced various degrees of starch gelatinization (Table 2). The degree of starch gelatinization of the feed was analyzed by a modified glucoamylase method for determining the degree of starch gelatinization of extruded products (Karkalas, 1985). This is based on a 70-min hydrolysis of the carbohydrate-rich substrate to glucose, following the principle that gelatinized starch is digested easily by glucoamylase to form glucose. The total starch is also determined by a similar procedure, except that intact or raw starch in the sample is gelatinized prior to enzymatic digestion.

Differences between treatment means during the metabolism trial were analyzed by two-way analysis of variance with processing of the carbohydrate source and processing of the diet as main factors (Statgraphics, 1991). All statistical procedures are as described by Snedecor and Cochran (1980).

Table 1 Dietary treatments fed to the weaner piglets.

Treatment	**1**	**2**	**3**	**4**	**5**	**6**
Maize	Raw	Raw	Raw	Extruded	Extruded	Extruded
Diet feed form	Meal	Pelleted	Extruded	Meal	Pelleted	Extruded

Table 2 Composition of the basic diet (as-fed basis)

Ingredients	%
Maize	44.09
Whey powder	2.00
Wheat bran	15.00
Soybean 47	21.78
Soybean full fat	8.00
Fishmeal 65	5.00
Oil-Sunflower	1.91
Limestone	1.91
Salt	0.05
Vit + min premix [a,b]	0.25
Antioxidant [c]	0.75
Nutrients (%)	
Dry Matter	88.95
Fat	6.58
Crude fiber	3.93
ME (MJ/kg)	13.80
Protein	23.01
Lysine	1.092
Methionine	0.365
Ca (Total)	1.000
P (Avail.)	0.276
Na	0.115
Cl	0.180

[a] Premix provided the following per kilogram complete diet: 11.025 IU vitamin A, 1.103 IU vitamin D3, 44 IU vitamin E, 4.4 mg meadione (medadione sodium bisulfite), 8.3 mg riboflavin, 29 mg d-pantothenic acid, 50 mg niacin, 166 mg choline chloride, and 33 ug vitamin B12.
[b] Premix provided the following of complete diet: 12 mg Mn, 165 mg Zn, 16 mg Cu, 0.3 mg I, and 0.3 Se.
[c] Bioret 20 was added at 750 g/ton.

Results and discussion

The chemical composition of the experimental diets is presented in Table 3. The effect of processing of the carbohydrate source on the metabolism data of pigs are presented in Table 4. The effect of processing of the diet on the metabolism data of piglets are presented in Table 5.

There were no statistical (P > 0.05) difference in the parameters between raw and extruded maize or meal, pellet and extruded diet feed forms.

Table 3 Chemical composition basis (DM Basis) of the experimental diets

Diets	1	2	3	4	5	6
Dry matter (g/kg)	909.9	908.8	807.0	913.3	910.4	883.40
Crude protein (g/kg)	238.8	232.20	233.40	232.9	232.70	235.80
Crude fiber (g/kg)	39.50	39.20	39.53	39.36	39.50	39.30
Starch gelatinization (%)	20.1	27.6	52	35.6	45.2	92

Table 4: The effect of carbohydrate processing on energy and nitrogen metabolism data (mean ± SE) of pigs.

Maize Treatment	Raw	Extruded	SE	P
Energy metabolism				
DMI (g/d)	1049.92	1069.20	0.00	0.58
DM digestibility (%)	83.78	84.78	0.7	0.38
DE (MJ/kg DM)	14.67	14.65	0.10	0.92
ME (MJ/kg DM)	14.50	14.46	0.10	0.75
Nitrogen metabolism data				
N intake (g/d)	40.20	39.58	0.1	0.35
N excretion				
Feaces (g /d)	5.43	5.12	0.30	0.47
Urine (g /d)	12.29	11.90	1.36	0.84
Total (g /d)	17.73	17.03	1.38	0.72
Appparent N digestibility (g/d)	86.95	86.72	0.73	0.82
Appparent N retension (g/d)	23.23	22.46	1.24	0.67
N retension (as % of N intake)	57.16	57.22	3.17	0.98

There were no significant difference ($P > 0.05$) in DE, DM, DMI, ME, or N between raw maize diet and an extruded maize diet. This finding is in accordance with the findings of Den Hartog *et al.* (1988) but in contrast with the findings of Medel *et al.* (1999); Aumaitre (1976) & Medel *et al.* (1999). Den Hartog *et al.* (1988) reported that total tract apparent digestibility (TTAD) did not differ between diets containing either 60% extruded or 60% raw maize. Medel *et al.* (1999) reported that total tract apparent digestibility of OM (organic matter) was improved with processed maize- and barley-based diets. Aumaitre (1976) also found significant improvements of 3-4% in TTAD of OM and CP (crude protein) due to processing of barley and maize.

Table 5: The effect of feed form on energy and nitrogen metabolism data (mean ± SE) of pigs.

Feed form	Meal	Pellet	Extruded	SE	P
Energy metabolism					
DMI (g/d)	1093.38	1071.06	1014.24	0.00	0.68
DM digestibility (%)	83.86	83.56	85.43	0.93	0.34
DE (MJ/kg DM)	14.73	14.65	14.60	0.12	0.77
ME (MJ/kg DM)	14.53	14.50	14.41	0.13	0.80
Nitrogen metabolism data					
N intake (g/d)	41.52	40.46	37.71	0.01	0.58
N excretion					
Feaces (g /d)	5.79	5.57	5.47	0.37	0.40
Urine (g /d)	10.56	13.84	11.89	1.67	0.58
Total (g /d)	16.35	19.43	16.37	1.69	0.36
Appparent N digestibility (g/d)	86.29	86.75	87.45	0.89	0.65
Appparent N retension (g/d)	25.51	21.06	21.96	1.52	0.12
N retension (as % of N intake)	61.44	52.71	57.41	3.88	0.31

The average dry matter intake (DMI) of a meal diet was 1093.38 g/day (Table 5) with a DM digestibility of 83.86%. That lead to no significant difference in the DE content (14.73 MJ/ kg) when compared to a pelleted diet which produced a DMI of 1071.06 g/day, DM digestibility of

83.56% and a DE content of 14.65 ± 0.19 MJ/kg. There were no significant difference in DE, DMI, ME, or N between the meal diet and the pelleted diet. Hanke *et al*. (1972), Baird (1973) and Wondra *et al*. (1993) attributed the improved performance with pelleting to increase nutrient digestibility and decreased feed wastage. It appears that the nutritional effects of pelleting are variable and depend on the age of the animal, diet composition and feed processing conditions (Van der Poel *et al*., 1989).

Extruding the diet had no significant effect (P > 0.05) on DMI (1014.24 g/d); DM digestibility (85.43%) or DE content (14.60 MJ/kg) and had no significant effect (P>0.05) on the N-metabolism data when compared to the meal or pelleted diet. This finding is in contrast with the findings of Honktrakul *et al*. (1999) & Johnson *et al*. (1999). Honktrakul *et al*. (1999) reported that pigs fed extruded diets had greater (P < 0.01) apparent digestibility of DM, CP, and energy than those fed either the control (pelleted) or expanded diets. Johnson *et al*. (1999) observed a significantly higher (P < 0.01) apparent digestibility of DM, N, and DE in a processed diet (extruded) when compared to a meal or pelleted diet. Johnson *et al*. (1999) reported lower ADFI values with complete expanded diets and postulated that the lower feed intake values might account for the increase in digestibility.

With each heat treatment there was a tendency for the degree of starch gelatinization to increase (Table 3). However, this increase was not correlated with an increase in apparent digestibility of DM, CP, and energy. Mercier (1980) and Bjork et al. (1985) found that extruded ground maize had an increased starch gelatinization, which improved the palatability and feed intake of maize-based products. Honktrakul *et al*. (1998) found that increasing the degree of gelatinization resulted in differences in digestibility and feed intake. However, the differences obtained were not sufficient enough to improve ADG or FCR and suggested that the variation in response to extrusion processing may not be related directly to the degree of gelatinization of the cereal grain.

It could be postulated that no differences were observed due to the fact that the trial was performed with growing pigs (±26 kg). Growing pigs may have enough pancreatic enzymes compared to and weaner piglets (± 7.25 kg). Due to the structure of the facilities and availability of equipment, grower pigs and instead of weaner piglets were used in the metabolism trial.

Conclusion

An improvement in digestibility due to carbohydrate processing e.g. maize extrusion and diet feed form e.g. pelleting and extrusion has been reported by some authors who attributed the improvement to an increased digestibility and/or a decreased feed wastage. In this experiment no significant difference was found in DMI, DE, N or DMI when an extruded maize diet is compared with a raw maize diet or when different diet feed forms are compared (meal, pellet, extrusion). Increasing the degree of gelatinization resulted in no significant difference in digestibility ($P > 0.05$) and/or feed intake. The study indicates that the increasing degree of gelatinization does not have an effect on the digestibility value of the feed consumed by growing pigs (26.2 ± 0.25 kg).

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General conclusion

Extrusion of the maize leads to depressions in performance and a reduction of 9.55% in FCR efficiency. From these experiment it appears that treatment of maize by extrusion had no effect on production traits of piglets weaned at 28 d. The piglets appear to have sufficient pancreatic and gastric enzyme activity to digest raw starch 1 week after weaning (28 d). One could postulate that extrusion cooking of maize could only be of benefit to piglets weaned between 17 to 21 d. Pelleting a diet improves FCR by 10% when compared to a meal diet. Although the improved performance with pelleting could not be explained by an increase in nutrient digestibility in the digestibility trial, one could postulate that in the growth trial weaner pigs were used and in the digestibility trial grower pigs were used. And that the age of the pigs used influenced the digestibility values. Extrusion of a diet improves FCR by 19% when compared to meal diet. Therefore, extrusion of the diet improves FCR by 9% when compared to a pelleted diet. One could attribute the increase in efficiency to increased palatability of the diet and that an extruded diet provides a higher quality pellet. It is thus recommended that feedmills or farmers use pelleting of piglet weaner diets and compare the improvement in performance due to extrusion up against the additional cost of extrusion.