USE OF FEED TECHNOLOGY TO IMPROVE THE NUTRITIONAL VALUE OF FEED INGREDIENTS AND DIETS FED TO PIGS

BY

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DISSERTATION

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ABSTRACT: Seven experiments were conducted to investigate effects of use of feed technology to improve the nutritional value of ingredients and diets fed to pigs. The objective of Exp. 1 and 2 was to determine the digestibility of CP, AA, and P, and the concentration of DE and ME, in corn ground to different particle sizes (i.e., 865, 677, 485, and 339 μm). Results of Exp. 1 and 2 indicated that the concentration of DE and ME increased ($P < 0.05$) linearly as the particle size of corn was reduced from 865 to 677, 485, or 339 μm, but this was not the case for CP, AA, or P digestibility. The objective of Exp. 3 was to test the hypothesis that addition of dietary lipids can be reduced as corn particle size was reduced without affecting growth performance or carcass composition of growing-finishing pigs. Results of this experiment indicated that by using corn ground to a smaller particle size, the amount of added fat may be reduced in diets fed to growing-finishing pigs without affecting animal growth performance or carcass composition, however, dressing percentage was increased ($P < 0.05$). Two subsequent experiments were conducted to test the hypothesis that reduced particle size of corn also will improve the caloric utilization of corn fed to weanling pigs. Results of these experiments indicated that G:F of weanling pigs was improved ($P < 0.05$) in diets containing corn ground to a particle size of 339 μm rather than a greater particle size, which confirmed that the ME of finely ground corn is greater than the ME of coarsely ground corn. Thus, less expensive diets may be formulated if corn is ground to a smaller particle size. In Exp. 6, the objective was to determine the effects of chemical, physical, or enzymatic treatments of distillers dried grains with solubles (DDGS) on concentration of DE and ME, and the digestibility of energy, OM, and detergent fiber. Results of Exp. 6 indicated that extrusion of DDGS or treatment with sodium hydroxide, calcium oxide, or a mixture of

hemicellulases and xylanases did not improve ME or increase the digestibility of GE, OM, NDF, or ADF. However, treatment of DDGS with a mixture of cellulases and xylanases resulted in an increase ($P < 0.05$) in digestibility of GE and OM and increased ($P < 0.05$) ME compared with untreated DDGS. Experiment 7 was conducted to test the hypothesis that pelleting and extrusion of diets, either alone or in combination, will improve nutrient and energy digestibility. Results of this experiment indicated that energy utilization was improved ($P < 0.05$) by pelleting or extrusion or by the combination of the technologies. The response to extrusion seems to be greater in high-fiber diets than in corn-soybean meal diets, but regardless of the concentration of fiber in the diet, the combination of extrusion and pelleting always increased ($P < 0.05$) the utilization of energy in the diet. In conclusion, use of fine grinding, enzyme addition, or extrusion and pelleting positively influence energy and nutrient digestibility in diets fed to pigs.

Key words: amino acid, digestibility, energy, fiber, pig, feed processing

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Pon tu mano junto a la mía,

y siempre sabré que estarás conmigo,

en la tristeza y el dolor.

En momentos de desesperación,

tu memoria jamás olvidare,

solo tu amor en mi mente yo tendre.

Solo piensa en mi amor,

y por siempre te recordare,

solo pon tu mano junto a la mía,

y entenderás, entenderás lo que es.

Koi

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CHAPTER 1

INTRODUCTION

In the U.S swine industry, a conventional diet based on corn and soybean meal fed to pigs is provided in a mash form and, in most cases, processing other than grinding and mixing is not practiced. However, due to the high cost of energy in pigs diets, use of high fiber ingredients such as soybean hulls, distillers dried grains with solubles (**DDGS**), and wheat middlings has increased. However, high fiber concentrations in the diet usually result in reduced energy and nutrient digestibility (Noblet and Le Goff, 2001; Bindelle et al., 2008) that negatively impacts growth performance and carcass composition of pigs (Lee et al., 2012).

Feed processing technologies such as changes in grinding procedures, expansion, extrusion, pelleting, and use of enzymes and chemicals may, however, be used to modify the structure of the ingredients and increase nutrient availability (Fahey et al., 1993; Wondra et al., 1995; Hancock and Behnke, 2001; Kim et al., 2002; Emiola et al., 2009; Zijlstra et al., 2009). This may have a positive effect on pig growth performance and carcass composition, but effects of different feed technologies on the nutritional value of feed ingredients and diets fed to pigs are not fully understood. Therefore, more research in this area is warranted, and the objectives of this dissertation are:

1) To determine the concentration of DE and ME and the digestibility of P, starch, CP, AA, and energy in corn ground to 4 different sizes and fed to growing pigs.

2) To test the hypothesis that addition of dietary lipids can be reduced as corn particle size is reduced without affecting growth performance or carcass composition of growing-finishing pigs.
3) To test the hypothesis that the caloric utilization of corn fed to weanling pigs is increased as particle size of corn is reduced.
4) To determine the energy and nutrient digestibility of diets with different concentrations of fiber that have been pelleted, extruded, or pelleted and extruded, and to test the hypothesis that pelleting and extrusion of diets, either alone or in combination, will improve nutrient and energy digestibility, and that the response is greater in high fiber diets than in low fiber diets.
5) To determine the effects of physical, chemical, and enzymatic pretreatments on concentration of DE and ME and on the ATTD of GE, OM, NDF, and ADF in DDGS.

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CHAPTER 2

EFFECTS OF FEED PROCESSING ON THE NUTRITIONAL VALUE OF FEED INGREDIENTS: LITERATURE REVIEW

INTRODUCTION

In the swine industry, the cost of feed has a high impact on the total production costs of pork. This is more notable when prices of feed are high. Therefore, maximizing the utilization of nutrients that are provided from the feed to the pig is among the strategies that can be used to reduce the impact of high feed prices on production costs.

Several methodologies have been used to determine the digestibility of P and AA in ingredients used in swine diets, but the preferred methods are determination of standardized total tract digestibility (**STTD)** of P and standardized ileal digestibility (**SID**) of AA (Stein et al., 2007; Almeida and Stein, 2010; NRC, 2012). Using values for STTD of P and SID of AA in diet formulation may reduce the excretion of P and N into the environment because values for STTD of P and SID of AA in individual feed ingredients are additive in mixed diets fed to pigs (Stein et al., 2005; NRC, 2012). Thus, fewer nutrients have to be included in the diets if values for STTD of P and SID of AA are used, which may reduce the cost of the diets.

Feed ingredients are usually processed using one or more feed processing techniques before feed is consumed. Most ingredients are ground before being consumed, which reduces the particle size and increases digestibility (Wondra et al., 1995d). Feed ingredients are also sometimes heated, which may reduce concentrations of antinutritional factors, but effects of heating on energy and nutrient digestibility have not

been consistent (Herkelman et al., 1992). Other processing techniques that may be used include expander processing (Thomas et al., 1997; Lundblad et al., 2011), pelleting (Hancock and Behnke, 2001; le Gall et al., 2009), and extrusion (Stein and Bohlke, 2007; Lundblad et al., 2011). Chemical and enzyme treatments may be used to solubilize the cellulose and hemicellulose fractions that form the cell wall of plants. Some of the chemicals used to increase fiber digestibility are sodium hydroxide (**NaOH**; Fahey et al., 1993; Felix et al., 2012; Morrow et al., 2013), ammonium (Realff and Abbas, 2004; Mosier et al., 2005), calcium oxide (**CaO**; Cobianchi et al., 2012), and calcium hydroxide (**$Ca(OH)_2$;** Lesoing et al., 1981). Exogenous enzymes such as cellulase, hemicellulase, xylanase, β-glucanase, α-galactosidase, or carbohydrase mixtures also may be used to increase energy and fiber digestibility in feed ingredients and diets (Park et al., 2003; Bals et al., 2006; Emiola et al., 2009; Adeola and Cowieson, 2011; Yañez et al., 2011). There is, however, a lack of information about effects of many of these processing techniques on energy and nutrient digestibility and the utilization of feed by pigs. There is also a lack of information about how combinations of different processing techniques may impact feed utilization by pigs.

CARBOHYDRATES IN DIETS FED TO PIGS

A conventional diet based on corn and soybean meal (**SBM**) used in a commercial swine farm contains 60 to 75 corn and 15 to 30% SBM. This indicates that a high proportion of the total pig energy intake comes from the carbohydrate fraction of the diet (Bach Knudsen et al., 2012). Carbohydrates are molecules that are present in plant feed ingredients that contain carbon, hydrogen, and oxygen (Bach Knudsen, 2011). Dietary

carbohydrates include monosaccharides, disaccharides, oligosaccharides, and polysaccharides, but only monosaccharides, such as glucose, fructose, and galactose, can be absorbed by pigs (Englyst and Hudson, 2005; NRC, 2012). Therefore, disaccharides, oligosaccharides, and polysaccharides need to be digested to their monomeric constituents before absorption.

There are α and β glycosidic bonds that connect different monosaccharides to form disaccharides, oligosaccharides, and polysaccharides (Bach Knudsen, 2011; NRC, 2012). Polysaccharides are composed of 10 or more units of monosaccharides linked together by glycosidic bonds (Cummings and Stephen, 2007). Starch is a polysaccharide and the main form of energy storage in grains (Liu, 2012). Starch is composed of amylose and amylopectin, which are polymers of D-glucose bound together by α-1-4 glycosidic bonds in the case of amylose and α-1-4 and α-1-6 bound in amylopectin. These bonds are easily digested by the enzymes secreted by pigs and most of the starch in most feed ingredients is, therefore, digested in the small intestine. However, there is a portion of the starch (called resistant starch) that is not digested in the small intestine and, instead, is fermented in the large intestine to produce short chain fatty acids (**SCFA**; Bach Knudsen and Canibe, 2000; Champ, 2004).

Resistant starch is present in the non-cell wall fraction of the plant (NRC, 2012) and its concentration depends of the type of cereals. For instance, resistant starch in wheat, dehulled barley, corn, and sorghum is 1.1, 6.4, 10.0, and 18.5%, respectively (Cervantes-Pahm et al., 2014), which indicates that the starch fraction that is resistant to digestion is variable among ingredients. Resistant starch may be classified in 4 types (Brown et al., 1995). Resistant starch 1 is considered physically inaccessible because it is

the starch that is encased by fibrous tissue, which prevents the starch digesting enzymes from reaching the starch. Resistant starch 2 is native starch, which is resistant to digestive enzymes due to the conformation of the granules. When the starch granule is heated (e.g., gelatinized) and then cooled, a retrograded starch is formed and, therefore, a new matrix of crystals that resist enzymatic hydrolysis is created. This is called resistant starch 3 (Brown. 2004). Resistant starch 4 refers to the starch that is modified by addition of chemicals. Thus, chemicals may result in new types of linkages that reduce the digestion of starch in the small intestine (Sajilata et al., 2006).

In corn, starch represents approximately 63% of the kernel and in high fibrous ingredients such as canola meal, distillers dried grain with solubles (**DDGS**), corn germ meal, sunflower meal, and soybean hulls, starch usually is in the range of 0 to 15% (NRC, 2012). In these ingredients, most of the carbohydrates are non-starch polysaccharides (**NSP**).

Non-starch polysaccharides are molecules that are not digested in the small intestine, but they may be fully or partially fermented in the small or large intestine (Cummings and Stephen, 2007; Bach Knudsen, 2011). Nonstarch polysaccharides consist of cell wall fractions (i.e., cellulose and hemicelluloses) and non-cell wall fractions (i.e., gums and resistant starch), and both of these fractions are poorly digested by monogastric animals (NRC, 2012).

Celluose is similar to the amylose structure of starch because it contains only glucose in linear forms, but the glycosidic bonds are β-1-4 in contrast to the α-1-4 bonds in amylose (Yen, 2001). This difference in bonds is what prevents cellulose from being digested by animal enzymes (NRC, 2012; Bach Knudsen, 2014).

Hemicelluloses are branched molecules composed of polysaccharides that contain 5 carbons (pentoses) or 6 carbons (hexoses; Cummings and Stephen, 2007). Glucose, mannose, and galactose are hexoses located as branches to the pentoses, arabinose and xylose, which act as a backbone that supports the structure of the hemicellulose fraction of the cell wall (Cummings and Stephen, 2007). Arabinoxylans and β-glucans are the main polysaccharides in the hemicellulose fraction of the cell wall (Bach Knudsen, 2014).

Arabinoxylans, like other NSP, also are located in the endosperm of the cell wall and contain D-xylose molecules linked together by β-1-4 bonds as the backbone with arabinose molecules attached to the xylan chain (Bedford, 1995; Bach Knudsen and Laerke, 2010). There can be one or more arabinose units attached to each xylose, and uronic acid, ferulic acid, and *p*-coumaric acid also may be attached to the xylose backbone (Holtekjølen et al., 2006; de Vries et al., 2013). Beta-glucans are molecules located in the endosperm of the cell wall between the aleurone layer and subaleurone layer in the wall (Malkki, 2001). Beta-glucans contain glucoses linked together with β-glycosidic bonds (i.e., β-(1-4 and 1-3)) and are present in yeast, wheat, barley, and oats (Annison and Choct, 1991; Cid et al., 1995; Kumar et al., 2012). This molecule may act as a barrier in the small intestine blocking the action of enzymes to digest protein and fat (Bach Knudsen et al., 1993), but microbes may get access to β-glucans due to its solubility (Oakenfull, 2001). Arabinoxylans and β-glucans are the main NSP in cereals and cereal co-products (Bach Knudsen, 1997). Arabinoxylans represent 50 and 70% of the total NSP in rye and wheat, respectively (Zijlstra et al., 1999; Bach Knudsen and Laerke, 2010), but only around 40 to 50% in corn, sorghum, and co-products from corn and sorghum (Jaworski et al., 2015).

There are different methodologies to classify carbohydrates (i.e., based on chemical properties or number of carbons). The digestible and non-digestible carbohydrate classification proposed by Bach Knudsen et al. (2012) indicates which carbohydrates are digested and absorbed as monosaccharides, and which carbohydrates are fermentable. The digestible carbohydrates (i.e., monosaccharides, disaccharides, and starch) are digested by the action of enzymes in the small intestine (Englyst and Hudson, 2005). Starch is hydrolyzed by α-amylase to maltose, isomaltose, and maltotriose (Bach Knudsen, 2011). The remaining disaccharides and oligosaccharides are hydrolyzed by the action of maltase, sucrase, and isomaltase to produce monosaccharides that are absorbed in the small intestine (Englyst and Hudson, 2000). These enzymes are produced by the enterocytes in the small intestine and transported to the brush border to hydrolyze disaccharides and oligosaccharides (Gray, 1992).

Non-digestible carbohydrates (i.e., oligosaccharides, resistant starch, and NSP) cannot be digested by endogenous enzymes in the small intestine due to the inability of endogenous enzymes to hydrolyze the β-bonds that link the monosaccharides together. Instead, these carbohydrates may be fermented in the large intestine by microbes, which results in synthesis of SCFA (Imoto and Namioka, 1978; Champ, 2004; Callan et al., 2007) that can be absorbed and utilized by the pigs, but the efficiency of energy utilization of SCFA is less than that of monosaccharides. Therefore, the energy value of feed ingredients is affected by the concentration of starch and fiber in the ingredient (Dégen et al., 2007; le Gall et al., 2009). However, the energy value of the fiber fraction may be increased by the use of exogenous enzymes that may contribute to hydrolysis of the β bonds in the NSP, which may increase the fermentability of those fibers.

PARTICLE SIZE OF FEED INGREDIENTS

Measuring Particle Size

Determining the mean particle size of feedstuffs that are commonly used in diets fed to pigs is not a well-established practice in feed mills in the U.S. However, energy and nutrient digestibility may be increased as the particle size of feedstuffs decreases (Wondra et al., 1995a,c; Mavromichalis et al., 2000; Kim et al., 2002; Fastinger and Mahan, 2003). Therefore, it is important to determine the optimal particle size of feed ingredients to maximize energy and nutrient digestibility.

The American Society of Agricultural Engineers has published a procedure for determining particle size and calculating the fineness of feedstuffs (ASAE, 2008). Particle size distribution and mean particle size of grinding of feedstuffs are determined using 100 g of feedstuff that is placed on the top of the test sieves (i.e., U.S sieve # 4, 6, 8, 12, 16, 20, 30, 40, 50, 70, 100, 140, 200, 270, and a solid metal pan), which are stacked from the biggest to the smallest aperture size sieve. The test sieves are located in a vibratory sieve shaker for 10 min. The amount of feedstuff that is accumulated in each of the test sieves is recorded and weighed to calculate particle size distribution and mean particle size. After determination of particle size, the surface area is calculated using the mean particle size of the feedstuff as a reference (ASAE, 2008).

Mills Used for Grinding

Grinding is used to reduce the particle size of a feed ingredient and it is accomplished with the use of different types of mills. The most common mills used in the industry are roller mills and hammer mills. Ingredients such as DDGS and SBM often are ground during the production process and, in most cases, no further grinding is needed

for these ingredients before diets are mixed. In contrast, cereal grains and pulse crops are usually not ground prior to entering the feed mill, and these ingredients, therefore, need to be ground.

In the feed industry, there are different preferences for using roller mills or hammer mills. These preferences often are based on the grinding capacity needed, electricity efficiency, and types of feedstuffs used (Hancock and Behnke, 2001). However, roller mills require more oversight and they are more complicated to operate and manage than hammer mills, but they have a better energy efficiency, and provide a more uniform particle size. Thus, there is less variation among the size of particles if a roller mill is used compared with a hammer mill (Wondra et al., 1994b; Hancock and Behnke, 2001). Hammer mills increase loss of moisture from the grain, are noisier, and are more costly to maintain than roller mills (McEllhiney, 1983), but a hammer mill system can be installed for about 50% of the cost of a roller mill (Vermeer, 1993). Corn that is ground with a hammer mill compared with a roller mill contains more uniform edges and the shape of the particles tends to be more spherical (Reece et al., 1985). However, a more uniform particle size distribution also is observed with the same mean particle size if a roller mill rather than a hammer mill is used, which results in a greater digestibility of DM, GE, and N, but this does not affect growth performance of pigs (Wondra et al., 1995b). Roller mills may be stacked so the grain is rolled not only once, but 2, 3, or even 4 times (Stark, 2013). This procedure allows roller mills to produce an end-product with a particle size of less than 500 μm.

Historically, most feed mills in the U.S. have used either roller mills or hammer mills, but not both, but recently, advances in milling technology have introduced systems

where ingredients are first rolled using 1, 2, or 3 sets of rollers and then processed in a hammer mill. This technology is known as "multiple stage grinding", and it is believed that this results in a more uniform particle size and reduced cost of grinding, but no comparative data between multiple stage grinding and single stage grinding have been published. It is also possible to sieve the material after the rollers so that only the larger particles are guided to the hammer mill, whereas smaller particles by-pass the hammer mill. Use of this procedure will minimize electricity usage and results in the most uniform particle size.

Electricity used to process feedstuffs is an important component in a feed mill's budget. Corn milled in a hammer mill at 600 μm rather than 1000 μm increased energy usage, and when particle size was decreased from 1,000 to 400 μm, the energy usage increased almost 2.5 times (Wondra et al., 1995a). The production rate (ton/h) also decreases as particle size is reduced (Healy et al., 1994). Likewise, electricity costs are more expensive for hammer mills compared with roller mills (Vermeer, 1993). Energy usage also is affected by the type of cereal that is ground (Hancock and Behnke, 2001).

Effect of Particle Size on Digestibility of Energy and Nutrients in Cereal Grains

Research to identify an optimal particle size of cereals has been conducted and effects of particle size on energy and nutrient digestibility have been reported (Wondra et al., 1995a,b,c,d; Mavromichalis et al., 2000; Kim et al., 2002; Fastinger and Mahan, 2003; Lawrence et al., 2003). Most recommendations for optimal particle size were generated between the 1960s and the 1990s depending on the type of cereal grain, type of milling, and physiological state of the pig (e.g., weanling pig, growing pig, finishing pig,

or sow). However, in most cases, a reduction in the particle size to 600 µm had a positive effect on nutrient and energy digestibility and growth performance (Wondra et al., 1995b).

A reduction of particle size of wheat from 920 to 580 µm increased apparent total tract digestibility (**ATTD**) of starch, but not of GE (Kim et al., 2005). However, pigs fed a barley-field pea diet with a particle size of 400 µm had an increase in ATTD of GE, DM, CP, and GE compared with pigs fed the same diet ground to 700 µm (Oryschak et al., 2002). A linear increase in ATTD of GE and CP, and in the SID of AA also has been observed when particle size of lupins was decreased from 1304 to 567 µm (Kim et al., 2009). The ATTD of DM and GE, and the concentration of ME, increased when pigs were fed DDGS ground to 308 µm compared with pigs fed DDGS ground to 818 µm, but particle size did not affect the ATTD of N and P (Liu et al., 2012).

Several experiments have focused on evaluating corn particle size because corn is one of the most common ingredients used in pig diets. The ATTD of DM, N, and GE in corn increased 5, 7, and 7 percentage units, respectively, when particle size was reduced from 1,200 to 400 µm (Wondra et al., 1995d), but the type of mill used to grind the corn may have an effect on energy and nutrient digestibility (Wondra et al., 1994b). Similar results were observed by Giesemann et al. (1990), who reported that finishing pigs fed a corn-based diet with a particle size of 641 µm had an increased ATTD of DM, N, and GE compared with pigs fed a diet with a mean particle size of 1,500 µm. Likewise, a reduction in particle size from 900 to 300 µm in corn and sorghum improved the ATTD of GE (Healy, 1992; Healy et al., 1994). The use of pelleting in combination with grinding also may increase ATTD of DM, GE, and N (Wondra et al., 1995a). In a 24 d experiment, energy and DM digestibility were determined on d 9 and pigs fed corn

ground to 1000 μm had a reduced ATTD of DM and GE compared with pigs fed corn ground to 500 μm (Kim et al., 2002). Other observations reported by Wondra et al. (1995c) indicated that ATTD of GE, DM, and N improved linearly and quadratically as the particle size of corn was reduced from 1,200 to 400 μm. Fecal excretion of GE, DM, and N also was reduced as corn particle size was reduced (Wondra et al., 1995c). However, particle size did not affect urine N excretion, but as particle size of corn was reduced from 1,200 to 400 μm, the ME of corn increased from 3,399 to 3,745 kcal/kg (Wondra et al., 1995c).

The ATTD of GE also is improved linearly when particle size of sorghum is decreased (Healy et al., 1994). A reduction of particle size of SBM from 949 to 185 μm had no effect on average SID of indispensable AA or dispensable AA, but a linear increase in the SID of Ile, Met, Phe, and Val was observed as particle size was reduced (Fastinger and Mahan, 2003). However, energy digestibility of SBM was not affected by decreasing the particle size of SBM from 949 to 185 μm. Nevertheless, it was suggested that SBM ground to 600 μm will have the best AA and energy digestibility (Fastinger and Mahan, 2003).

The ATTD of N and DM in wheat also increase as particle size is reduced from 1,300 to 600 μm (Mavromichalis et al., 2000), but this is not the case for barley because the ATTD of OM, energy, or CP is not affected by particle size (Medel et al., 2000). This indicates that the effect of reduction in particle size is unique and depends on each specific ingredient.

Effect of Particle Size on Growth Performance and Sow Productivity

Reduction of cereal grain particle size may increase enzyme surface action, which leads to increased energy and nutrient digestibility (Kim et al., 2002; Fastinger and Mahan, 2003). However, this increase in digestibility is not always translated into a positive effect on growth performance because pigs may compensate for a low digestibility by eating more feed. The best results on growth performance are obtained in weanling pigs and finishing pigs if wheat is ground to 600 and 1,300 µm, respectively (Mavromichalis et al., 2000).

Carcass dressing percentage was increased in pigs fed corn ground to 400 µm compared with pigs fed corn ground to 1,000 µm (Wondra et al., 1995a). The reason for this observation may be that the weight of the intestines is reduced with reduced particle size of corn. In contrast, Mavromichalis et al. (2000) reported that there was no effect on carcass dressing percentage when pigs were fed wheat ground to 600 µm compared with pigs fed wheat ground to 1,300 µm. Thus, it is not clear how particle size influences carcass dressing percentage.

Feed intake may be improved if particle size of wheat is reduced from 1,200 to 980 µm, but this did not have an effect on overall G:F (Seerley et al., 1988). Likewise, pigs (93-114 kg) fed wheat ground to 600 µm had improved G:F compared with pigs fed wheat ground to 1,300 µm (Mavromichalis et al., 2000), but the same effect was not observed from 67 to 93 kg. In contrast, Hancock and Behnke (2001) reported that for each 100 micron decrease in particle size of corn, the G:F ratio in growing pigs will be improved by 1.3%. Likewise, Wondra et al. (1995b) reported that the G:F ratio was 7% greater in pigs fed corn ground to 400 µm compared with pigs fed corn ground to 800 µm.

Pigs have a greater preference for corn when the particle size is reduced than for sorghum that was ground to the same particle size as corn (Healy et al.,1994), and Kim et al. (2005) hypothesized that reduction of particle size does not have the same effect among cereals grains. Pigs fed corn ground to 1,000 rather than 400 μm had reduced ADFI and increased G:F, which is likely a result of the greater energy value in corn ground to 400 μm compared with corn ground to 1,000 μm (Wondra et al., 1995a). In contrast, growth performance of pigs fed SBM ground to 639 μm or 444 μm was not different from that of pigs fed SBM ground to 965 or 1,226 μm (Lawrence et al., 2003). It was hypothesized that the reason for this observation is the low inclusion level of SBM in the diet (Lawrence et al., 2003). Thus, the effect of reduced particle size may only be measurable if a high inclusion rate of the ingredient is used in the diet.

Relatively little research investigating the effect of corn particle size on sow BW and litter performance has been reported. A reduction in particle size of corn from 1,200 to 400 μm does not affect BW or back fat losses in lactating sow (Wondra et al., 1995d). However, there was a linear decrease in ADFI of sows as particle size of corn was increased from 400 to 1,200 μm and a decrease in litter BW gain also was observed (Wondra et al., 1995d).

Effect of Particle Size on Ulcer Development

The stomach of the pig has 4 different regions (esophageal region, cardiac region, fundic region, and pyloric region; Yen, 2001). The esophageal region is the non-glandular region, whereas, the cardiac, fundic, and pyloric regions are the glandular regions. Each region has specific characteristics to maintain the function of the stomach. However, the functions of the stomach may be interrupted if pigs develop ulcers, and it is

possible that particle size of feed ingredients impact the risk of pigs developing ulcers. There are different types of ulcers such as peptic ulcers and esophagogastric ulcers that may affect the glandular area and the non-glandular esophageal portion of the stomach (Mahan et al., 1966). However, the esophageal region is the region that is most at risk of developing gastric ulcers if pigs are fed ingredients with a reduced particle size (Mahan et al., 1966; Reimann et al., 1968; Pickett et al., 1969; Maxwell et al., 1970) because the mucus in the glandular portion of the stomach has a protective function (Ohara et al., 1993; Varum et al., 2010). However, a reduced particle size of grain is not the only factor that may trigger development of ulcers. There are other factors such as type or intensity of production (Kowalczyk, 1969; Ramis et al., 2004) and type of housing (Amory et al., 2006) that also may increase the risk of pigs developing ulcers. The development of ulcers increases as pigs are fed pelleted diets that contain corn ground to 400 μm compared with pigs fed non-pelleted diets (Wondra et al., 1995a,b). However, growth performance may not always be affected by the presence of ulcers, and pigs fed pelleted diets usually have greater ADG and G:F than pigs fed unpelleted diets.

Development of ulcers is considered one of the major economical losses in the U.S. swine industry (Friendship, 2003), and the presence of esophagogastric ulcers have increased lately in the U.S. pork industry due to increased use of pelleting (Hancock and Behnke, 2001). However, this is not only a concern in the U.S. In the UK, 79% of pigs from 60 farms had some level of ulcers (Swaby and Gregory, 2012) and in a survey related to the presence of gastric ulcers in pigs on 16 commercial farms in the UK, it was observed that 19.1% of the commercial farms had some prevalence of ulcers (Amory et al., 2006). It is hypothesized that the formation of ulcers starts within 7 d after pigs are

provided a diet ground to a small particle size and it is also assumed that keratinization and erosions of stomach tissue may be ameliorated when pigs are fed a coarse diet for 7 d (Maxwell et al., 1970). It also has been proposed that this may be achieved if pigs are fed coarse diets 40 h prior to slaughter (Reimann et al., 1968). Development of ulcers is followed by colonization of *Helicobacter spp* and the presence of this microorganism is more evident in the fundic and pyloric regions than in the esophageal and cardiac regions (Rodriguez et al., 2009). Pigs fed either a finely ground diet or a pelleted diet produced a higher secretion of chloride in the stomach compared with pigs fed a coarsely ground diet or a non-pelleted diet (Mobeler et al., 2010), which promote the presence of *Helicobacter spp* in the stomach (Morgan et al., 1991; Eaton et al., 1995).

One of the reasons for development of ulcers is that fine grinding may result in reduced pH in the stomach (Mahan et al., 1966). Pepsin activity also is increased as particle size of corn decreases (Maxwell et al., 1970). Pigs fed diets that are either finely ground or pelleted have greater concentrations of chloride in the esophageal region of the stomach compared with pigs fed either coarse or unpelleted diets (Mobeler et al., 2010). This may be due to an increased mixing in the stomach and more watery digesta, which results in an increase in HCl secretion.

There is evidence that pigs fed corn with less variation in particle size tend to have less keratinization in the stomach (Wondra et al., 1995b) and pigs fed corn ground to 400 µm have more ulcers and keratinization in the esophageal region compared with pigs fed corn ground to 1,200 µm (Wondra et al., 1995a). Likewise, when sows are fed corn ground to 1,200 µm, only 25% of the sows developed ulcers, but if sows were fed corn ground to 400 µm, 77% of the sows developed ulcers (Wondra et al., 1995a). Pigs

fed diets containing wheat ground to 600 µm developed more ulcers and had more tissue keratinization compared with pigs fed diets containing wheat ground to 1,300 µm, but this did not have an effect on G:F (Mavromichalis et al., 2000).

Effect of Particle Size on Feed Flowability and Handling

There is relatively little information about the effect of particle size on feed flowability and handling, but it has been hypothesized that reduced particle size may result in poor flowability (Appel, 1994). This concurs with observations by Liu et al. (2012) who reported that as particle size of DDGS was reduced from 818 to 308 µm, flowability of the diet was reduced. Likewise, SBM ground to 639 µm had a greater angle of repose than SBM ground to 965 µm (Lawrence et al., 2003). However, if a bowl type feeder is used and if feed is added twice daily, a reduced particle size does not reduce flowability of the diet (Wondra et al., 1995d). Likewise, pelleting of diets also will prevent the bridging problems, dustiness, ingredient segregation, and increased bulk density that are common problems when diets are ground to less than 600 µm (Skoch et al., 1983a; Wondra et al., 1995a). The palatability of corn with a particle size of 444 µm was not less than that of corn ground to 619 µm when fed to lactating sows (Pettigrew et al., 1985).

THERMAL TREATMENTS

Most diets fed to pigs are provided in a mash form after the ingredients have been ground and mixed. These types of diets are relatively inexpensive compared with diets that are pre-processed with steam conditioning followed by pelleting, or expansion or extrusion, or a combination of expansion or extrusion and pelleting. Effects of these

processing techniques on energy and nutrient digestibility of diets or feed ingredients have been investigated and effects on growth performance of pigs also have been reported (Ohh et al., 2002; Rehman and Shah, 2005; Stein and Bohlke, 2007; Jha et al., 2011; Liu et al., 2013). The objectives of using processing technologies are to improve energy and nutrient digestibility in ingredients (Hancock and Behnke, 2001) as well as to stimulate feed intake in the case of weanling pigs (Zijlstra et al., 2009). Thus, it is believed, that the nutritional value of ingredients and diets may be improved by feed processing (Zijlstra et al., 2009).

Feed processing often involves application of a source of heat, but excessive heat may result in the Maillard reaction (Gerrard, 2002). The Maillard reaction takes place between an amino group in an AA and a carbonyl group of a reducing sugar (Nursten, 2005), which reduces the availability and digestibility of AA (Fontaine et al., 2007; Gonzales-Vega et al., 2011; Almeida et al., 2013). Heating followed by cooling also may result in retrogradation of the starch, which will then become less digestible and, therefore, the energy value may be reduced (Sauber and Owens, 2001).

Addition of phytase to feed is a common technique used in pig diets to hydrolyze the bond between P and the phytate molecule. However, pelleting or expansion or extrusion of diets may reduce the efficiency of phytase and other exogenous enzymes because of the heat that is applied (Slominski et al., 2007). Therefore, phytase and other enzymes need to be thermostable at the temperature used during feed processing to avoid loss of activity. Alternatively, phytase and other enzymes that are available in a liquid form also may be sprayed on the pellets after production.

Steam Conditioning

The main objective of steam conditioning is to establish conditions that will result in production of a durable pellet (Hancock and Behnke, 2001). During conditioning, the temperature increases to 75ºC and the moisture increases 3 to 4 percentage units in the feed mixture for approximately 1 min (Svihus and Zimonja, 2011). Addition of either steam or water results in formation of a liquid layer on top of the ingredients that helps bind certain particles in the mixture (Obernberger and Thek, 2010). It is believed that the durability of the pellet is increased and the heat damage of the starch is reduced if ingredients are conditioned prior to pelleting (Zijlstra et al., 2009). Therefore, the conditioning step is important because there are several factors that may impact the quality of the pellet such as particle size of ingredients and the type of ingredients included in the diet (Hancock and Behnke, 2001).

Steam conditioning may be completed by a single pass or a 2-pass conditioner, which influences the length of time the ingredients will be in the conditioner. The longer feedstuffs are exposed to the steam, the greater is the starch gelatinization and protein denaturation (Hancock and Behnke, 2001), because the granules in the starch become hydrated and swell due to absorption of water (Fellows, 2000). However, the cooling after heating may lead to formation of retrograded starch, which leads to formation of crystals that reduce enzymatic starch digestibility (Brown, 2004; Htoon et al., 2009).

Pelleting

Use of steam and pressure are the principles behind pelleting technology. Steam increases the temperature of the feed and the steamed ingredients are subsequently pelleted to a determined pelleted size using pressure (Zijlstra et al., 2009). Effects of

different pellet sizes have been investigated, but it has been suggested that diets for nursery and finishing pigs may be processed using a single die with 4 to 5 mm holes without affecting growth performance (Hancock and Behnke, 2001). The effect of die thickness was investigated on the SID of AA in corn and wheat fed to pigs and no significant effects were observed on AA digestibility when the size of the die increased from 16 to 24 mm and from 16 to 20 mm, respectively (Lahaye et al., 2007). It is important to determine the quality of pellets produced. Thus, pellet hardness and pellet durability index are good indicators of pellet quality (Thomas and van der Poel, 1996) and it is believed that expansion or extrusion prior to pelleting may increase the pellet durability index in diets based on cereal grains (Traylor et al., 1999). Pelleting changes the physico-chemical characteristics of the ingredients due to the heat that is applied during the process (Zijlstra et al., 2009), and pelleting usually improves feed intake of weanling pigs compared with diets provided in a mash form (Steidinger et al., 2000).

Starch in cereals grains that are pelleted is more likely to be digested in the small intestine due to the gelatinization of starch that may be accomplished by pelleting (Jensen and Becker, 1965). Likewise, a decrease in dustiness and increased handling properties, bulk density, and reduction in segregation of components in feed ingredients are some of the advantages of using pelleting (Hancock and Behnke, 2001; Svihus and Zimonja, 2011). However, the acquisition and maintenance of equipment for pelleting may be expensive (Svihus and Zimonja, 2011).

In terms of applicability, pelleting is a well-known technology that results in an increase in feed conversion (Richert and DeRouchey, 2010) and feed efficiency may be improved by 6 to 7% if diets are pelleted (Steidinger et al., 2000; Hancock and Behnke,

2001; Richert and DeRouchey, 2010). The main reason for this observation is that feed wastage is reduced and digestibility of energy is improved because of gelatinization of starch (Richert and DeRouchey, 2010; NRC, 2012) that occurs when cereal grains are processed in the presence of heat. Therefore, pelleting also may impact feed intake and gut function of the pig (Svihus and Zimonja, 2011). Pelleting a corn-soybean meal diet increased digestibilities of DM, N, and GE by 5 to 8% compared with feeding the same diet in a meal form (Wondra et al., 1995a). Likewise, Lahaye et al. (2008) reported that pelleting a wheat-canola meal diet improved the ileal digestibility of CP and AA. Similar results of pelleting diets containing wheat and SBM compared with un-pelleted diets also were reported (vande Ginste and de Schrijver, 1998). Diets fed to growing and finishing pigs based on corn and wheat middlings that were pelleted increased the digestibility of GE and G:F (Skoch et al., 1983b). Recently, it was reported that pigs fed pelleted diets had a greater feed efficiency compared with pigs fed meal diets, and reduced performance of pigs fed diets containing high-fiber by-products was ameliorated if the diet was pelleted (Fry et al., 2012). It is, therefore, possible that the positive effects of pelleting on energy and nutrient digestibility are greater in high fiber diets than in low fiber diets, but this hypothesis has not been tested.

Extrusion

In association with pelleting, extrusion is a technology that often is used in the feed production industry. In the United States, only 5% of the pet food is not extruded (Spears and Fahey, 2004), which demonstrates the importance of this technology for the pet food production industry. The extrusion process consists of pressuring the feed material through a barrel by the use of single or twin-screw extruders, which results in

generation of heat (Fellows, 2000; Hancock and Behnke, 2001; Richert and DeRouchey, 2010). Both types of extruders may be used on the whole diet or on individual ingredients. The objective of extrusion is to increase energy and nutrient digestibility in cereal grains, which is expected to have a positive effect on feed conversion rate and, possibly, growth performance of pigs (Hancock and Behnke, 2001). Extrusion results in a more severe change in the physico-chemical characteristics of the feedstuff compared with pelleting (Zijlstra et al., 2009) because of the change in temperature, pressure, friction, and attrition of the feedstuffs inside the extruder (Hancock and Behnke, 2001). Extrusion of the whole diet compared with pelleting improved feed conversion by 8% and DM and CP digestibility were improved by 3 and 6%, respectively (Sauer et al., 1990). However, feed intake of pigs is not always improved when diets containing wheat or sorghum are extruded (Durmic et al., 2002). Ileal digestibility of DM is improved by extrusion of corn, but AA digestibility is not different between extruded and non-extruded corn (Muley et al., 2007). Ileal digestibility of CP was greater in extruded soybean meal compared with non-extruded soybean meal (Chae et al., 1997), but that is not always the case (Navarro et al., 2014). Extrusion of field peas has a positive effect on the ATTD of GE and on the apparent ileal digestibility of most indispensable AA (Stein and Bohlke, 2007; Htoo et al., 2008) and the DE of field peas was improved by 4.8% by extrusion (Stein and Bohlke, 2007). There is an increase in nutrient digestibility if ingredients that have high concentrations of fiber are extruded, but it may not always be economical to extrude diets for growing-finishing pigs (Hancock and Behnke, 2001). Apparent total tract digestibility of DM and CP was not different when a flaxseed-field pea mix was extruded using either a twin-screw extruder or a single-screw extruder (Htoo et al., 2008). However, ATTD of

GE and the concentration of DE were greater in the diet extruded using a single-screw compared with the diet extruded using a twin-screw extruder (Htoo et al., 2008). Likewise, extrusion also may increase the solubility of dietary fiber, which in turn may result in an increased energy digestibility because soluble fibers are much more fermentable by pigs than insoluble fibers (Urriola et al., 2010). It is, therefore, possible that the benefits of extrusion and pelleting are greater in high fiber diets than in low fiber diets, but this hypothesis has not been investigated. As a result of the positive effects of extrusion on digestibility and feed efficiency, many feed companies in Europe extrude diets for pigs and most of the compound feed in Europe is pelleted.

Expansion

Expansion is also known as a shear conditioning process. The reduced temperature and retention time that feed ingredients are exposed to in the expansion process are the main differences between this process and extrusion technology (Fancher et al., 1996). This is the reason there is less starch gelatinization if feed ingredients are processed using expansion technology compared with using extrusion technology (Liu et al., 2013). It is unusual that expanded feed is offered to pigs in mash form. Instead, most expanded feed also goes through a steam condition step and pelleting (Laurinen et al., 1998; Johnston et al., 1999; Lundblad et al., 2009). It has been proposed that pelleting may be replaced by expansion (Zijlstra et al., 2009) because, during expansion, the physico-chemical characteristics of the feed are modified (van der Poel et al., 1998) due to the high pressure that is used in the process (Hancock and Behnke, 2001). However, nutrient and energy digestibility were not improved by pigs fed expanded diets based on wheat and barley compared with pigs fed un-expanded diets (Callan et al., 2007). In

contrast, Traylor et al. (1999) reported that there was an increase in energy and nutrient digestibility when growing pigs were fed an expanded corn-SBM-based diet compared with pigs fed an un-expanded corn-SBM based diet. However, digestibility of DM, NDF, and CP were not improved if pigs were fed an expanded diet containing barley and wheat bran-wheat middlings (Laurinen et al., 1998). Usually a complex phase 1 diet contains corn, SBM, soybean oil, and animal protein. Expansion of different portions of a complex diet (e.g., corn, corn-SBM, or corn-soybean meal-oil) in combination with highly digestible animal protein results in an increase in ADG when fed to weanling pigs compared with pigs fed a whole complex diet that was expanded (Johnston et al., 1999). However, when a wheat-fish meal-SBM based diet was either expanded or extruded and fed to weanling pigs for 36 d, the greater G:F for pigs fed the extruded diet compared with pigs fed the expanded diet was mainly due to a greater digestibility of starch in the extruded diet (Lundblad et al., 2011). The pellet durability index of a corn- and barley-based diet was improved by adding water into the mixer followed by expansion of the diet (Lundblad et al., 2009). It is, thus, possible that expansion in combination with pelleting may result in a better quality pellet (Hancock and Behnke, 2001).

CHEMICAL TREATMENTS

Chemical processes that may be used to increase the nutritional value of feed ingredients include hydrolytic and oxidative agents (Fahey et al., 1993). Most research using chemical treatments has been conducted using ruminant animals because it is believed that mainly high fiber ingredients will benefit from chemical treatments. However, some high fiber feed ingredients fed to pigs such as DDGS and other corn co-

products have become important ingredients in diets fed to pigs due to their relatively low cost (Stein, 2012). Almost 90% of the total fiber in DDGS is insoluble fiber and only 40% of insoluble fiber in DDGS is fermented (Urriola et al., 2010). In contrast, more than 90% of the soluble dietary fiber is fermented, but soluble fiber accounts for only 10% of the total fiber in DDGS (Urriola et al., 2010). Therefore, any treatment that can solubilize some of the insoluble fibers in DDGS or other corn co-products is expected to result in increased energy contribution from the fibers because of the increased fermentability of soluble fiber.

Sodium Hydroxide

Sodium hydroxide is considered a hydrolytic agent that may solubilize a portion of the hemicellulose, lignin, and silica constituents of the plant cell wall. The solubilization is mainly due to changes in the lignin-hemicellulose matrix that takes place when the cell wall is in contact with NaOH (Fahey et al., 1993). Changes in the plant cell wall may improve access of microbial enzymes to the constituents of the plants (Fahey et al., 1993). Sodium hydroxide also has been used to remove feathers from hens as an alternative procedure compared with rubber picking fingers, but the nutritional value of the feathers removed with this procedure was not improved compared with the conventional method (Kim and Patterson, 2000).

There is limited information about the effect of NaOH treatments on energy and nutrient digestibility of ingredients fed to pigs, whereas much research has been conducted with ruminant animals (Braman and Abe, 1977; Hunt et al., 1984; Miron et al., 1997; Felix et al., 2012; Morrow et al., 2013). Treatment with NaOH increases rumen digestibility of OM in barley straw from 52 to 76% and the digestibility of DM by 22% in

other crop residues (Fahey et al., 1993). Dairy cows fed a diet that contained sorghum grain treated with 4% NaoH had a greater digestibility of NDF compared with dairy cows fed a diet with untreated sorghum grain (Miron et al., 1997). Sodium hydroxide also has been used to reduce the acidity of DDGS in an attempt to prevent the increase in acidosis that is sometimes observed if DDGS is fed to ruminants. Felix et al. (2012) reported that there is an increase in ruminal pH of heifers fed DDGS treated with NaOH compared with heifers fed un-treated DDGS, which is expected to reduce the incidence of ruminal acidosis and may increase NDF degradation in the rumen. Pigs fed bird-proof sorghum treated with NaOH had higher nitrogen and energy digestibility (Kemm and Ras, 1985). Likewise, pigs fed *Leucaena leucocephala* leaf meal treated with NaOH had improved N retention compared with pigs fed untreated *Leucaena leucocephala* meal (Echeverria et al., 2002), which may be due to a reduction in the concentration of tannins in *Leucaena leucocephala* leaf meal treated with NaOH (Acamovic and D' Mello, 1994). However, pigs fed cooked soybeans that were treated with NaOH had reduced growth performance compared with pigs fed untreated cooked soybeans (Young and Smith, 1973). It is possible that NaOH reduced the palatability of the diet (Young and Smith, 1973). There is, however, limited information about effects of treating co-products from cereal grains with NaOH, and it is also not known if oilseed meals other than SBM may benefit from treatment with NaOH.

Ammonia

Anhydrous NH_3, NH_4OH, thermoammoniation, and urea also have been used to treat fibrous materials. A combination of ammonia and high pressure may improve solubilization and fermentability of fiber if fed to ruminants (Realff and Abbas, 2004;

Bals et al., 2006), because this treatment may result in hydrolysis of the hemicellulose and cellulose fractions of the cell wall (Mosier et al., 2005; Bals et al., 2006), which make the cell wall more susceptible to be fermented by microbes (Oji et al., 2007). There is, however, no information about effects of these procedures on the fermentability of fiber by pigs. It is possible that ammonia treatment may be used to increase the energy value of fibrous ingredients fed to pigs but, to our knowledge, no research has been reported to test this hypothesis. Sheep fed a diet containing a mix of corn cobs, corn husks, and corn stalks treated with 3% aqueous ammonia had improved digestibility of N, DM, NDF, ADF, and OM compared with sheep fed a diet with an untreated mix (Oji et al., 2007). Aqueous ammonia also has been used to remove the negative effects of aflatoxins B_1 in corn fed to pigs (Jensen et al., 1977).

Calcium Oxide and Calcium Hydroxide

Calcium oxide or $Ca(OH)_2$ also may be used to treat fibrous materials, but it is a less common treatment. However, castor seed meal treated with CaO may replace up to 33% of SBM in diets for dairy cows without affecting milk production or growth performance (Cobianchi et al., 2012). An experiment conducted by Lesoing et al. (1981) demonstrated that digestibility of DM, OM, cellulose, and hemicelluloses increased in lambs fed wheat straw treated with $Ca(OH)_2$ in combination with NaOH compared with lambs fed a diet with untreated wheat straw. Feedlot cattle fed diets containing Brix sugar cane treated with CaO also had increased digestibility of NDF (Magalhaes et al., 2012), further indicating that CaO treatment may be used to increase the digestibility of OM and GE in ruminants. However, growth performance was not improved if feedlot cattle were fed corn stover and modified wet distillers grains with solubles treated with CaO

compared with cattle fed untreated corn stover and modified wet distillers grains with solubles (Duckworth, 2013). Treatment of fibrous materials with either CaO, $Ca(OH)_2$, or NaoH solubilize more of the hemicellulose fraction than the cellulose fraction of the cell wall (Lesoing et al., 1981). Calcium hydroxide also has been used to decontaminate corn infected with *Fusarium* mycotoxins (Rempe et al., 2013).

ENZYME TREATMENTS

Exogenous enzymes are commonly used in Northern European pig diets because most diets in Northern Europe are based on barley or wheat instead of corn. These ingredients have high concentrations of β-glucans and arabinoxylans (Li et al., 1996a; Mavromichalis et al., 2000), and exogenous β-glucanases and xylanases may contribute to the hydrolysis of these fractions (Owusu-Asiedu et al., 2010).

The effect of dietary exogenous carbohydrate digesting enzymes (hemicellulases, cellulases, xylanases, pectinases, β-glucanases, and α-galactosidases) on digestibility of energy and nutrients in corn and wheat DDGS fed to pig has been studied (Emiola et al., 2009; Yañez et al., 2011), but results have been inconsistent. Pigs fed a barley-SBM diet supplemented with β-glucanases had increased energy and CP digestiblity, but this was not the case if pigs were fed wheat-SBM, corn-SBM, or rye-SBM diets with addition of β-glucanases (Li et al., 1996b). However, pigs that were fed a wheat-DDGS-based diet supplemented with carbohydrase enzymes (xylanase, β-glucanase, and cellulase) had a greater GE digestibility compared with pigs fed diets that were not supplemented with enzymes (Emiola et al., 2009). In contrast, when xylanase was added to a corn-DDGS based diet, no improvement in energy digestibility was observed (Yañez et al., 2011).

Addition of cellulase to DDGS may theoretically result in release of glucose that may be absorbed in the small intestine (Bals et al., 2006), but data to demonstrate this effect under practical conditions are lacking. Pigs fed a sorghum-SBM diet supplemented with the cellulase enzyme did not have improved growth performance or digestibility of DM, N, or GE compared with pigs fed a non-supplemented diet (Kim et al., 1998; Park et al., 2003). However, addition of enzymes as cocktails tends to have a better effect compared with addition of single enzymes. Kim et al. (2003) reported that pigs fed a corn-SBM based diet with addition of a cocktail of enzymes that contained α-galactosidase, β-mannanase, and β-mannosidase had improved energy and AA digestibility and improved G:F compared with pigs fed the same diet without enzymes. A similar response was reported by Omogbenigun et al. (2004) who demonstrated that addition of enzymes (i.e., cellulase, galactanase, mannanase, and pectidase) as a cocktail had a positive effect on GE, starch, NSP, and CP digestibility in diets containing corn, SBM, canola meal, barley, peas, wheat, and wheat by-products fed to pigs.

Exogenous enzymes usually are added during the diet mixing process. Therefore, these enzymes need to be thermostable if any thermal treatment is used. The enzymes also need to be stable in the conditions of the gastrointestinal tract of the pig to avoid reducing activity. However, if exogenous enzymes are used to treat ingredients before they are included in the diet, less variables need to be considered (e.g., thermal treatment, stomach pH, and time). Pigs fed a diet containing pretreated SBM with protease enzyme had no change in G:F compared with pigs fed the untreated SBM (Rooke et al., 1998). This is likely a result of the fact that no improvement in CP and AA digestibility is observed in protease-treated SBM compared with untreated SBM (Caine et al., 1997).

CONCLUSIONS

Fiber is the most indigestible nutrient in pig diets. Therefore, feed technology needs to target this fraction to increase its utilization by pigs. Physical treatments available include roller and hammer mills. Thermal treatments available include pelleting, extrusion, and expansion. Chemicals treatments such as NaOH, ammonia, CaO, and $Ca(OH)_2$ also may be used. Carbohydrate-digesting enzymes also may be used individually or as cocktails to improve fermentation of the indigestible fraction of the diets. There is, however, a lack of knowledge about the ideal particle size that provides the best utilization of energy and nutrients from ingredients by pigs. Likewise, interactions among type of diet and physical or thermal treatments have not been investigated and effects of chemical treatments and enzymes additions to diets fed to pigs containing high fiber ingredients, are not well understood.

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CHAPTER 3

EFFECTS OF REDUCING THE PARTICLE SIZE OF CORN ON THE CONCENTRATION OF DIGESTIBLE AND METABOLIZABLE ENERGY AND ON THE DIGESTIBILITY OF ENERGY AND NUTRIENTS BY GROWING PIGS

ABSTRACT: Two experiments were conducted to determine the apparent ileal digestibility (AID) of starch and GE, the standardized ileal digestibility (SID) of CP and AA, the concentration of DE and ME, and the standardized total tract digestibility (STTD) of P in corn ground to 4 different particle sizes (i.e., 865, 677, 485, and 339 μm). In Exp. 1, 10 growing barrows (initial BW: 29.2 ± 1.35 kg) were surgically equipped with a T-cannula in the distal ileum and randomly allotted to a replicated 5 × 5 Latin square design with 5 diets and 5 periods in each square. One lot of corn was divided into 4 batches that were ground to the specified particle sizes and each batch was used in one diet that contained 96.55% corn (as-fed basis) as the only source of starch, GE, and AA. A N-free diet was used to determine endogenous losses of CP and AA. Ileal digesta were collected for 8 h on d 6 and 7 of each period. Results indicated that the AID of starch and GE was increased (linear, $P < 0.05$) as the particle size decreased from 865 to 339 μm. With the exception of Trp, there was no impact of corn particle size on the SID of CP or any indispensable AA. In Exp. 2, 40 growing barrows (initial BW 22.8 ± 2.13 kg) were placed in metabolism cages and allotted to a randomized complete block design with 4 diets and 10 replicate pigs per diet. Each of the 4 diets contained one of the 4 batches of corn used in Exp. 1 (97.7%, as-fed basis) as the only source of GE and P. Vitamins and

all minerals except P were included in the diets to meet the requirements for growing pigs. Feces and urine were collected quantitatively for 5 d. Results indicated that the concentration of ME was 3,826, 3,868, 3,895, and 3,964 kcal/kg DM for corn ground to a mean particle size of 865, 677, 485, and 339 μm, respectively. The ME concentration increased (linear and quadratic, $P < 0.01$) as the particle size decreased. The STTD of P was 37.4, 37.3, 37.1, and 37.8% for corn ground to a mean particle size of 865, 677, 485, and 339 μm, respectively, and these values were not different. In conclusion, decreasing the particle size of corn from 865 to 339 μm linearly increased the concentration of DE and ME and the AID of starch and GE in corn, but the particle size of corn did not affect the STTD of P or the SID of indispensable AA and CP.

Key words: amino acids, corn, energy digestibility, particle size, pig, starch

INTRODUCTION

Grinding of feed ingredients is used to reduce the particle size and increase energy and nutrient digestibility (Wondra et al., 1995d; Laurinen et al., 2000; Mavromichalis et al., 2000; Kim et al., 2002) and it is usually accomplished with the use of either roller mills, hammer mills, or a combination of roller and hammer mills. It is currently recommended that corn grain be milled to an average particle size of 640 to 650 μm (Wondra et al., 1995b; Kim et al., 2002), but the apparent total tract digestibility (**ATTD**) of energy, DM, and N in corn fed to finishing pigs or sows increases as the particle size of the grain is reduced (Healy et al., 1994; Wondra et al., 1995a-d). There is also a tendency for an increase in the SID of AA in soybean meal as particle size is reduced (Fastinger and Mahan, 2003), but there is no effect of particle size on the ATTD

of P in distillers dried grains with solubles (Liu et al., 2012). However, there are no data that demonstrate the effects of particle size on the standardized ileal digestibility (**SID**) of AA, the apparent ileal digestibility (**AID**) of starch and GE, or the standardized total tract digestibility (**STTD)** of P in corn grain.

Therefore, the objectives of the present experiments were to determine the concentration of DE and ME, the STTD of P, the AID of starch and GE, and the SID of AA and CP in corn grain that was ground to different particle sizes and fed to growing pigs. The hypothesis that there is a linear increase in the concentration of DE and ME and in the digestibility of AA, starch, GE, and P in corn, as particle size is reduced was tested.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocols for these experiments. Pigs used in the experiments were the offspring of G-performer boars mated to F-25 gilts (Genetiporc, Alexandria, MN). The same batch of corn (Pioneer P0528) was used in all diets in both experiments and the corn was grown in IA in 2011. The corn grain was first rolled using an automatic roller mill (Model CSU 500, 2 stage; Automatic Equipment Mfg. Co., Pender, NE) to obtain a particle size of 2,000 μm. The rolled grain was then divided into 4 batches that were ground using a hammer mill (Model #EL-9506-TF; Bliss Industries, Ponca City, OK) with 15.88, 9.53, 3.97, or 1.19 mm screens to obtain average final particle sizes of 865, 677, 485, and 339 μm, respectively. The grain was milled at the Pioneer Hi-Bred Feed Mill in Johnston, IA, and stored at 15ºC until used (Table 3.1).

Exp. 1: Ileal Digestibility of CP, AA, Starch, and GE

Diets, Animals, and Experimental Design. Experiment 1 was designed to determine the AID and the SID of CP and AA and the AID of starch and GE in the 4 batches of corn ground to different particle sizes. Ten growing barrows (initial BW: 29.2 ± 1.35 kg) were equipped with a T-cannula in the distal ileum according to procedures adapted from Stein et al. (1998). Pigs were allotted to a replicated 5 × 5 Latin square design with 5 diets and 5 periods in each square. Pigs were housed in individual pens (1.2 × 1.5 m) in an environmentally controlled room. A feeder and a nipple drinker were installed in each pen.

Five diets were formulated (Tables 3.2 and 3.3). Four of the diets each contained 1 of the 4 batches of corn (96.55%, as-fed basis) and corn was the only ingredient contributing AA, CP, starch, and GE to the diet. The last diet was a N-free diet that was used to measure basal endogenous losses of AA and CP. Chromic oxide (0.4%) was included in all diets as an indigestible marker and vitamins and minerals were included in all diets to meet or exceed current requirement estimates (NRC, 1998).

Feeding and Sample Collection. All pigs were fed at a level of 3 times the maintenance energy requirement (i.e., 106 kcal ME per kg $^{0.75}$; NRC, 1998). The daily allotment of feed was divided into 2 equal meals that were provided at 0700 and 1700 h. Water was available at all times throughout the experiment. Pig weights were recorded at the beginning and at the end of each period and the amount of feed supplied each day was recorded. The initial 5 d of each period was considered an adaptation period to the diet. During the adaptation period, 50 g of an AA mixture (Table 3.5) was provided at each meal in addition to the allotted quantity of the experimental diet. The reason for adding

the AA mixture was to reduce the effects of feeding diets that did not meet the pig's requirement for all AA (Pedersen et al., 2007). Ileal digesta were collected for 8 h on d 6 and 7. A 225-mL plastic bag was attached to the cannula barrel by a zip tie, and digesta that flowed into the bag were collected. Bags were removed whenever they were filled with digesta, or at least once every 30 min. They were then stored at -20ºC to prevent bacterial degradation of AA in the digesta.

Sample Analysis. At the conclusion of the experiment, ileal samples were thawed, mixed within animal and diet, and a subsample was collected for chemical analysis. Ileal digesta samples were lyophilized and finely ground prior to chemical analysis. All samples of digesta, diets, and ingredients were analyzed for DM (Method 930.15; AOAC Int., 2007), CP by combustion (Method 999.03; AOAC Int., 2007) using a Rapid N cube apparatus (Elementar Americas Inc, Mt. Laurel, NJ), starch (Method 76-13; AACC Int., 2000) using a modified starch assay kit (product code STA-20, Sigma, St. Louis, MO), and AA [Method 982.30 E (a, b, c); AOAC Int., 2007]. Chromium concentrations of diets and ileal digesta were also determined (Fenton and Fenton, 1979). All diet and ingredient samples also were analyzed for ash (Method 942.05; AOAC Int., 2007) and for GE using an isoperibol bomb calorimetry (Model 6300, Parr Instruments, Moline, IL), ADF (Method 973.18; AOAC Int., 2007), and NDF (Holst, 1973). Ingredients were analyzed for acid hydrolyzed ether extract (**AEE**), which was determined by acid hydrolysis using 3*N* HCl (Sanderson, 1986) followed by crude fat extraction with petroleum ether (Method 2003.06, AOAC Int., 2007) on a Soxtec 2050 automated analyzer (FOSS North America, Eden Prairie, MN) and for P and Ca by inductively coupled plasma spectroscopy (Method 975.03; AOAC Int., 2007) after wet ash sample preparation

(Method 975.03; AOAC Int., 2007). Bulk density, filling angle of repose, and water binding capacity (**WBC**) in the corn grain were determined as described by Cromwell et al. (2000), Appel (1994), and Robertson et al. (2000), respectively.

Calculations and Statistical Analysis. Particle size distribution and mean particle size of the corn samples were determined using 100 g of grain that was placed on top of the test sieves (U.S. sieve # 4, 6, 8, 12, 16, 20, 30, 40, 50, 70, 100, 140, 200, 270, and a solid metal pan), which were stacked from the greater to the smallest aperture size. The test sieves then were placed in a vibratory sieve shaker for 10 min. The feedstuff material in each of the test sieves was recorded and weighed for calculations of particle size distribution and mean particle size. After determination of the mean particle size as described by ASAE (2008), the surface area was calculated using mean particle size of the grain as a reference (ASAE, 2008).

Values for AID, basal endogenous losses, and SID of CP and AA in the diets were calculated (Stein et al., 2007) and the AID of starch and GE was calculated using the same equation as for AID of CP and AA. Data were analyzed by ANOVA using the MIXED procedure (SAS Institute Inc., Cary, NC). Least Squares Means were used to calculate mean values for each independent variable. Homogeneity of variances among treatments was confirmed using the HOVTEST of SAS. Outliers were determined using the UNIVARIATE procedure of SAS as values that deviated from the treatment mean by more than 1.5 times the interquantile range (Devore and Peck, 1993). Two outliers were detected and removed from the data set (the outliers were from pigs fed the diets containing corn ground to a mean particle size of 677 and 865 μm, respectively). Orthogonal polynomial contrasts were used to analyze effects of decreasing corn particle

size. The particle size of each batch of corn was used in the calculations to determine the appropriate coefficients for unequally spaced particle sizes of corn using the interactive matrix language procedure in SAS. The pig was the experimental unit, and an α-value of 0.05 was used to assess significance among means and tendencies were considered if $P > 0.05$ and $P \leq 0.10$.

Exp. 2: Total tract digestivility of GE and P

Diets, Animals, and Experimental Design. Experiment 2 was designed to determine the concentration of DE and ME, the ATTD of GE, and the ATTD and STTD of P in the 4 batches of corn that were used in Exp. 1. Forty barrows (initial BW 22.8 ± 2.13 kg) were allotted to a randomized complete block design with 4 diets and 10 replicate pigs per diet and placed in metabolism cages that were equipped with a feeder and a nipple drinker, fully slatted floors, a screen floor, and urine trays, which allowed for the total, but separate, collection of urine and fecal materials from each pig.

Four corn-based diets that contained 97.7% corn were formulated (Tables 3.2 and 3.4). Vitamins and minerals were included in the diets to meet the requirement for growing pigs (NRC, 1998) with the exception that no inorganic P was used, and all P in the diets originated from corn. The 4 diets were similar with the exception that the corn used in each diet was ground to a different mean particle size (i.e., 865, 677, 485, and 339 μm) as explained for Exp. 1.

Feeding and Sample Collection. The quantity of feed provided per pig daily was calculated as 3 times the estimated requirement for maintenance energy (i.e., 106 kcal ME per kg $^{0.75}$; NRC, 1998) for the smallest pig in each replicate and divided into 2 equal meals that were fed at 0800 and 1700 h. Water was available at all times. Individual pig

BW was recorded at the beginning and at the end of the experiment and the amount of feed supplied each day was also recorded.

The experimental diets were fed to pigs for 12 d. The initial 5 d were considered an adaptation period to the diet, and urine and fecal samples were collected during the following 5 d according to standard procedures using the marker to marker approach (Adeola, 2001). Feces were collecting twice daily and stored at -20ºC immediately after collection. Urine buckets were placed under the metabolism cages to permit total collection. They were emptied in the morning and afternoon and a preservative of 50 mL of 6*N* HCl was added to each bucket when they were emptied. The collected urine was weighed and a 20% subsample was stored at -20ºC.

Sample Analysis. At the conclusion of the experiment, urine samples were thawed and mixed, and a subsample was collected for analysis. Fecal samples were dried at 65ºC in a forced-air oven and ground through a 1-mm screen in a Wiley mill (model 4; Thomas Scientific, Swedesboro, NJ) before analyses. Urine samples were prepared and lyophilized before energy analysis as previously described (Kim et al., 2009a). All samples were analyzed in duplicate. Diets were analyzed for CP, ash, NDF, ADF, and Ca as described for Exp. 1, and diets, feces, and urine samples were analyzed for GE as described for Exp. 1. Diets and fecal samples were also analyzed for DM and P as described for Exp. 1.

Calculations and Statistical Analysis. The quantities of energy lost in the feces and in the urine, respectively, were calculated, and the DE and ME in each of the 4 diets were calculated (Widmer et al., 2007). The DE and ME in the corn included in each diet was then calculated by dividing the DE and ME for the corn diet by the inclusion rate of corn

in the diet. The amount of P in the feces was subtracted from the P in the diet and the ATTD of P was calculated (Almeida and Stein, 2010) and by correcting the ATTD of P for the basal endogenous loss of P (200 mg/kg DMI; Stein, 2011), values for STTD of P were calculated.

Data were analyzed by ANOVA using the Proc Mixed Procedure of SAS (SAS Institute Inc., Cary, NC) as described for Exp. 1. Least Squares Means, homogeneity of variances, and identification of outliers were determined as described for Exp. 1, but no outliers were observed. The effect of decreasing the particle size of corn was analyzed by orthogonal polynomial contrasts as described for Exp 1.

RESULTS

Grinding did not change the gross composition of the corn grain and in general, the nutrient composition was in agreement with values for yellow dent corn (NRC, 2012). The standard deviation (**SD**) of the particle size and bulk density decreased (linear and quadratic, $P < 0.01$) as the particle size decreased from 865 to 339 μm (Table 3.6). In contrast to the SD, surface area of particle sizes increased (linear and quadratic, $P < 0.01$) as the particle size was reduced. Filling angle of repose also increased (linear $P < 0.01$) as corn particle size was reduced. There were no differences among treatments in WBC.

Exp. 1: Ileal Digestibility of CP, AA, Starch, and GE

The AID of starch and GE increased (linear, $P < 0.05$) as the particle size decreased from 865 to 339 μm (Table 3.7), but there were no differences in the AID of CP or indispensable AA among diets, except for the AID of Trp, which was reduced at the greatest particle size (quadratic $P < 0.05$). The average AID of indispensable AA was

also not different among treatments. Likewise, the AID of all dispensable AA was not different among diets, except that the AID of Gly increased (linear, $P < 0.01$) as particle size of corn decreased. The SID of CP and all indispensable and dispensable AA was not affected by the particle size of corn (Table 3.8), except for the SID of Trp, which was reduced as particle size was reduced (quadratic $P < 0.05$) The average SID of indispensable and dispensable AA also was not different among diets.

Exp. 2: Total Tract Digestivility of GE and P

There were no differences in GE intake or in fecal or urine excretion of GE among pigs fed diets containing corn ground to different particle sizes (Table 3.9). However, the ATTD of GE was increased (linear and quadratic, $P < 0.01$) as the particle size decreased from 865 to 339 μm. The concentration of DE (as-fed and DM basis) increased (linear and quadratic, $P < 0.05$) as the particle decreased from 865 to 339 μm. Likewise, the ME concentration, calculated on an as-fed or on a DM basis, increased from 3,311 to 3,432 kcal/kg and from 3,826 to 3,964 kcal/kg, respectively, when corn particle size decreased from 865 to 339 μm.

There were no differences in ADFI and P intake among pigs fed the 4 experimental diets (Table 3.10). The concentration of P in feces increased linearly ($P < 0.01$) as corn particle size decreased from 865 to 339 μm. However, there were no differences in total P output and absorbed P among diets. Likewise, the ATTD and STTD of P did not change as particle size of corn changed.

DISCUSSION

Cereal grains and pulse crops are usually ground before being included in diets fed to pigs. Both roller mills and hammer mills can be used to grind cereal grains and the choice between them often is based on the grinding capacity needed, electricity efficiency, and type of feedstuffs used (Hancock and Behnke, 2001). A roller mill is more energy efficient than a hammer mill, but roller mills can usually not grind corn to particle sizes of less than approximately 600 μm, whereas hammer mills can grind corn to 300 μm or less. In some previous experiments in which particle sizes of corn have been evaluated, the greatest particle size was achieved using a roller mill, whereas the smaller particle sizes were obtained using a hammer mill (Wondra et al., 1994c,d). By using such an approach, it is not possible to distinguish between effects of mill type and effects of changing particle size. In the present experiment, grains were first rolled and then processed in a hammer mill. By using this approach, we attempted to eliminate the effect of mill type on digestibility values. This type of grinding also is used in many newer feed mills in which a 2-stage or a multistage grinding system is used to minimize variation in particle size and maximize grinding efficiency.

The concentration of GE, CP, DM, P, Ca, AEE, and AA in the corn used in this experiment is in agreement with recently reported values (Pedersen et al., 2007; Soares et al., 2011; NRC, 2012). The decrease in SD and the increase in surface area that was observed as particle size decreased are in agreement with values reported by Wondra et al. (1994d). The increased filling angle of repose as the mean corn particle size decreased indicates that as particle size is reduced, flowability of the feed also may be reduced. This observation concurs with data demonstrating that diets containing finely ground distillers

dried grains with solubles or soybean meal have a poor flowability compared with diets containing coarser ground distillers dried grains with solubles and soybean meal (Lawrence et al., 2003; Liu et al., 2012). The reduction in bulk density observed as corn particle size decreased may exacerbate the poor flowability of finely ground corn compared with coarsely ground corn because bulk density may be an indicator of efficient handling capacity in bins and feeders (Rosentrater, 2012).

Water binding capacity reflects the amount of water that may be retained after the fiber is stressed (Cho et al., 1997). The lack of differences in water binding capacity among corn ground to different particle sizes indicates that absorption of water is not influenced by the particle size of corn.

Pigs fed ingredients with a reduced particle size may develop gastric ulcers (Mahan et al., 1966; Maxwell et al., 1970; Wondra et al., 1995a) and development of ulcers is considered one of the major reasons for economical losses in the U.S. swine industry (Friendship, 2003). However, because of the short time diets were fed in the present experiments, it was not possible to investigate effects of diets on development of ulcers.

Exp. 1: Ileal Digestibility of CP, AA, Starch, and GE

The AID and SID of AA in corn obtained in this experiment are within the range of values reported in previous experiments (Bohlke et al., 2005; NRC, 2012). The fact that particle size of corn did not influence the AID and SID of AA concurs with observations by Fastinger and Mahan (2003) who reported that a reduction in particle size of soybean meal from 949 to 185 μm has no effect on the SID of indispensable AA.

In contrast, the SID of AA in lupins increases as particle size decreases (Kim et al., 2009b).

Values for the AID of starch that were observed in this experiment for corn ground to 485 or 677 μm concur with values reported by Everts et al. (1996) and Cervantes-Pahm et al. (2014). Starch is the main form of energy storage in grains (Liu, 2012) and it is mainly digested in the small intestine. However, there is a portion of the starch that is not well digested, and this starch will be fermented in the large intestine (Champ, 2004). The concentration of starch in corn used in this experiment concurs with values reported by Li et al. (2006). The increase in the AID of GE and starch in corn that was observed as particle size decreased is likely a result of increased access to the starch granules for α-amylase, which increases starch digestibility (Reece et al., 1985; Kim et al., 2002; Fastinger and Mahan, 2003). The reduced surface area of grain ground to the greater particle size may have contributed to the reduced access for enzymes (Al-Rabadi et al., 2009).

It is likely that the starch that was not digested in the small intestine was fermented in the large intestine (Bach Knudsen, 2011; NRC, 2012). Therefore, synthesis and absorption of short-chain fatty acids is likely greater in corn ground to a mean particle size of 865 μm than in corn ground to 339 μm and digestibility of starch is increased in grain with large surface area due to a small particle size (Al-Rabadi et al., 2009). Our results support that hypothesis, which indicates that reduction of cereal grain particle size may increase the effectiveness of starch degrading enzymes. However, the fact that AID and SID of CP and AA were not influenced by particle size indicates that protein-digesting enzymes were not hindered by the reduced surface area and greater

particle size in the corn ground to 865 µm. Thus, it appears that finer grinding and greater surface area is more important for starch digesting enzymes to gain access to the starch granules than it is for proteases to gain access to dietary proteins. However, differences among feed ingredients may exist and results from this experiment with corn should, therefore, not be extrapolated to other ingredients.

Exp. 2: Total tract digestivility of GE and P

The concentration of GE, DE, and ME in corn observed in this experiment concurs with reported values (Widmer et al., 2007; NRC, 2012; Rojas and Stein, 2013) and the ATTD of GE was also in good agreement with reported values (Pedersen et al., 2007; Baker and Stein, 2009). The DE:ME ratio obtained for all particle sizes is within the range of reported values (Widmer et al., 2007; NRC, 2012). The increase in DE and ME that was observed as the particle size was reduced is less than the increase reported by Wondra et al. (1994c) when grain with different particle sizes was fed to sows, but in agreement with data reported by Oryschak et al. (2002). The reason for this difference is most likely that sows have a greater ability to ferment fiber and nutrients compared with growing pigs (Noblet and Shi, 1993). The ATTD of GE in DDGS and the concentration of DE and ME also increased when pigs were fed DDGS ground to 308 µm compared with pigs fed DDGS ground to 818 µm (Liu et al., 2012). In contrast, if the particle size of lupins is decreased from 1304 to 567 µm, the ATTD of energy is not affected (Kim et al., 2009b). It is not clear why there is this difference among feed ingredients. The observation that there is no difference in GE excreted in the urine among treatments indicates that the entire improvement in ME of corn that was observed as particle size was reduced is due to the increase in energy digestibility.

The STTD of P in corn that was calculated in this experiment is in agreement with values reported by Li et al. (2013) and NRC (2012). The observation that particle size did not affect the ATTD or STTD of P in corn also concurs with observations by Liu et al. (2012) who reported that reduction of particle size in distillers dried grains with solubles did not influence the ATTD of P. Thus, it appears that reduction in particle size or increases in surface area of corn ground grain are not effective in improving P digestibility in pigs. The reason may be that to increase P digestibility in corn, the enzyme, phytase, is needed and pigs do not secrete phytase in the small intestine.

Conclusions

Reducing the particle size of corn from 865 to 339 μm linearly increased the AID of starch and GE and the concentration of DE and ME in corn. However, there were no effects of corn particle size on the STTD of P or the SID of indispensable AA and CP, except for Trp. The increase in ME may result in improved G:F in pigs and, therefore, reduced feed costs, and even with increases in grinding costs associated with finer grinding, it is likely beneficial to reduce the particle size of corn. However, research to verify this hypothesis is needed. Likewise, the possible effects of corn particle size on gastric ulcers need to be investigated.

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TABLES

Table 3.1. Chemical and physical composition of corn with different particle sizes, as-fed basis

	Corn particle size, μm			
Item	865	677	485	339
GE, kcal/kg	3,920	3,900	3,914	3,870
DM, %	86.54	86.40	86.71	86.30
CP, %	7.08	7.23	7.25	7.00
Ash, %	1.15	1.39	1.23	1.10
AEE[1], %	3.45	3.51	3.53	3.57
NDF, %	11.06	10.01	9.29	9.25
ADF, %	2.41	2.27	2.24	1.91
Starch, %	62.90	61.19	62.73	64.42
P, %	0.31	0.34	0.30	0.29
Ca, %	0.03	0.03	0.03	0.03
Indispensable, AA %				
Arg	0.35	0.37	0.35	0.35
His	0.20	0.21	0.20	0.20
Ile	0.24	0.26	0.25	0.24
Leu	0.85	0.84	0.83	0.83
Lys	0.25	0.26	0.25	0.25
Met	0.14	0.14	0.13	0.14
Phe	0.35	0.35	0.35	0.35
Thr	0.25	0.24	0.25	0.25

Table 3.1. (Cont.)

Trp	0.06	0.05	0.05	0.05
Val	0.35	0.38	0.36	0.35
Dispensable, AA %				
Ala	0.51	0.52	0.51	0.51
Asp	0.49	0.50	0.49	0.49
Cys	0.15	0.15	0.14	0.15
Glu	1.28	1.25	1.26	1.26
Gly	0.30	0.30	0.30	0.30
Pro	0.64	0.62	0.64	0.63
Ser	0.32	0.30	0.30	0.31
Tyr	0.20	0.22	0.20	0.21
Total AA	6.93	6.96	6.86	6.87

[1]AEE = acid hydrolyzed ether extract.

Table 3.2. Composition of experimental diets containing corn that was ground to different particle sizes and in the N-free diet, as-fed basis, Exp. 1 and Exp. 2

	Exp 1		Exp 2
Item, %	Corn[1]	N-free	Corn[1]
Ground corn	96.55	-	97.70
Sucrose	-	20.00	-
Cornstarch	-	67.60	-
Solka floc	-	4.00	-
Soybean oil	-	4.00	-
Ground limestone	0.85	0.20	1.60
Magnesium oxide	-	0.10	-
Potassium carbonate	-	0.40	-
Dicalcium phosphate	1.50	2.60	-
Sodium chloride	0.40	0.40	0.40
Chromic oxide	0.40	0.40	-
Vitamin mineral premix[2]	0.30	0.30	0.30
Total	100.00	100.00	100.00

[1]Four diets that contained corn ground to a mean particle size of 339, 485, 677, or 865 μm were formulated within each experiment.

[2]Provided the following quantities of vitamins and microminerals per kilogram of complete diet: vitamin A as retinyl acetate, 11,128 IU; vitamin D_3 as cholecalciferol, 2,204 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.58 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin as nicotinamide and

Table 3.2. (Cont.)

nicotinic acid, 44 mg; folic acid, 1.58 mg; biotin, 0.44 mg; Cu, 10 mg as copper sulfate; Fe, 125 mg as iron sulfate; I, 1.26 mg as potassium iodate; Mn, 60 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; and Zn, 100 mg as zinc oxide.

Table 3.3. Analyzed nutrient composition of experimental diets, as-fed basis, Exp. 1

Item	Corn particle size, μm				N-free[1]
	865	677	485	339	
GE, kcal/kg	3,678	3,700	3,726	3,725	3,753
DM, %	86.72	86.59	86.58	86.59	90.87
CP, %	6.65	6.21	7.16	7.00	0.30
Ash, %	4.55	3.93	3.93	4.04	3.91
NDF, %	8.83	8.34	8.13	8.75	4.62
ADF, %	1.97	2.18	2.16	2.01	3.19
Starch, %	66.22	61.79	59.71	63.13	-
Indispensable, AA %					
Arg	0.33	0.30	0.33	0.34	0.01
His	0.19	0.18	0.19	0.19	0.00
Ile	0.24	0.22	0.24	0.23	0.01
Leu	0.80	0.78	0.81	0.82	0.03
Lys	0.23	0.22	0.23	0.24	0.01
Met	0.13	0.12	0.13	0.13	0.00
Phe	0.33	0.32	0.34	0.34	0.02
Thr	0.23	0.23	0.24	0.25	0.01
Trp	0.04	0.05	0.05	0.06	0.03
Val	0.35	0.32	0.34	0.34	0.00
Dispensable, AA %					
Ala	0.48	0.47	0.49	0.50	0.03
Asp	0.47	0.45	0.47	0.48	0.02
Cys	0.14	0.13	0.13	0.14	0.00

Table 3.3. (Cont.)

Glu	1.20	1.17	1.21	1.24	0.04
Gly	0.29	0.27	0.29	0.30	0.02
Pro	0.61	0.59	0.62	0.63	0.06
Ser	0.26	0.28	0.27	0.30	0.01
Tyr	0.19	0.18	0.20	0.21	0.01
Total AA	6.51	6.28	6.58	6.74	0.31

[1]N-free = nitrogen free diet.

Table 3.4. Analyzed composition of experimental diets containing corn that was ground to different particle sizes, as-fed basis, Exp. 2

	Corn particle size, μm			
Item	865	677	485	339
GE, kcal/kg	3,799	3,736	3,776	3,783
DM, %	86.54	86.5	86.54	86.57
CP, %	6.85	6.85	6.97	6.77
Ash, %	2.54	2.86	2.60	2.90
P, %	0.31	0.28	0.26	0.28
Ca, %	0.51	0.75	0.66	0.61
NDF, %	9.78	9.72	8.03	8.26
ADF, %	1.89	1.85	1.80	1.55

Table 3.5. Composition of the AA mixture used in Exp. 1, as-fed basis[1]

AA	Inclusion, %
L-Gly	41.20
L-Lys-HCl	20.50
DL-Met	3.30
L-Thr	8.40
L-Trp	2.70
L-Ile	6.30
L-Val	7.40
L-His	3.70
L-Phe	6.50
Total	100.00

[1]The AA mixture was fed to the pigs used in Exp. 1 in the amount of 100 g per d for the initial 5 d of each period, but the mixture was not fed on d 6 and 7 when ileal digesta were collected.

Table 3.6. Physical composition of corn grains, as fed basis[1]

Item	Corn particle size, µm				SEM	*P*-value	
	865	677	485	339		Linear	Quadratic
SD[2] of particle size	3.15	3.20	2.92	1.89	0.02	< 0.01	< 0.01
Surface area cm^2/g	101.4	132.1	166.6	164.5	1.97	< 0.01	< 0.01
Filling angle of repose, º	46.8	50.7	54.9	57.4	0.13	< 0.01	0.07
Bulk density, g/L	650.6	631.5	601.4	564.5	1.91	< 0.01	< 0.01
Water binding capacity, g/g	2.2	2.2	2.3	2.3	0.03	0.19	0.71

[1]Data are least squares means of 2 observations per treatment.

[2]SD = Standard deviation.

Table 3.7. Apparent ileal digestibility (AID) of GE, starch, CP, and AA (%) in corn that was ground to different particle sizes and fed to growing pigs, Exp. 1[1]

Item	Corn particle size, μm					*P*-value	
	865	677	485	339	Pooled SEM	Linear	Quadratic
GE, %	66.1	69.2	71.6	74.3	4.77	0.03	0.96
Starch, %	89.0	92.6	93.9	96.6	1.32	< 0.01	0.82
CP, %	43.6	42.2	51.2	48.9	4.97	0.11	0.94
Indispensable AA, %							
Arg	70.9	68.1	72.7	71.4	3.03	0.56	0.65
His	74.6	75.0	74.8	72.4	2.30	0.37	0.34
Ile	62.0	62.4	63.1	60.1	4.23	0.65	0.48
Leu	77.1	79.3	78.7	77.8	2.06	0.74	0.23
Lys	51.7	53.7	54.4	54.7	5.92	0.59	0.86
Met	76.2	75.7	76.7	76.5	2.47	0.74	0.88
Phe	71.1	72.0	73.2	71.1	2.91	0.81	0.40
Thr	46.6	51.4	49.4	46.5	5.86	0.92	0.28
Trp	43.0	56.9	56.5	52.5	6.30	0.06	0.01
Val	65.1	65.1	64.3	61.1	4.12	0.21	0.43
Mean	67.9	68.4	68.6	67.5	3.34	0.92	0.69
Dispensable AA, %							
Ala	65.3	66.5	67.9	69.1	3.18	0.15	0.95
Asp	61.2	61.7	61.7	62.0	4.08	0.83	0.97
Cys	66.5	66.7	63.9	62.7	3.24	0.12	0.63
Glu	75.8	77.2	77.1	76.8	2.15	0.61	0.53

Table 3.7. (Cont.)

Gly	21.1	26.7	30.6	41.3	5.98	< 0.01	0.44
Ser	63.6	69.4	66.0	66.9	3.10	0.51	0.24
Tyr	60.8	61.9	64.6	63.5	4.04	0.25	0.70
Mean	54.6	50.9	58.1	59.2	4.60	0.15	0.36
All AA	61.0	59.7	64.1	63.6	3.46	0.23	0.75

[1]Data are least squares means of 10 observations, except for the treatments with corn ground to 677 and 865 μm, which had only 9 observations.

Table 3.8. Standardized ileal digestibility (SID) of CP and AA (%) in corn that was ground to different particle sizes and fed to growing pigs, Exp. 1[1]

Item	Corn particle size, µm				Pooled SEM	*P*-value	
	865	677	485	339		Linear	Quadratic
CP %	71.7	72.2	77.2	75.5	4.97	0.28	0.83
Indispensable AA, %							
Arg	93.1	92.4	94.8	92.8	3.03	0.85	0.84
His	83.0	83.9	83.2	80.8	2.30	0.33	0.26
Ile	75.3	76.8	76.3	73.9	4.23	0.68	0.38
Leu	83.5	86.0	85.0	84.1	2.06	0.84	0.19
Lys	72.3	72.5	74.9	74.7	5.84	0.59	0.99
Met	82.3	82.4	82.9	82.6	2.47	0.80	0.95
Phe	80.8	82.1	82.7	80.6	2.91	0.96	0.34
Thr	68.9	73.6	70.7	66.9	5.86	0.63	0.23
Trp	70.3	78.6	78.2	70.6	6.34	0.87	0.02
Val	77.8	79.0	77.4	74.1	4.13	0.22	0.29
Mean	80.8	81.8	81.3	80.0	3.34	0.77	0.54
Indispensable AA, %							
Ala	79.3	80.8	81.6	82.5	3.17	0.23	0.91
Asp	77.1	78.2	77.6	77.5	4.08	0.95	0.79
Cys	77.8	78.9	76.1	74.0	3.23	0.13	0.36
Glu	83.5	85.1	84.7	84.2	2.15	0.74	0.44

Table 3.8. (Cont.)

Gly	82.3	88.2	95.0	84.8	8.11	0.57	0.26
Ser	80.7	85.3	82.5	81.7	3.10	0.96	0.21
Tyr	75.2	77.0	78.3	76.5	4.04	0.56	0.45
Mean	89.6	90.9	93.7	92.7	4.15	0.40	0.80
All AA	84.7	84.2	87.5	86.4	3.46	0.39	0.98

[1]Data are least squares means of 10 observations, except for the treatments with corn ground to 677 and 865 μm, which had only 9 observations.

[2]Values for SID were calculated by correcting the values for AID for basal ileal endogenous losses. Basal ileal endogenous losses were determined (g/kg of DMI) as CP, 21.50; Arg, 0.84; His, 0.18; Ile, 0.37; Leu, 0.60; Lys, 0.56; Met, 0.09; Phe, 0.37; Thr, 0.59; Trp, 0.13; Val, 0.51; Ala, 0.77; Asp, 0.86; Cys, 0.18; Glu, 1.06; Gly, 2.20; Ser, 0.51; and Tyr, 0.32.

Table 3.9. Concentration of digestible energy (DE) and metabolizable energy (ME), and apparent total tract digestibility (ATTD) of gross energy (GE) in corn that was ground to different particle sizes, as-fed basis, Exp. 2[1]

	Corn particle size, μm					*P*-value	
Item	865	677	485	339	Pooled SEM	Linear	Quadratic
GE intake, kcal/d	3,425	3,587	3,497	3,500	133.17	0.91	0.85
GE in feces, kcal/d	386.9	385.6	341.8	325.9	29.62	0.16	0.39
GE in urine, kcal/d	94.3	87.6	100.9	106.5	10.32	0.12	0.16
ATTD of GE, %	88.7	89.2	90.3	91.6	0.51	< 0.01	< 0.01
DE, kcal/kg	3,402	3,441	3,492	3,547	24.58	0.01	0.01
DE, kcal/kg DM	3,932	3,978	4,035	4,097	28.40	0.02	0.02
ME, kcal/kg	3,311	3,346	3,371	3,432	19.54	< 0.01	< 0.01
ME, kcal/kg DM	3,826	3,868	3,895	3,964	22.58	< 0.01	< 0.01

[1]Data are means of 10 observations per treatment.

Table 3.10. Effect of particle size on apparent total tract digestibility (ATTD) and standardized total tract digestibility (STTD) of P in corn, Exp. 2[1]

Item	Corn particle size, µm				Pooled SEM	*P*-value	
	865	677	485	339		Linear	Quadratic
Feed intake, g DM/d	796.8	800.8	778.1	782.2	33.80	0.58	0.95
P intake, g/d	2.48	2.67	2.60	2.57	0.12	0.63	0.22
P in feces, %	2.15	2.31	2.56	2.65	0.12	< 0.01	0.91
P output, g/d	1.71	1.84	1.79	1.81	0.12	0.49	0.44
Absorbed P, g/d	0.77	0.83	0.81	0.76	0.10	0.92	0.69
ATTD of P, %	31.3	31.1	31.0	29.6	3.32	0.67	0.81
STTD of P[2], %	37.4	37.3	37.1	37.8	2.99	0.99	0.87

[1]Data are means of 10 observations per treatment.

[2]Values for STTD were calculated by correcting values for ATTD for basal EPL (200 mg/kg DMI; Stein, 2011).

CHAPTER 4

ADDITION OF DIETARY LIPIDS CAN BE REDUCED IF CORN IS GROUND TO A SMALLER PARTICLE SIZE WITHOUT IMPACTING GROWTH PERFORMANCE OR CARCASS CHARACTERISTICS OF GROWING – FINISHING PIGS

ABSTRACT: In a previous experiment, it was documented that the ME of corn grain increases linearly as the particle size of corn is decreased from 865 to 339 μm. Because of this increase in ME of corn, it was hypothesized that addition of dietary lipids can be reduced if corn particle size is reduced without affecting growth performance and carcass characteristics of growing-finishing pigs. A total of 72 individually penned pigs, 36 gilts and 36 barrows (initial BW: 32.00 ± 1.58 kg), were randomly allotted to 4 dietary treatments in a 2 × 4 factorial design with sex (gilts and barrows) and corn particle size (i.e., 865, 677, 485, and 339 μm) as factors. There were 18 replicate pigs (i.e., 9 gilts and 9 barrows) per treatment. Pigs were fed a 3 phase program with phase 1 diets being offered from approximately 32 to 62 kg, phase 2 diets from 62 to 94 kg, and phase 3 diets from 94 to 129 kg. Within each phase, 4 corn-soybean meal based diets were formulated, and the only difference among diets was that the corn that was used was ground to the 4 specified particle sizes and soybean oil was added to the diets in decreasing amounts as corn particle size was reduced to reflect the increase in ME in corn with reduced particle size. Results of the experiment indicated that initial BW, final BW, overall ADFI, and overall ADG were not different among treatments, but final G:F ratio for gilts decreased (linear, $P < 0.05$) as the particle size decreased, but that was not the case for barrows

(interaction, $P < 0.05$). However, G:F ratio did not change ($P > 0.05$) if calculated based on HCW because dressing percentage increased (linear, $P < 0.01$) as particle size decreased. Back fat, HCW loin eye area, and carcass fat-free lean percentage were not different among treatments. There were no incidences of ulcers in the esophageal region of the stomach regardless of the particle size of corn, but parakeratosis in the esophageal region increased ($P < 0.05$) as particle size of corn decreased. The concentration of VFA in cecal contents decreased (linear, $P < 0.01$) as the particle size decreased. In conclusion, by using corn ground to a smaller particle size, the amount of added fat may be reduced in the diets without affected animal growth performance or carcass composition, except that dressing percentage will increase. Thus, diets containing corn ground to a smaller particle size will be less expensive to formulate compared with diets containing corn ground to a greater particle size.

Key words: carcass characteristics, corn, fatty acids, growth performance, particle size, pigs

INTRODUCTION

Grinding of feed ingredients is used to reduce the particle size and thereby increase the digestibility of energy and nutrients. Reduction of cereal grain particle size may increase enzyme surface action, which leads to increased energy and nutrient digestibility (Kim et al., 2002; Fastinger and Mahan, 2003). In a recent experiment, we demonstrated that a reduction in the particle size of corn from 865 to 677, 485, or 339 µm results in a linear increase in the ME of corn and ME values of 3,816, 3,868, 3,895, and 3,964 kcal/kg DM were calculated for the 4 particle sizes (Rojas and Stein, 2013). These

results are in agreement with previous data (Wondra et al., 1994a-d). The primary reason for the increased ME in corn ground to a smaller particle size is that the apparent ileal digestibility of starch is increased as corn particle is reduced (Rojas and Stein, 2013). In contrast, the standardized total tract digestibility of P and the standardized ileal digestibility of AA in corn were not influenced by corn particle size (Rojas and Stein, 2013). Because of the increased ME of corn ground to a smaller particle size, less added fat is needed in diets containing corn ground to a smaller particle size compared with diets containing corn with a greater particle size, if diets are formulated to a constant ME. It is, therefore, expected that addition of fat can be reduced without impacting pig growth performance if corn is ground to a smaller particle size, but this hypothesis has not been verified. Therefore, the objectives of this experiment were to test the hypothesis that addition of dietary lipids can be reduced as corn particle size is reduced without affecting growth performance or carcass composition of growing and finishing pigs. A second objective was to test the hypothesis that synthesis of VFA in the hindgut of pigs is reduced if corn ground to a reduced particle size is included in the diet, because of reduced quantities of starch entering the hindgut.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocol for this experiment.

Animals, Housing, Diets, and Experimental Design

Pigs used in the experiment were the offspring of G-performer boars mated to F-25 gilts (Genetiporc, Alexandria, MN). Corn (Pioneer P 0528) was grown in Iowa in 2011. The procedures used to obtain the desired mean particle sizes (i.e., 865, 677, 485, and 339 μm) of corn was described previously (Rojas and Stein, 2013; Table 4.1). Soybean meal (**SBM**) that was sourced locally (Solae, Gibson City, IL) was also used.

A total of 36 gilts and 36 barrows with an average initial BW of 32.00 ± 1.58 kg were used. All pigs were housed individually in pens (0.9 × 1.8 m) with fully slatted concrete floors. A feeder and a nipple drinker were provided in each pen. Feed and water were provided on an ad libitum basis throughout the experiment. Pigs were fed a 3 phase program (Tables 4.2 and 4.3) with phase 1 diets being offered from approximately 32 to 62 kg, phase 2 diets from approximately 62 to 94 kg, and phase 3 diets from approximately 94 to 129 kg. Within each phase, 4 corn-SBM based diets were formulated to meet or exceed current nutrient requirements (NRC, 2012). Diets within each phase were formulated using corn that was ground to 865, 677, 485, or 339 μm containing values for ME of 3,816, 3,868, 3,895, and 3,964 kcal/kg DM, respectively (Rojas and Stein, 2013). Diets within each phase were formulated to the same concentration of ME and addition of soybean oil was reduced to reflect the increase in ME that was assumed as particle size of corn was reduced. Pigs were randomly allotted to the 4 dietary treatments in a 2 × 4 factorial design with sex (gilts and barrows) and corn particle size as factors. Nine gilts and 9 barrows were allotted to each diet. Two blocks of 36 pigs (18 gilts and 18 barrows) were used for a total of 72 pigs. The 2 blocks were allotted to

treatment diets 7 d apart and pigs in each block were harvested 1 wk apart to maintain the same number of days on feed for all pigs.

Feeding and Data Collection

All pigs were allowed ad libitum access to feed and water throughout the experiment. Individual pig BW was recorded at the start of the experiment, at the end of phase 1, at the end of phase 2, and at the conclusion of the experiment (d 93). Phases 1 and 2 each lasted 29 d and phase 3 lasted 35 d. Daily feed allotments were recorded as well and feed left in the feeders was recorded on the same days as pig weights were recorded. At the conclusion of the experiment, data were summarized to calculate ADG, ADFI, and G:F for each pig within each phase and overall for each sex and diet.

Slaughter, Sample Collection, and Carcass Evaluation

On d 93 of the experiment, feed was removed from the feeders and the final BW of pigs was recorded. After an overnight fast, pigs were transported to the Meat Science Laboratory at the University of Illinois (Urbana, IL) to be slaughtered. Pigs were handled, weighted, and slaughtered as described by Lee et al. (2013). The HCW, pH of the longissimus dorsi (**LD**), back fat at the 10^{th} rib, and the loin eye area (**LEA**) were also measured as described by Lee et al. (2013). The digestive tract was flushed with water to remove digesta, and liver, heart, kidney, spleen, stomach, and the intestines were patted dry and weighed. The score for the incidence of ulcers and parakeratosis in the pars esophageal section of the stomach was determined as described by Nielsen and Ingvartsen (2000).

Feces were collected from the anus of the pigs by hand stimulation on the last day of the experiment and pH of the fecal samples was immediately measured using a pH

meter (Accumet Basic, Fisher Scientific, Pittsburgh, PA). The pH of contents collected from the stomach, the ileum, and the cecum were measured at slaughter. Cecal samples (20 g) were also collected at slaughter and mixed with 2*N* HCl in a 1:1 ratio and these samples were stored at -20ºC until analyzed for VFA.

Chemical and Physical Analysis

Diets and ingredients were analyzed for GE using an isoperibol bomb calorimetry (Model 6300 Parr Instruments, Moline, IL), DM (method 930.15; AOAC Int., 2007), CP by combustion (method 999.03; AOAC Int., 2007) on a Rapid N cube apparatus (Elementar Americas Inc, Mt Laurel, NJ), and ash (method 942.05; AOAC Int., 2007). Acid hydrolyzed ether extract (**AEE**) was determined by acid hydrolysis using 3*N* HCl (Sanderson, 1986) followed by crude fat extraction using petroleum ether (method 2003.06, AOAC Int., 2007) on a Soxtec 2050 automated analyzer (FOSS North America, Eden Prairie, MN), and for AA [method 982.30 E (a, b, c); AOAC Int., 2007]. The 4 samples of corn ground to different particle sizes were analyzed for total starch (Thivend et al., 1972), ADF (method 973.18; AOAC Int., 2007), NDF (Holst, 1973), and P and Ca were analyzed by the inductively coupled plasma spectroscopy procedure (method 975.03; AOAC Int., 2007) after wet ash sample preparation (method 975.03; AOAC Int., 2007). All diets and ingredients were ground through a 1-mm screen in a Wiley mill (model 4; Thomas Scientific, Swedesboro, NJ) before analysis. All samples were analyzed in duplicate. The concentration of VFA in cecal samples was measured using the cecal sample that was preserved in HCl. Preparation of the cecal sample for VFA analysis was as described by Urriola and Stein (2010) except that 2 mL of the cecal digesta-HCl mixture was mixed with 8 mL of distilled water. The procedures to

determine VFA were described by Erwin et al. (1961) and Urriola and Stein (2010). Bulk density and filling angle of repose of ingredients and diets were determined as described by Cromwell et al. (2000) and Appel (1994), respectively.

Calculations and Statistical Analysis

Particle size distribution and mean particle size of the corn samples were determined as described previously (Rojas and Stein, 2013). Average daily feed intake, ADG, and G:F were calculated for each treatment and phase and for the entire experimental period. The overall G:F ratio based on HCW was calculated by subtracting the hot carcass weight of pigs at the start of the experiment (Kil, 2008) from the hot carcass weight of pigs at slaughter and divide by the overall ADFI.

Data were analyzed as a 2 × 4 factorial with sex and diet as factors using the MIXED procedure (SAS Inst. Inc., Cary, NC). The model included sex, particle size, and the sex × particle size interaction as fixed effects and block as the random effect. However, interactions between diet and sex were not significant for the response variables analyzed, except for ADFI from d 0 to 29 and G:F ratio from d 29 to 58 and d 0 to 93. Thus, the interaction was removed from the final model and only main effects of sex and particle size were included for the variables that had no interaction. For variables with interaction, interaction was included in the model and results for both gilts and barrow were calculated separately. Homogeneity of variances was confirmed using the HOVTEST of SAS. Outliers were determined using the UNIVARIATE procedure of SAS. Least Squares Means were used to calculate mean values for each independent variable. Linear and quadratic contrasts were used to analyze effects of reducing corn particle size on response variables. Appropriate coefficients for unequally spaced particle

sizes of corn were determined using the interactive matrix language procedure in SAS. Data for stomach morphology were compared using the chi-square (PROC FREQ of SAS), but the average of the lesion of the stomach was analyzed using the MIXED procedure. The pig was the experimental unit for all analyses and an α-value of 0.05 was used to assess significance among means. Tendencies were considered when $P > 0.05$ but $P \leq 0.10$.

RESULTS

One pig fed the diet containing corn with a particle size of 677 μm was removed from the experiment in the second phase because this pig developed a belly abscess. All other pigs remained in good health throughout the experiment and all pigs readily consumed their assigned diets.

Filling angle of repose increased ($P < 0.05$) and bulk density was reduced ($P < 0.05$) as corn particle size was reduced (Table 4.4). This was true for diets used in all 3 phases.

Growth Performance and Ulcer Development

The starting weight and the final weight in each of the 3 phases were not different among dietary treatments (Table 4.5). Likewise, no differences among treatments were observed for ADG in any of the 3 phases or for the overall period. In phase 1, ADFI of gilts increased (linear, $P < 0.01$) as particle size of corn decreased, but for barrows, no effect of particle size was observed (interaction, $P < 0.05$). However, no differences among treatments were observed for ADFI during phase 2 and for the overall

experimental period, but the ADFI for phase 3 increased (linear, $P < 0.05$) as particle size of corn was reduced, regardless of sex of the animals.

The G:F for phase 1 decreased (linear, $P < 0.05$) as particle size of corn was reduced. In phase 2 and over the entire experimental period, G:F of gilts also decreased (linear, $P < 0.01$) as particle size of corn was reduced, but for barrows, no differences among treatments were observed (interaction, $P < 0.05$). During the third phase, no effects of particle size on G:F were observed regardless of sex. If G:F was calculated based on HCW, there were no differences among dietary treatments, regardless of sex of the animals.

Initial BW was greater ($P < 0.01$) in barrows than in gilts. Likewise, barrows had greater ($P < 0.01$) final BW at the end of each of the 3 phases than gilts and the ADG was greater ($P < 0.01$) for barrows in each of the 3 phases and for the overall experiment than for gilts. The ADFI was also greater ($P < 0.01$) for barrows than for gilts for phases 2 and 3 and for the overall experiment, but gilts had greater ($P < 0.01$) G:F than barrows for phase 3, but this was not the case for phase 1.

There were no incidences of ulcers in the stomach of pigs regardless of dietary treatment (Table 4.6). However, the incidences of total stomach parakeratosis increased ($P < 0.01$) as particle size of corn decreased, but minor or medium incidence of parakeratosis were not different among treatments. In contrast, major parakeratosis and average stomach score were greater ($P < 0.05$) in pigs fed corn ground to a finer particle size than in pigs fed corn ground to a coarser particle size.

Carcass Characteristics

There were no differences in live BW, carcass fat-free lean (**FFL**), or HCW among dietary treatments (Table 4.7), but dressing percentage increased (linear, $P < 0.01$) as corn particle size decreased. Values for back fat, LEA, and pH of LEA were not different among dietary treatments, but total organ weight as a percentage of HCW decreased (linear, $P < 0.01$) as corn particle size was reduced. The weight of the empty viscera also decreased (linear, $P < 0.01$) as corn particle size was reduced, but no differences in the weights of liver, heart, kidney, spleen, or stomach were observed among dietary treatments.

Live BW was less ($P < 0.01$) in gilts than in barrows and HCW, dressing percentage, and back fat were also less ($P < 0.01$) in gilts than in barrows. However, no differences were observed for LEA and pH of LEA, but FFL and organ weight as a percentage of HCW were greater ($P < 0.01$) for gilts than for barrows. Organs were heavier ($P < 0.01$) in barrows than in gilts except for spleen and total empty viscera where differences were not observed.

pH and Volatile Fatty Acid Concentration

The pH in the stomach and ileal contents were not affected by treatments, but pH in the cecal and colon contents increased (linear, $P < 0.01$) as the particle size of corn was reduced (Table 4.8). In contrast, the concentration of acetate, propionate, and butyrate in cecal contents was reduced (linear, $P < 0.01$) as corn particle size was reduced.

The pH of the stomach, ileum, cecum, and colon were not different between barrows and gilts. Likewise, no differences were observed in the concentration of acetate, propionate, and butyrate.

DISCUSSION

Physical Characteristics of Diets

The filling angle of repose and bulk density are considered indirect indicators of feed flowability and handling capacity, respectively (Appel, 1994; Cromwell et al., 2000). The filling angle of repose is the angle at which a pile of material maintains its slope without falling apart and it is affected by the physical properties of feed materials such as shape, particle size, and porosity (Lawrence et al., 2003; Rosentrater, 2012). Bulk density represents the amount of feed material that can be stored in bins, containers, and feeders that have a specific volume (Rosentrater, 2012). Therefore, both filling angle of repose and bulk density are important measurements that need to be considered when particle size of cereal grains are modified. A greater filling angle of repose indicates that there is reduced flowability of the feed material and a lower value for bulk density means that less feed material can be stored per volume unit. The reduction in bulk density that was observed as the particle size of diets was reduced indicates that less feed material can be stored in a given bin or feeder if corn is ground to a smaller particle size. An increase in the filling angle of repose in diets containing SBM or distillers dried grains with solubles with a finer particle size have been reported (Lawrence et al., 2003; Liu et al., 2012) and the current data for corn support the observations with SBM and distillers dried grains with solubles. This indicates that there is a poorer flowability of diets if corn, SBM, or distillers dried grains with solubles is ground to a finer particle size than to a coarser particle size.

Growth Performance and Ulcer Development

By formulating diets to a constant ME, the amount of added fat could be reduced as particle size of corn was reduced. The observation that there were no differences among diets in animal growth performance if corrected for HCW despite the differences in inclusion of soybean oil in the diets, indicates that diet costs can be reduced if corn is ground to a finer particle size. The difference in the overall G:F observed in gilts is likely the result of differences in gut fill because HCW was not different among treatments. However, if diet energy concentration is not balanced, there is a reduced ADFI and increased G:F in pig fed corn ground to 400 μm compared with pigs fed corn ground to 1,000 μm (Wondra et al., 1995a). This is likely a result of the greater energy value in corn ground to 400 μm compared with corn ground to 1,000 μm (Wondra et al., 1995a). Improvements in G:F also were observed if finishing pigs were fed wheat that was ground to 600 μm compared with pigs fed wheat ground to 1,300 μm (Mavromichalis et al., 2000). In contrast, growth performance of pigs fed SBM that was ground to 639 μm or 444 μm was not different from that of pigs fed SBM ground to 965 or 1,226 μm (Lawrence et al., 2003). It was hypothesized that the reason for this observation is the relatively low inclusion level of SBM in the diet (Lawrence et al., 2003). Thus, the effect of reduced particle size may only be measurable if a high inclusion rate of the ingredient is used in the diet. Therefore, it may be hypothesized that reduction of particle sizes does not have the same effect among all feed ingredients (Kim et al., 2005).

The esophageal region is the region in the pig stomach that has the greatest risk of developing gastric ulcers when pigs are fed ingredients with a reduced particle size because of the lack of protective mucus in the esophageal region (Mahan et al., 1966;

Maxwell et al., 1970; Varum et al., 2010). Pigs fed corn ground to 1,200 µm have less ulcers and keratinization in the esophageal region compared with pigs fed corn ground to 400 µm (Wondra et al., 1995a). In sows, development of ulcers and parakeratosis increases as particle size of corn decreases from 1,200 to 400 µm (Wondra et al., 1995a) or if a pelleted diet is fed instead of a mash diet (Hancock and Behnke, 2001). The greater average stomach score observed as corn particle decreased had no effect on pig growth performance. This concurs with observations indicating that G:F was not affected in pigs fed diets containing wheat ground to 600 µm even though those pigs had more parakeratosis in the esophageal region compared with pigs fed diets containing wheat ground to 1,300 µm (Mavromichalis et al., 2000). However, parakeratosis may develop into ulcers if pigs are stressed as is often the case in commercial production systems (Ramis et al., 2004).

Carcass Characteristics

The increase in dressing percentage that was observed as pigs were fed diets containing corn ground to a smaller particle size is partly due to a reduction in the intestinal weight. This observation is in agreement with data by Wondra et al. (1995a), and indicates that a greater proportion of diet energy and nutrients is directed towards carcass tissue synthesis compared with synthesis of intestinal tissue. The lack of an effect of corn particle size on FFL is in agreement with data indicating that wheat ground to either 1,300 or 600 µm have no effect on FFL (Mavromichalis et al., 2000).

pH and Volatile Fatty Acid Concentration

The lack of an effect of corn particle size on pH in stomach and ileal contents is in agreement with values reported by Kim et al. (2009) and is likely a result of the fact that

most VFA are synthesized in the hindgut. The increase in pH of cecal and colon contents that were observed as corn particle size was reduced, was a result of less VFA being synthesized as corn particle size decreased. This observation concurs with data reported in lupins ground to different particle sizes (Kim et al., 2009), and is likely a result of less fermentation taking place in the hindgut of pigs fed the diets containing corn ground to the smaller particle sizes compared with corn ground to the greater particle sizes (Callan et al., 2007). The apparent ileal digestibility of starch is increased as particle size of corn is reduced (Rojas and Stein, 2013), which in turn results in less substrate for the microbes for fermentation in the hindgut. Fermentation in the hindgut is, therefore, reduced as corn particle size is reduced which is also demonstrated by the reduction in VFA concentration and the increase in cecal and colonic digesta pH that was observed as corn particle size was reduced. An increase in intestinal weight as a result of increased fermentation was also reported by Kass et al. (1980), and is likely a result of increased microbial activity in the hindgut of pigs fed diet containing corn ground to a coarser particle size. To our knowledge, there has been no previous report on the effects of corn particle size on pH or VFA concentrations in intestinal contents of pigs.

Conclusions

The increased concentration of ME in finely ground corn that has previously been reported makes it possible to reduce the inclusion of added lipids in diets containing finely ground corn, which will result in reduced diet costs. Results of the growth performance experiment confirmed this hypothesis and also indicated that the dressing percentage is improved if diets containing corn ground to a reduced particle size are used.

Although pigs fed diets containing corn ground to a smaller particle size developed some level of parakeratosis, this did not affect G:F.

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TABLES

Table 4.1. Chemical and physical composition of corn with different particle sizes and conventional soybean meal (SBM), as-fed basis

Item	Corn particle size, µm				SBM
	865	677	485	339	
GE, kcal/kg	3,920	3,900	3,914	3,870	4,197
DM, %	86.54	86.40	86.71	86.30	91.60
CP, %	7.08	7.23	7.25	7.00	47.73
Ash, %	1.15	1.39	1.23	1.10	5.67
AEE[1], %	3.45	3.51	3.53	3.57	2.05
NDF, %	11.06	10.01	9.29	9.25	-
ADF, %	2.41	2.27	2.24	1.91	-
Starch, %	62.90	61.19	62.73	64.42	-
P, %	0.31	0.34	0.30	0.29	-
Ca, %	0.03	0.03	0.03	0.03	-
Indispensable, AA %					
Arg	0.35	0.37	0.35	0.35	3.39
His	0.20	0.21	0.20	0.20	1.22
Ile	0.24	0.26	0.25	0.24	2.20
Leu	0.85	0.84	0.83	0.83	3.78
Lys	0.25	0.26	0.25	0.25	3.02
Met	0.14	0.14	0.13	0.14	0.64
Phe	0.35	0.35	0.35	0.35	2.35
Thr	0.25	0.24	0.25	0.25	1.81

Table 4.1. (Cont.)

Trp	0.06	0.05	0.05	0.05	0.72
Val	0.35	0.38	0.36	0.35	2.45
Dispensable, AA %					
Ala	0.51	0.52	0.51	0.51	2.04
Asp	0.49	0.50	0.49	0.49	5.30
Cys	0.15	0.15	0.14	0.15	0.62
Glu	1.28	1.25	1.26	1.26	7.91
Gly	0.30	0.30	0.30	0.30	1.98
Pro	0.64	0.62	0.64	0.63	2.35
Ser	0.32	0.30	0.30	0.31	2.04
Tyr	0.20	0.22	0.20	0.21	1.67
Total AA	6.93	6.96	6.86	6.87	45.49
Physical composition					
Mean particle size, μm	865	677	485	339	785
SD[2] of particle size	3.15	3.20	2.92	1.89	1.90
Surface area, cm^2/g	101.4	132.1	166.6	164.5	71.1
Filling angle of repose, º	46.8	50.7	54.9	57.4	73.2
Bulk density, g/L	650.6	631.5	601.4	564.5	705.6

[1]AEE = acid hydrolyzed ether extract.

[2]SD = standard deviation.

Table 4.2. Composition of experimental phase 1 and phase 2 diets, as-fed basis

	Corn particle size, μm							
	Phase 1				Phase 2			
Item	865	677	485	339	865	677	485	339
Ingredients, %								
Ground corn	66.07	67.17	67.14	67.76	71.47	72.61	72.52	73.22
Soybean meal, 48% CP	27.50	26.90	27.30	27.40	22.20	21.60	22.10	22.20
Soybean oil	3.60	3.12	2.78	2.00	3.74	3.23	2.85	2.00
Ground limestone	0.92	0.95	1.00	0.92	0.90	0.92	0.98	0.87
Dicalcium phosphate	0.90	0.87	0.77	0.92	0.71	0.68	0.57	0.74
L-Lysine HCL	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
DL-Methionine	0.10	0.10	0.11	0.10	0.07	0.07	0.08	0.07
L-Threonine	0.06	0.04	0.05	0.05	0.06	0.04	0.05	0.05
Sodium chloride	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin-mineral premix[1]	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Analyzed composition								
GE, kcal/kg	4,308	4,113	4,077	4,075	4,140	4,110	4,087	4,035

Table 4.2. (Cont.)

ME, kcal/kg[2]	3,396	3,396	3,396	3,396	3,412	3,412	3,412	3,412
DM, %	90.91	88.93	89.00	89.18	88.14	89.03	89.01	88.64
CP, %	18.62	18.32	18.44	18.59	15.05	15.00	15.44	15.51
SID of Lys, %[2]	0.98	0.98	0.98	0.98	0.85	0.85	0.85	0.85
STTD of P, %[2]	0.31	0.31	0.31	0.31	0.27	0.27	0.27	0.27
Ash, %	4.74	3.71	4.15	4.04	3.29	3.42	3.82	4.02
AEE[3], %	6.34	5.35	5.04	4.52	6.39	6.05	5.35	4.64
Indispensable, AA %								
Arg	1.25	1.14	1.20	1.22	1.01	0.94	1.02	1.01
His	0.48	0.45	0.47	0.48	0.41	0.38	0.42	0.41
Ile	0.80	0.73	0.77	0.80	0.66	0.60	0.68	0.65
Leu	1.56	1.51	1.57	1.63	1.38	1.29	1.43	1.39
Lys	1.32	1.03	1.20	1.11	0.94	0.87	0.95	0.92
Met	0.35	0.34	0.42	0.36	0.31	0.27	0.29	0.29
Phe	0.91	0.86	0.90	0.92	0.77	0.70	0.78	0.77
Thr	0.71	0.67	0.68	0.72	0.60	0.57	0.60	0.62
Trp	0.24	0.21	0.21	0.24	0.19	0.18	0.19	0.19

Table 4.2. (Cont.)

Val	0.93	0.86	0.93	0.95	0.82	0.71	0.80	0.77
Dispensable, AA %								
Ala	0.91	0.87	0.92	0.94	0.81	0.77	0.83	0.81
Asp	1.87	1.71	1.82	1.86	1.51	1.39	1.53	1.49
Cys	0.28	0.27	0.26	0.28	0.25	0.22	0.24	0.24
Glu	3.17	3.00	3.15	3.23	2.70	2.49	2.77	2.69
Gly	0.77	0.71	0.75	0.77	0.65	0.61	0.66	0.65
Pro	1.04	1.01	1.06	1.08	0.94	0.88	0.96	0.93
Ser	0.74	0.72	0.75	0.77	0.64	0.62	0.64	0.64
Tyr	0.60	0.58	0.60	0.62	0.52	0.46	0.52	0.51
Total AA	17.93	16.67	17.66	17.98	15.11	13.95	15.31	14.98

[1]Provided the following quantities of vitamins and micro minerals per kilogram of complete diet: Vitamin A as retinyl acetate, 11,128 IU; vitamin D_3 as cholecalciferol, 2,204 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.58 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin as nicotinamide and nicotinic acid, 44 mg; folic acid, 1.58 mg; biotin, 0.44 mg; Cu, 10 mg as copper sulfate; Fe, 125 mg as iron sulfate; I, 1.26 mg as potassium iodate; Mn, 60 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; and Zn, 100 mg as zinc oxide.

Table 4.2. (Cont.)

[2]ME values were calculated rather than analyzed (NRC, 2012; Rojas and Stein, 2013). The standardized ileal digestibility (SID) of Lys and the standardized total tract digestibility (STTD) of P were calculated (NRC, 2012).

[3]AEE = acid hydrolyzed ether extract.

Table 4.3. Composition of experimental phase 3 diets, as-fed basis

	Corn particle size, μm			
Item	865	677	485	339
Ingredients, %				
Ground corn	76.33	77.57	77.45	78.22
Soybean meal, 48% CP	17.40	16.80	17.30	17.40
Soybean oil	3.87	3.30	2.92	2.00
Ground limestone	0.82	0.83	0.90	0.78
Dicalcium phosphate	0.60	0.55	0.45	0.64
L-Lysine HCL	0.15	0.15	0.15	0.15
DL-Methionine	0.06	0.05	0.07	0.05
L-Threonine	0.07	0.05	0.06	0.06
Sodium chloride	0.40	0.40	0.40	0.40
Vitamin-mineral	0.30	0.30	0.30	0.30
Total	100.00	100.00	100.00	100.00
Analyzed composition				
GE, kcal/kg	4,114	4,088	4,050	4,012
ME, kcal/kg[2]	3,412	3,412	3,412	3,412
DM, %	89.89	89.48	89.25	87.93
CP, %	14.24	14.02	14.12	14.07
SID of Lys, %[2]	0.73	0.73	0.73	0.73
STTD of P, %[2]	0.24	0.24	0.24	0.24
Ash, %	3.25	3.34	3.26	3.24
AEE[3], %	6.49	6.35	5.84	5.04
Indispensable, AA %				
Arg	0.87	0.85	0.86	0.96
His	0.36	0.36	0.36	0.39

Table 4.3. (Cont.)

Ile	0.57	0.57	0.56	0.62
Leu	1.27	1.30	1.24	1.37
Lys	0.80	0.73	0.82	0.86
Met	0.27	0.28	0.30	0.29
Phe	0.67	0.67	0.66	0.73
Thr	0.56	0.57	0.54	0.62
Trp	0.16	0.17	0.18	0.18
Val	0.68	0.71	0.72	0.73
Dispensable, AA %				
Ala	0.74	0.75	0.74	0.80
Asp	1.30	1.27	1.28	1.44
Cys	0.21	0.21	0.23	0.24
Glu	2.42	2.40	2.38	2.61
Gly	0.57	0.56	0.57	0.66
Pro	0.86	0.88	0.84	0.93
Ser	0.58	0.57	0.57	0.63
Tyr	0.44	0.44	0.45	0.50
Total AA	13.33	13.29	13.3	14.56

[1]Provided the following quantities of vitamins and micro minerals per kilogram of complete diet: Vitamin A as retinyl acetate, 11,128 IU; vitamin D_3 as cholecalciferol, 2,204 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.58 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin as nicotinamide and nicotinic acid, 44 mg; folic acid, 1.58 mg; biotin, 0.44 mg; Cu, 10 mg as copper sulfate;

Table 4.3. (Cont.)

Fe, 125 mg as iron sulfate; I, 1.26 mg as potassium iodate; Mn, 60 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; and Zn, 100 mg as zinc oxide.

[2]ME values were calculated rather than analyzed (NRC, 2012; Rojas and Stein, 2013). The standardized ileal digestibility (SID) of Lys and the standardized total tract digestibility (STTD) of P were calculated (NRC, 2012).

[3]AEE = acid hydrolyzed ether extract.

Table 4.4. Physical composition of experimental diets, as-fed basis[1]

Item	Corn particle size, μm	Filling angle of repose, º	Bulk density, g/L
Phase 1	865	47.1	713
	677	48.8	696
	485	50.6	667
	339	54.8	645
Phase 2	865	46.0	704
	677	49.2	690
	485	52.1	670
	339	54.0	631
Phase 3	865	46.6	702
	677	48.1	683
	485	51.3	661
	339	54.5	627
SEM		0.60	8.60
P-value[2]	Linear	< 0.01	< 0.01
	Quadratic	0.04	0.56

[1]Data are least square means of 3 observations per treatment, except for the variables standard deviation of particle size and surface are, which hand only 2 observations.

[2]*P*-value represents the data for phase 1. *P*- value for phases 2 and 3 are not shown, but the follow the same trend as phase 1.

Table 4.5. Growth performance of pigs fed diets containing corn ground to different particle sizes[1]

Item	Corn particle size, μm				Statistics			Sex		Statistics	
	865	677	485	339	Pooled SEM	Linear *P*-value	Quadratic *P*-value	Barrows	Gilts	Pooled SEM	*P*-value
BW, kg											
Day 0	32.0	31.9	32.2	32.0	0.44	0.47	0.64	32.6	31.5	0.27	0.01
Day 29	62.8	62.1	62.3	61.9	1.18	0.40	0.84	64.9	59.7	0.58	< 0.01
Day 58	94.7	94.1	93.8	93.7	2.16	0.53	0.85	99.4	88.8	0.98	< 0.01
Day 93	130.0	128.6	130.2	129.8	2.90	0.88	0.75	136.2	123.0	1.41	< 0.01
ADG, kg/d											
Day 0 - 29	1.03	1.01	1.00	0.99	0.03	0.30	0.79	1.07	0.94	0.01	< 0.01
Day 29 - 58	1.06	1.07	1.05	1.06	0.04	0.80	0.93	1.15	0.97	0.02	< 0.01
Day 58 - 93	1.01	0.98	1.04	1.03	0.17	0.29	0.71	1.05	0.98	0.02	< 0.01
Day 0 - 93	1.03	1.02	1.03	1.03	0.03	0.97	0.76	1.09	0.96	0.01	< 0.01
ADFI, kg/d											
Day 0 – 29[2]											
Gilts	1.88	1.94	1.95	2.10	0.06	< 0.01	0.35	-	-	-	-
Barrows	2.33	2.32	2.30	2.20	0.07	0.18	0.45	-	-	-	-

Table 4.5. (Cont.)

Day 29 – 58	3.01	3.03	3.05	3.11	0.12	0.27	0.70	3.35	2.74	0.05	< 0.01
Day 58 – 93	3.24	3.32	3.44	3.47	0.12	0.04	0.85	3.63	3.10	0.06	< 0.01
Day 0 – 93	2.81	2.85	2.90	2.94	0.10	0.09	0.98	3.12	2.63	0.04	< 0.01
G:F											
Day 0 – 29	0.49	0.47	0.47	0.46	0.01	0.03	0.52	0.47	0.48	0.01	0.38
Day 29 – 58[2]											
Gilts	0.36	0.37	0.36	0.32	0.01	< 0.01	0.02	-	-	-	-
Barrows	0.34	0.34	0.33	0.36	0.01	0.53	0.15	-	-	-	-
Day 58 – 93	0.31	0.30	0.30	0.30	0.01	0.19	0.31	0.29	0.32	0.01	< 0.01
Day 0 – 93[2]											
Gilts	0.38	0.37	0.37	0.35	0.01	< 0.01	0.45	-	-	-	-
Barrows	0.36	0.34	0.35	0.36	0.01	0.82	0.06	-	-	-	-
Day 0 – 93[3]	0.28	0.28	0.28	0.28	0.01	0.18	0.44	0.28	0.28	0.01	0.41

[1]Data are means of 18 observations per particle size treatment, except for the treatment with corn particle size of 677 μm, which had only 17 observations. For sex, data are means of 36 observations for males and 35 observations for females.

[2]Particle size × sex interaction ($P < 0.05$).

[3]G:F calculated based on HCW.

Table 4.6. Stomach morphology from finishing pigs fed diets containing corn ground to different particle sizes[1]

Item	Corn particle size, μm				Statistics	
	865	677	485	339	Pooled SEM	*P*-value
Normal, %	50.00	29.41	5.56	0.00	-	< 0.01
Minor parakeratosis, %	33.33	64.71	61.11	44.44	-	0.21
Medium parakeratosis, %	16.67	0.00	22.22	22.22	-	0.22
Major parakeratosis, %	0.00	5.88	11.11	33.33	-	0.02
Average stomach score[2]	0.67	0.80	1.39	1.89	0.19	< 0.01

[1]Data are means of 18 observations per treatment, except for the treatment with corn particle size of 677 μm, which had only 17 observations. Data are expressed as a frequency of incidence of parakeratosis in the esophagael region in the stomach of the pig.

[2]Score system ranged from 0 to 10 (0 = no evidence of ulcers or parakeratosis and 10 = severe damage in tissue).

Table 4.7. Weights of carcass and body components of growing pigs fed diets containing corn ground to different particle sizes[1]

Item	Corn particle size, µm				Statistics			Sex		Statistics	
	865	677	485	339	Pooled SEM	Linear *P*-value	Quadratic *P*-value	Barrows	Gilts	Pooled SEM	*P*-value
Live wt, kg	127.4	127.0	127.3	127.4	2.88	0.99	0.88	133.7	120.7	1.42	< 0.01
HCW, kg	101.1	101.3	101.7	102.3	2.44	0.57	0.87	107.3	95.8	1.15	< 0.01
Dressing[2], %	79.30	79.78	79.82	80.29	0.31	< 0.01	0.97	80.27	79.32	0.17	< 0.01
Back fat, cm	2.23	2.22	2.48	2.25	0.19	0.53	0.51	2.69	1.88	0.09	< 0.01
LEA[3], cm^2	54.52	53.44	51.32	52.92	1.43	0.19	0.35	52.46	53.65	0.89	0.35
pH of LEA[4]	5.60	5.57	5.63	5.62	0.03	0.25	0.65	5.63	5.58	0.02	0.07
FFL[5], %	53.29	53.06	51.71	52.74	0.99	0.31	0.46	50.68	54.77	0.49	< 0.01
Organ wt[6], %	6.43	6.07	6.06	5.78	0.12	< 0.01	0.79	5.92	6.25	0.08	< 0.01
Organ wt, kg											
Liver	1.81	1.78	1.76	1.74	0.05	0.21	0.92	1.83	1.71	0.03	< 0.01
Heart	0.48	0.51	0.49	0.47	0.02	0.44	0.08	0.51	0.47	0.01	< 0.01
Kidney	0.44	0.46	0.47	0.45	0.01	0.22	0.10	0.47	0.44	0.01	< 0.01
Spleen	0.18	0.17	0.19	0.18	0.01	0.11	0.76	0.18	0.19	0.01	0.08
Stomach	0.56	0.56	0.55	0.55	0.02	0.45	0.92	0.57	0.54	0.01	0.16

Table 4.7. (Cont.)

Empty	3.01	2.65	2.72	2.52	0.11	< 0.01	0.34	2.80	2.64	0.06	0.08

[1]Data are means of 18 observations per particle size treatment, except for the treatment with corn particle size of 677 μm, which had only 17 observations. For sex, data are means of 36 observations for males and 35 observations for females.

[2]Dressing % = HCW / live wt × 100.

[3]LEA = loin eye area.

[4]pH = Measured at the 10th rib in the loin eye (longissimus dorsi).

[5]FFL = carcass fat-free lean.

[6]Organ wt, % of HCW.

Table 4.8. The pH of the contents of stomach, ileum, cecum, and colon and concentration of VFA in cecal contents from finishing pigs fed diets containing corn ground to different particle sizes[1]

Item	Corn particle size, µm				Statistics			Sex		Statistics	
	865	677	485	339	Pooled SEM	Linear *P*-value	Quadratic *P*-value	Barrows	Gilts	Pooled SEM	*P*-value
pH											
Stomach	4.86	4.99	4.50	4.12	0.42	0.10	0.42	4.73	4.51	0.26	0.55
Ileum	6.74	6.86	6.87	6.82	0.09	0.42	0.27	6.83	6.81	0.05	0.79
Cecum	6.04	6.20	6.54	6.64	0.09	< 0.01	0.94	6.36	6.36	0.06	0.98
Colon	5.85	5.94	6.20	6.25	0.08	< 0.01	0.94	6.10	6.01	0.05	0.15
Short-chain fatty acids, ug/ml in cecal contents											
Acetate	2537	2286	1973	1846	136	< 0.01	0.79	2206	2113	85	0.44
Propionate	872	794	690	617	48	< 0.01	0.85	768	720	29	0.24
Butyrate	702	611	391	226	57	< 0.01	0.20	518	447	34	0.14

[1]Data are means of 18 observations per particle size treatment, except for the treatment with corn particle size of 677 µm, which had only 17 observations. For sex, data are means of 36 observations for males and 35 observations for females.

CHAPTER 5

REDUCING CORN PARTICLE SIZE INCREASES CALORIC EFFICIENCY IN WEANLING PIGS

ABSTRACT: Results of a previous experiment indicated that reduction of the particle size of corn from 865 to 339 μm linearly increased the concentration of ME in corn fed to growing pigs. Therefore, 2 experiments were conducted to test the hypothesis that reduced particle size of corn also will improve the caloric utilization of corn fed to weanling pigs. In both experiments, pigs (weaned at the age of approximately 21 d) were fed a common diet for 14 d post-weaning. A total of 128 pigs were used in each experiment (initial BW of 9.41 ± 1.54 and 9.95 ± 1.95 kg in Exp. 1 and Exp. 2, respectively) and in each experiment, pigs were randomly allotted to 4 diets in a randomized complete block design. All diets were formulated to meet or exceed current nutrient requirements of 11 to 25 kg pigs. There were 4 pigs per pen and 8 replicate pens per treatment. The same batches of corn, soybean meal, and fish meal were used in all diets in both experiments, but the corn that was used was ground to different particle sizes (i.e., 865, 677, 485, or 339 μm). In Exp. 1, all diets had the same ingredient composition, and the only difference among diets was the particle size of the corn that was used. As a consequence, the calculated ME of the diets increased as particle size of corn decreased. In Exp. 2, a reduced amount of soybean oil was added to the diets to adjust the ME value as the particle size of the corn used in the diets decreased, and all diets were formulated to contain 3,413 kcal ME per kg. Results of Exp. 1 indicated that final BW and ADG were not affected by corn particle size, but ADFI decreased (linear, P

< 0.05) and G:F increased (linear, P < 0.05) from 0.65 to 0.66, 0.70, and 0.69 for pigs fed diets containing corn ground to a mean particle size of 865, 677, 485, and 339 μm, respectively. In Exp. 2, final BW, ADG, and ADFI were not influenced by corn particle size, but G:F increased (linear, P < 0.05) from 0.62 to 0.63, 0.63, and 0.65 as corn particle size decreased from 865, 677, 485, and 339 μm, respectively. Combined, these results confirmed that the ME of the diets containing corn with the smaller particle size of corn was increased compared with the ME of diets containing corn with greater particle size. It also appeared that the increased addition of soybean oil to diets with corn ground to the greater particle sizes in Exp. 2 was not effective in compensating for the reduced ME in the corn ground to the greater particle size. In conclusion, weanling pigs utilize more energy from corn ground to a smaller particle size than if corn is ground to a greater particle size.

Key words: corn, energy, fat, growth performance, particle size, weanling pig

INTRODUCTION

Processing of feed ingredients or diets may increase nutrient digestibility (Hancock and Behnke, 2001; NRC, 2012). One of the main purposes of grinding of feed ingredients is to reduce the particle size, which may increase nutrient digestibility (Fastinger and Mahan, 2003) and increase growth performance. Thus, grinding is used to increase the nutritional value of ingredients. As an example, there is a linear increase in the ME of corn as the particle size of corn is reduced from 865 to 339 μm (Rojas and Stein, 2013), which is mainly due to an increase in the apparent ileal digestibility of starch and an increase in both ileal and total tract digestibility of GE. In a previous

experiment, it was demonstrated that addition of dietary lipids may be reduced as corn particle size is reduced without reducing the calculated ME of the diet or growth performance of growing-finishing pigs because of the increased ME in corn with a reduced particle size (Rojas and Stein, 2014). However, there are no data to demonstrate if this concept can also be used to formulate diets for weanling pigs. Therefore, the objective of the present experiments was to test the hypothesis that the caloric utilization of corn fed to weanling pigs is increased as particle size of corn is reduced.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocols for these experiments. Two experiments were conducted and pigs used in both experiments were the offspring of G-performer boars mated to F-25 gilts (Genetiporc, Alexandria, MN) and they were weaned at approximately 21 d of age. Pigs were fed a common diet that contained corn, soybean meal, lactose, whey powder, plasma protein, vitamins, and minerals for 14 d post-weaning prior to the start of the experiment. The corn was grown in Iowa in 2011 and first processed using an automatic roller mill (Model CSU 500, 2 stage; Automatic Equipment Mfg. Co., Pender, NE) to obtain a mean particle size of 2,000 μm. Then, the rolled corn grain was divided into 4 batches that were ground through 15.88, 9.53, 3.97, or 1.19 mm screens using a hammer mill (Model #EL-9506-TF; Bliss Industries, Ponca City, OK) to obtain mean final particle sizes of 865, 677, 485, and 339 μm, respectively (Table 5.1). The ground corn was stored at 15ºC until used and the corn used in the

present experiments was from the same batches as the corn used in the previous experiments (Rojas and Stein, 2013, 2014).

In both experiments, pigs were housed in 1.2 × 1.4 m pens with fully slatted floors. A feeder and a nipple drinker were provided in each pen. Feed and water were provided on an ad libitum basis throughout the experiments. There were 4 pigs per pen and 8 replicate pens per treatment in both experiments.

Exp. 1: Maintaining Ingredient Composition among Diets

Experiment 1 was designed to test the hypothesis that the G:F is improved if diets fed to weanling pigs contain corn ground to a smaller rather than a greater particle size. A total of 128 weaned pigs with an average initial BW of 9.41 ± 1.54 kg were randomly allotted, after they had been fed a common diet for 14 d, to a randomized complete block design with 4 experimental diets that were fed for 3 weeks. The 4 diets were based on corn, soybean meal, soybean oil, and fish meal (Table 5.2), and all diets were formulated to meet or exceed current nutrient requirements (NRC, 2012). The only difference among the 4 diets was that corn ground to a mean particle size of 865, 677, 485, or 339 μm were used in the 4 treatment diets. It was assumed that the ME in the 4 sources of corn was 3,311, 3,346, 3,371, and 3,432 kcal/kg, respectively (Rojas and Stein, 2013), and the calculated ME was 3,269, 3,290, 3,306, and 3,343 kcal/kg for diets containing corn ground to a mean particle size of 865, 677, 485, and 339 μm, respectively.

Individual pig BW was recorded at the start and at the conclusion of the experiment. Daily feed allotments were recorded and feed left in the feeders was recorded on the last d of the experiment. On the last d of the experiment, freshly voided feces were also collected from 2 pigs per pen and pH of the fecal samples was immediately

measured using a pH meter (Accumet, Basic, Fisher Scientific, Pittsburgh, PA). Pigs were then fasted for 8 h and 2 average-sized pigs in all pens were bled via jugular venipuncture in heparinized tubes. Blood samples were stored on ice until centrifuged (2,000 revolutions per minute at 5°C for 15 min) and plasma was harvested and analyzed for plasma urea nitrogen (**PUN**) immediately after centrifugation.

Bulk density and filling angle of repose of diets were determined as described by Cromwell et al. (2000) and Appel (1994), respectively. Diets and ingredients were analyzed for GE using an isoperibol bomb calorimetry (Model 6300, Parr Instruments, Moline, IL), DM (method 930.15; AOAC Int., 2007), CP by combustion (method 999.03; AOAC Int., 2007) using a Rapid N cube apparatus (Elementar Americas Inc, Mt Laurel, NJ), and ash (method 975.03; AOAC Int., 2007). Diets and ingredients were also analyzed for acid hydrolyzed ether extract that was determined by acid hydrolysis using 3*N* HCl (Sanderson, 1986) followed by crude fat extraction using petroleum ether (method 2003.06, AOAC Int., 2007) on a Soxtec 2050 automated analyzer (FOSS North America, Eden Prairie, MN) and for AA (method 982.30 E [a, b, c]; AOAC Int., 2007). All diets and ingredients were ground through a 1-mm screen in a Wiley mill (model 4; Thomas Scientific, Swedesboro, NJ) before analysis.

At the conclusion of the experiment, data were summarized to calculate ADG, ADFI, and G:F for each pen and treatment group and data for fecal pH, filling angle of repose, bulk density, and caloric efficiency were summarized within treatment group. Caloric efficiency was calculated as the ADFI multiplied by the concentration of ME in the diet and divided by the ADG. Data were analyzed using the MIXED Procedure (SAS Inst. Inc., Cary, NC). Homogeneity of the variances among treatments was confirmed

using the HOVTEST = BF procedure of SAS. The UNIVARIATE procedure of SAS was used to test for outliers, but no outliers were identified. Diet was the fixed effect and replicate was the random effect. Least Squares Means were used to calculate mean values for each independent variable. Linear and quadratic contrasts were used to analyze effects of reducing corn particle size on response variables. Appropriate coefficients for unequally spaced particle sizes of corn were determined using the interactive matrix language procedure in SAS. The pen was the experimental unit for all calculations and an α-level of 0.05 was used to assess significance among means, and tendencies were considered if $P > 0.05$ and $P \leq 0.10$.

Exp. 2: Maintaining Calculated ME among Diets

Experiment 2 was designed to test the hypothesis that the increase in caloric value of corn that is a result of grinding to reduced particle sizes can be taken advantage of by reducing the inclusion of soybean oil in the diet without reducing pig growth performance. A total of 128 pigs that had been fed a common diet during the initial 14 d post weaning, and had an average BW of 9.95 ± 1.95 kg, were used. Pigs were randomly allotted to 4 treatment diets in a randomized complete block design; experimental diets were provided on an ad libitum basis for 3 weeks. The 4 diets were all based on corn, soybean meal, soybean oil, and 3% fish meal (Table 5.3), and all diets were formulated to meet or exceed current nutrient requirements (NRC, 2012). In contrast to the diets used in Exp. 1, diet ME values were adjusted by reducing the amount of soybean oil in the diets as the particle size of the corn used in the diets decreased. The assumed ME for soybean oil was 8,574 kcal/kg (NRC, 2012) and the assumed ME for the 4 sources of corn ground to a mean particle size of 865, 677, 485, and 339 μm was 3,311, 3,346, 3,371, and 3,432

kcal/kg, respectively (Rojas and Stein, 2013). By adjusting the inclusion of soybean oil, all diets were formulated to contain 3,413 kcal ME/kg.

Individual pig BW, daily feed allotments, and feed left in the feeders were recorded as explained for Exp. 1 to calculate ADG, ADFI, and G:F for each pen and treatment group. Diets were also ground and analyzed for GE, DM, CP, ash, acid hydrolyzed ether extract, and for AA as described for Exp. 1. On the last day of the experiment, fecal samples were collected and pH in fecal samples was measured as described for Exp. 1, and bulk density, filling angle of repose, and caloric efficiency of the diets were also determined as explained for Exp. 1. Data were also summarized and analyzed as explained for Exp. 1.

RESULTS AND DISCUSSION

Diets for both experiments were formulated based on standardized ileal digestibility of AA, standardized total tract digestibility of P, and ME from published values in corn, soybean meal, fish meal, and soybean oil (NRC, 2012; Rojas and Stein, 2013). In Exp. 1, diets were formulated to be equal in CP and digestible Lys and to contain an increased concentration of energy as particle size decreased. Values for analyzed CP and Lys in the diets were close to formulated values. The diets used in Exp. 2 also were formulated to be similar in CP and Lys and analyzed values confirmed that this was the case.

In both experiments, the filling angle of repose of the diets increased (linear, $P < 0.01$) as corn particle size decreased, whereas bulk density decreased in the diets (linear and quadratic, $P < 0.01$) as particle size of corn decreased (Table 5.4). These observations

are in agreement with previous data reported for soybean meal (Lawrence et al., 2003), and distillers dried grains with solubles (Liu et al., 2012). The increase in the filling angle of repose as particle size of corn decreased indicates that the flowability of the diets in bins and feeders may also be reduced. The decrease in bulk density that was observed as corn was ground to a smaller particle size indicates that as corn particle size decreases, the quantity of diet that can be stored in a given bin space is reduced.

In Exp. 1, there were no differences in the initial or the final BW among pigs fed the 4 dietary treatments and ADG and PUN were also not different among treatments (Table 5.5). In contrast, ADFI decreased and values for G:F increased, as the particle size of corn decreased (linear, $P < 0.05$). This result is in agreement with previous data (Healy et al., 1994; Wondra et al., 1995b). The increased ADFI observed in pigs fed diets containing corn ground to a greater particle size represents an attempt by the pigs to compensate for the reduction in ME in diets containing the corn with greater particle size. This observation concurs with values reported by Healy et al. (1994) and Mavromichalis et al. (2000). The increased G:F that was observed as particle size of corn was reduced was expected because corn ground to a smaller particle size contains more ME than corn ground to a greater particle size (Wondra et al., 1995a; Rojas and Stein, 2013).

The increase (linear, $P < 0.01$) in pH of fecal samples that was observed as particle size of corn decreased indicates that synthesis of VFA decreases as particle size decreases. This observation is in agreement with data from growing-finishing pigs fed corn ground to a finer particle size indicating that pH increases and VFA concentration in cecal samples decreases as corn particle size is reduced (Rojas and Stein, 2014). The reason for the reduced synthesis of VFA is most likely that reduced corn particle size

results in increased prececal digestibility of starch (Rojas and Stein, 2013), which in turn results in reduced substrate for fermentation in the hindgut. Thus, less VFA is synthesized in the hindgut when pigs are fed diets that contain finely ground corn compared with diets that contain coarsely ground corn (Callan et al., 2007; Rojas and Stein, 2014).

Plasma urea nitrogen is an indicator of efficiency of AA utilization (Waguespack et al., 2011). Maximum AA utilization is represented by low values of PUN, whereas greater values for PUN indicate that there is an imbalance of AA in the diets (Coma et al., 1995). The lack of an effect of corn particle size on PUN indicates that there was no difference in AA utilization among weanling pigs fed diets that contained corn ground to different particle sizes. This observation supports results indicating that the standardized ileal digestibility of CP and AA is not influenced by corn particle size (Rojas and Stein, 2013), and it was, therefore, expected that similar quantities of AA would be available for protein synthesis in all diets. The observation that there is no difference in PUN among treatments confirms that this likely was the case.

Caloric efficiency represents the relationship between daily energy intake and daily BW gain. In other words, it is the amount of energy needed to gain 1 kg of BW. The increase (linear, $P < 0.05$) in caloric efficiency that was observed in Exp.1 as particle size of corn decreased indicates that pigs fed diets containing corn ground to a finer particle size need less feed to gain 1 kg of BW (i.e., 3.7% more efficient) compared with pigs fed a diet containing corn ground to a coarser particle size. This observation is in agreement with data reported by de Jong et al. (2013).

In Exp. 2, the initial and the final BW among pigs were not influenced by dietary treatment (Table 5.6). Likewise, no differences among treatments were observed for ADG and ADFI, but G:F increased (linear, $P < 0.05$) as corn particle size decreased. This observation indicates that the decreased addition of soybean oil to diets containing corn ground to a finer particle size was not effective in fully accounting for the increase in ME of the corn ground to the finer particle size. This result is in contrast to our hypothesis and in contrast with results of our previous experiment with growing-finishing pigs (Rojas and Stein, 2014). It is possible that the reason the reduction in soybean oil did not fully account for the increased ME in finely ground corn is that weaned pigs are limited in the utilization of fat (Tokach et al., 1995). Weanling pigs may have reduced digestibility of fat compared with older pigs because of reduced secretion of lipase (Cera et al., 1990) or because older pigs have a greater lipid deposition than younger pigs (de Lange et al., 2001). If that is the case, then we may have overestimated the ME of fat in this experiment, which explains why we were not able to maintain a constant G:F among pigs fed the 4 experimental diets. It is also possible that the lack of a constant G:F among pigs was due to the ME value used to formulated the diets. This value was measured using growing-finishing pigs rather than young pigs and pig BW may affect energy digestibility (Noblet and Shi, 1994).

The caloric efficiency increased (linear, $P < 0.05$) as particle size of corn decreased, which is in agreement with observations from Exp. 1. Thus, the data for caloric efficiency confirm results for G:F and indicate that pigs fed diets containing coarsely ground corn were not able to efficiently digest or absorb the energy from soybean oil to compensate for the reduced ME in the coarsely ground corn.

As was the case in Exp. 1, fecal pH also increased (linear, $P < 0.05$) as the particle size of corn in the diets decreased. This observation supports the hypothesis of decreased synthesis of VFA in the hindgut of pigs as corn particle size decreases.

In conclusion, the G:F of weanling pigs is improved if diets contain corn ground to a particle size of 339 μm rather than a greater particle size, which indicates that the ME of finely ground corn is greater than the ME of more coarsely ground corn. As a consequence, the inclusion of dietary fat may be reduced if corn is ground to a finer particle size, but the amount of fat that may be removed from the diets without reducing pig growth performance remains to be determined.

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TABLES

Table 5.1. Analyzed nutrient composition of corn with different particle sizes, conventional soybean meal (SBM), and fish meal, as-fed basis

	Corn particle size, μm					
Item	865	677	485	339	SBM	Fish meal
GE, kcal/kg	3,942	3,900	3,851	3,870	4,241	4,231
DM, %	86.54	86.4	86.71	86.3	88.07	91.00
CP, %	7.08	7.23	7.25	7.00	47.66	62.48
Ash, %	1.15	1.39	1.23	1.10	6.47	21.90
AEE[1], %	3.45	3.51	3.53	3.57	1.86	5.74
Indispensable, AA %						
Arg	0.35	0.37	0.35	0.35	3.55	3.56
His	0.20	0.21	0.20	0.20	1.20	1.20
Ile	0.24	0.26	0.25	0.24	2.04	2.21
Leu	0.85	0.84	0.83	0.83	3.70	4.02
Lys	0.25	0.26	0.25	0.25	2.80	4.55
Met	0.14	0.14	0.13	0.14	0.69	1.65
Phe	0.35	0.35	0.35	0.35	2.38	2.24
Thr	0.25	0.24	0.25	0.25	1.92	2.34
Trp	0.06	0.05	0.05	0.05	0.70	0.62
Val	0.35	0.38	0.36	0.35	2.17	2.65
Dispensable, AA %						
Ala	0.51	0.52	0.51	0.51	2.10	3.75
Asp	0.49	0.50	0.49	0.49	5.56	5.26

Table 5.1. (Cont.)

Cys	0.15	0.15	0.14	0.15	0.65	0.44
Glu	1.28	1.25	1.26	1.26	8.53	7.33
Gly	0.30	0.30	0.30	0.30	2.05	4.46
Pro	0.64	0.62	0.64	0.63	2.40	2.80
Ser	0.32	0.30	0.30	0.31	2.47	2.05
Tyr	0.20	0.22	0.20	0.21	1.76	1.84
Total AA	6.93	6.96	6.86	6.87	46.67	52.97

[1]AEE = acid hydrolyzed ether extract.

Table 5.2. Composition of experimental diets, as-fed basis. Exp. 1

Item	Diets			
	865 µm	677 µm	485 µm	339 µm
Ingredient, %				
Ground corn	61.56	61.56	61.56	61.56
Soybean meal, 47.7% CP	32.00	32.00	32.00	32.00
Fish meal	3.00	3.00	3.00	3.00
Soybean oil	1.00	1.00	1.00	1.00
Ground limestone	0.77	0.77	0.77	0.77
Dicalcium phosphate	0.59	0.59	0.59	0.59
L-Lys HCl	0.17	0.17	0.17	0.17
DL-Met	0.14	0.14	0.14	0.14
L-Thr	0.07	0.07	0.07	0.07
Sodium chloride	0.40	0.40	0.40	0.40
Vitamin-mineral premix[1]	0.30	0.30	0.30	0.30
Total	100.00	100.00	100.00	100.00
Analyzed composition				
GE, kcal/kg	3966	3951	3974	3971
ME, kcal/kg[2]	3269	3290	3306	3343
DM, %	86.65	86.33	86.26	87.30
CP, %	21.83	21.11	22.13	22.02
Ash, %	5.17	5.51	5.66	5.50
AEE[3], %	2.86	3.00	2.52	2.96
Indispensable, AA %				
Arg	1.46	1.42	1.49	1.47
His	0.55	0.54	0.57	0.58
Ile	0.90	0.87	0.92	0.92

Table 5.2. (Cont.)

Leu	1.83	1.79	1.85	1.86
Lys	1.36	1.39	1.43	1.41
Met	0.44	0.43	0.43	0.49
Phe	1.05	1.02	1.07	1.07
Thr	0.86	0.86	0.90	0.91
Trp	0.24	0.25	0.28	0.26
Val	0.99	0.96	1.03	1.03
Dispensable, AA %				
Ala	1.09	1.08	1.12	1.12
Asp	2.23	2.16	2.28	2.26
Cys	0.29	0.30	0.31	0.30
Glu	3.71	3.61	3.74	3.72
Gly	0.95	0.94	1.00	1.00
Pro	1.22	1.20	1.25	1.23
Ser	0.93	0.93	0.94	1.00
Tyr	0.73	0.70	0.73	0.74
Total AA	20.83	20.45	21.34	21.37

[1]Provided the following quantities of vitamins and micro minerals per kilogram of complete diet: Vitamin A as retinyl acetate, 11,128 IU; vitamin D_3 as cholecalciferol, 2,204 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.58 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin as nicotinamide and nicotinic acid, 44 mg; folic acid, 1.58 mg; biotin, 0.44 mg; Cu, 10 mg as copper sulfate;

Table 5.2. (Cont.)

Fe, 125 mg as iron sulfate; I, 1.26 mg as potassium iodate; Mn, 60 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; and Zn, 100 mg as zinc oxide.

[2]ME values were calculated rather than analyzed (NRC, 2012; Rojas and Stein, 2013).

[3]AEE = acid hydrolyzed ether extract.

Table 5.3. Composition of experimental diets, as-fed basis. Exp. 2

Item	Diets			
	865 µm	677 µm	485 µm	339 µm
Ingredient, %				
Ground corn	58.66	59.07	59.36	60.09
Soybean meal, 47.7% CP	32.00	32.00	32.00	32.00
Fish meal	3.00	3.00	3.00	3.00
Soybean oil	3.86	3.45	3.16	2.43
Ground limestone	0.78	0.78	0.78	0.78
Dicalcium phosphate	0.59	0.59	0.59	0.59
L-Lys HCl	0.18	0.18	0.18	0.18
DL-Met	0.15	0.15	0.15	0.15
L-Thr	0.08	0.08	0.08	0.08
Sodium chloride	0.40	0.40	0.40	0.40
Vitamin-mineral premix[1]	0.30	0.30	0.30	0.30
Total	100.00	100.00	100.00	100.00
Analyzed composition				
GE, kcal/kg	4136	4152	4141	4074
ME, kcal/kg[2]	3413	3413	3413	3413
DM, %	88.89	88.91	88.70	88.36
CP, %	20.53	21.69	20.85	21.02
Ash, %	5.03	4.95	4.80	4.77
AEE[3], %	6.71	6.28	6.12	4.15
Indispensable, AA %				
Arg	1.41	1.42	1.39	1.39
His	0.55	0.55	0.54	0.54
Ile	0.90	0.91	0.89	0.91

Table 5.3. (Cont.)

Leu	1.76	1.75	1.76	1.78
Lys	1.38	1.35	1.34	1.35
Met	0.51	0.48	0.49	0.47
Phe	1.02	1.02	1.02	1.03
Thr	0.83	0.86	0.85	0.82
Trp	0.26	0.26	0.25	0.26
Val	1.03	1.04	1.01	1.04
Dispensable, AA %				
Ala	1.06	1.06	1.05	1.07
Asp	2.13	2.16	2.13	2.14
Cys	0.28	0.30	0.30	0.31
Glu	3.54	3.51	3.52	3.57
Gly	0.96	0.98	0.94	0.95
Pro	1.23	1.22	1.21	1.23
Ser	0.81	0.81	0.84	0.80
Tyr	0.68	0.67	0.67	0.68
Total AA	20.34	20.35	20.20	20.34

[1]Provided the following quantities of vitamins and micro minerals per kilogram of complete diet: Vitamin A as retinyl acetate, 11,128 IU; vitamin D_3 as cholecalciferol, 2,204 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.58 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin as nicotinamide and nicotinic acid, 44 mg; folic acid, 1.58 mg; biotin, 0.44 mg; Cu, 10 mg as copper sulfate;

Table 5.3. (Cont.)

Fe, 125 mg as iron sulfate; I, 1.26 mg as potassium iodate; Mn, 60 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; and Zn, 100 mg as zinc oxide.

[2]ME values were calculated rather than analyzed (NRC, 2012; Rojas and Stein, 2013).

[3]AEE = acid hydrolyzed ether extract.

Table 5.4. Physical characteristics of experimental diets, as-fed basis. Exp. 1 and 2[1]

Item	Diets				SEM	*P*-value	
	865 µm	677 µm	485 µm	339 µm		Linear	Quadratic
Exp. 1							
Filling angle of repose, º	47.3	49.1	51.2	53.6	0.64	< 0.01	0.36
Bulk density, g/L	699.1	693.2	683.0	663.3	3.23	< 0.01	0.04
Exp. 2							
Filling angle of repose, º	46.5	48.9	51.9	54.6	0.56	< 0.01	0.21
Bulk density, g/L	699.8	690.0	683.0	667.1	3.42	< 0.01	0.10

[1]Data are means of 3 measurements per treatment.

Table 5.5. Growth performance, fecal pH, and plasma urea nitrogen (PUN) of pigs fed diets containing corn ground to different particle sizes and formulated to a different ME[1], Exp. 1

	Corn particle size, µm					*P*-value	
Item	865	677	485	339	Pooled SEM	Linear	Quadratic
Initial BW, kg	9.42	9.43	9.43	9.36	0.52	0.20	0.14
Final BW, kg	19.04	19.14	19.26	18.60	0.90	0.29	0.11
ADG, kg/d	0.46	0.46	0.47	0.44	0.02	0.37	0.16
ADFI, kg/d	0.71	0.71	0.67	0.64	0.03	0.02	0.34
G:F	0.65	0.66	0.70	0.69	0.01	< 0.01	0.86
pH of feces	5.84	5.97	6.09	6.24	0.05	< 0.01	0.67
PUN[2], mg/dl	9.75	10.56	9.00	10.50	0.72	0.87	0.70
Energy efficiency							
ME intake /d, kcal	2,318	2,325	2,231	2,136	116.34	0.05	0.40
Caloric efficiency[3]	5,040	5,030	4,752	4,857	103.32	0.05	0.71

[1]Data are means of 8 observations per treatment.

[2]PUN = plasma urea nitrogen.

[3]Caloric efficiency is expressed as kcal ME/kg gain.

Table 5.6. Growth performance and fecal pH of pigs fed diets containing corn ground to different particle sizes, but formulated to a constant ME[1], Exp. 2

	Corn particle size, µm					*P*-value	
Item	865	677	485	339	Pooled SEM	Linear	Quadratic
Initial BW, kg	9.95	9.97	9.94	9.94	0.66	0.51	0.45
Final BW, kg	18.90	19.62	19.56	19.47	1.14	0.22	0.20
ADG, kg/d	0.45	0.48	0.48	0.47	0.02	0.36	0.28
ADFI, kg/d	0.74	0.78	0.76	0.73	0.04	0.72	0.11
G:F	0.62	0.63	0.63	0.66	0.01	0.02	0.46
pH in feces	5.82	5.89	6.03	6.27	0.08	< 0.01	0.25
Energy efficiency							
ME intake /d, kcal	2,514	2,647	2,594	2,485	150.27	0.73	0.11
Caloric efficiency[2]	5,532	5,471	5,409	5,209	99.72	0.03	0.44

[1]Data are means of 8 observations per treatment.

[2]Caloric efficiency is expressed as kcal ME/kg gain.

CHAPTER 6

EFFECTS OF PELLETING AND EXTRUSION ON ENERGY AND NUTRIENT DIGESTIBILITY IN DIETS CONTAINING DIFFERENT LEVELS OF FIBER FED TO PIGS

ABSTRACT: An experiment was conducted to determine effects of pelleting, extrusion, and the combination of extrusion and pelleting on energy and nutrient digestibility in diets containing low, medium, or high levels of fiber. Three diets were formulated: 1) the low fiber diet contained corn and soybean meal; 2) the medium fiber diet contained corn, soybean meal, and 25% distillers dried grains with solubles (DDGS); and 3) the high fiber diet contained corn, soybean meal, 25% DDGS, and 20% soybean hulls. Each diet was divided into 4 batches after mixing. One batch was not further processed and fed in a meal form; one batch was pelleted at 85^{o}C; one batch was extruded at 115^{o}C using a single screw extruder; and one batch was extruded at 115^{o}C and then pelleted at 85^{o}C. Thus, 12 different diets were produced. A total of 24 growing pigs (initial BW: 26.5 ± 1.5 kg) with a T-cannula installed in the distal ileum were allotted to the diets in a split-plot design with 8 pigs allotted to the low fiber diets; 8 pigs were allotted to the medium fiber diets; and 8 pigs were allotted to the high fiber diets. Diets were fed to the pigs during four 14-d periods. Within each type of diet, the 8 pigs were fed the diets produced using the 4 processing technologies. Thus, there were 8 replicate pigs per diet. Pigs were adjusted to their type of diet for 14 d before the experiment started. Pigs were adjusted to their diets for 14 d before the experiment was initiated. Each of the four 14-d periods consisted of 5 d for adaptation, 5 d of fecal collection according to the marker to marker

approach, and ileal digesta was collected on d 13 and 14. Results indicated that processing, regardless of weather it was pelleting, extrusion, or pelleting and extrusion combined, improved ($P < 0.05$) the apparent ileal digestibility (AID) of starch and most indispensable AA. In most cases, there were no differences between the pelleted, the extruded, and the extruded plus pelleted diets. The apparent total tract digestibility (ATTD) of GE also was improved ($P < 0.05$) by pelleting and by the combination of extrusion plus pelleting. The ME for pelleted diets was greater ($P < 0.05$) than for meal diets for the low and medium fiber diets, but this was not the case for the high fiber diet (Interaction, $P < 0.05$). Diets that were extruded had greater ME ($P < 0.05$) compared with the meal diets for medium and high fiber. These data indicate that energy utilization may be improved by pelleting or extrusion or by the combination of the two technologies, but the response seems to be greater for extrusion in diets that are relatively high in fiber.

Key words: amino acids, energy, extrusion, fiber, pelleting, pig

INTRODUCTION

Pelleting is a well-known technology that results in increased feed conversion rate by 6 to 7% (Hancock and Behnke, 2001; Richert and DeRouchey, 2010). The main reason for this observation is believed to be that feed wastage is reduced if diets are pelleted and digestibility of energy is improved because of gelatinization of starch (Richert and DeRouchey, 2010; NRC, 2012). Pelleting of a corn-soybean meal diet increased digestibility of DM, N, and GE when compared with the same un-pelleted diet (Wondra et al., 1995). Recently, it was reported that reduced performance in pigs fed diets containing high fiber by-products was ameliorated if the diet was pelleted (Fry et al.,

2012). However, the effects of pelleting on energy and nutrient digestibility in high fiber diets when compared to low fiber diets is not known.

Extrusion in the United States is mainly used in the pet feed and aquaculture feed industries and consists of heating, pressuring, and steam conditioning (Hancock and Behnke, 2001). This technology may be used on the whole diet or on individual ingredients. Extrusion of field peas has a positive effect on the apparent total tract digestibility (**ATTD**) of GE and on the apparent ileal digestibility (**AID**) of starch and most indispensable AA (Stein and Bohlke, 2007; Htoo et al., 2008). Extrusion also may increase the solubility of dietary fiber, which in turn may result in an increased energy digestibility because soluble fibers are much more fermentable by pigs than insoluble fibers (Urriola et al., 2010). The benefits of extrusion and pelleting in high fiber diets when compared to low fiber diets have not been investigated. The objective of this experiment was to test the hypothesis that pelleting, extrusion, or the combination of extrusion and pelleting are all more effective in improving nutrient and energy digestibility in high fiber diets than in diets containing less fiber.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at the University of Illinois (Urbana, IL) reviewed and approved the protocol for this experiment.

Sourcing of Ingredients, Processing, and Feed Mixing

Diets containing 3 different levels of fiber (low, medium, or high) were processed at the Bühler Pilot Plant located in Uzwil, Switzerland. The low-fiber diet was based on corn and soybean meal, the medium-fiber diet was based on corn, soybean meal, and

25% distillers dried grains with solubles (**DDGS**), and the high-fiber diet was based on corn, soybean meal, 25% DDGS, and 20% soybean hulls (Tables 6.1, 6.2, 6.3, and 6.4). Vitamins and minerals were included in all diets to meet or exceed current requirement estimates for growing pigs (NRC, 2012). All diets also contained 0.5% titanium dioxide as an indigestible marker. All raw materials were sourced by Bühler AG (Uzwil, Switzerland). Before mixing the diets, all ingredients were ground using a Bühler horizontal hammer mill model DFZC 655 to a mean particle size of 600 μm. Diets were mixed using a Bühler Speedmix DFML paddle mixer. One batch of each diet was mixed, and this batch then was divided into 4 sub-batches. One sub-batch of each diet was fed in meal form without any further processing. One sub-batch of each diet was pelleted at 85ºC after conditioning for 120 seconds using a Bühler DNSA short term conditioner with a length of 800 mm and a diameter of 250 mm. Pelleting took place at a temperature of 85^{o}C using a 55 kW pellet press model Bühler DPDB 304.75 with a die of 4 × 70 mm. Pelleted diets were cooled in a Bühler Model DFKG counter flow cooler. One sub-batch was extruded at a temperature of 115^{o}C using a Bühler Model AHSF 133 single screw extruder with a diameter of 133 mm. The last sub-batch was first extruded at 115^{o}C and then pelleted at 85^{o}C. Following diet processing, diets were packaged in 600 kg plastic coated tote bags and shipped from Uzwil, Swizerland, to the University of Illinois using ocean freight.

Animals, Housing, and Experimental Design

Pigs used in this experiment were the offspring of G-performer boars mated to F-25 gilts (Genetiporc, Alexandria, MN). Twenty-four growing barrows (initial BW: 26.5 ± 1.5 kg) were equipped with a T-cannula in the distal ileum. Pigs were allotted to the diets

in a split-plot design with 8 pigs allotted to the low fiber diets; 8 pigs were allotted to the medium fiber diets; and 8 pigs were allotted to the high fiber diets. Diets were fed to the pigs during four 14-d periods. Within each type of diet, the 8 pigs were fed the diets produced using the 4 processing technologies in such way that 2 pigs were fed each diet in each period and no pig received the same diet twice. Thus, there were 8 replicate pigs per diet. Pigs were housed individually in metabolism crates in an environmentally controlled room. A feeder and a nipple drinker were installed in each crate, and a screen and a funnel placed below the slatted floor of the crates allowed for the total, but separate, collection of feces and urine from each pig.

Feeding and Sample Collection

Feed was provided in a daily amount of 3.3 times the maintenance energy requirement (i.e., 197 kcal of ME/kg of $BW^{0.60}$; NRC, 2012) of the smallest pig in each replicate. The total amount of feed was divided into 2 equal meals that were fed at 0800 and 1700 h. Water was available throughout the experiment.

To adapt the pigs to the level of fiber in the diets, pigs within each type of diet were fed a mixture of the 4 batches for 14 d before starting the experiment. Pig weights were recorded at the beginning and at the end of each period. The initial 5 days of each period was considered an adaptation period to the diet. Fecal and urine samples were quantitatively collected from d 6 to 11 using the marker to marker approach (Adeola, 2001) and ileal digesta were collected for 8 h on d 13 and 14 using standard operating procedures (Stein et al., 1998).

At the conclusion of the experiment, ileal samples were thawed, mixed within animal and diet, and a sub-sample was lyophilized and finely ground. Feces were

collected twice daily and stored at -20ºC immediately after collection. Urine collections started on d 6 at 0800 h and ceased on d 11 at 0800 h. Urine buckets were placed under the metabolism crates to permit total collection. Buckets were emptied in the morning and afternoon and a preservative of 50 mL of 6*N* HCl was added to each bucket when they were emptied. The collected urine was weighed and a 20% subsample was stored at -20ºC.

Fecal samples were dried at 65ºC in a forced-air oven and ground through a 1-mm screen in a Wiley mill (model 4; Thomas Scientific, Swedesboro, NJ) before analyses and urine samples were thawed and mixed within animal and diet, and a subsample was lyophilized before energy analysis (Kim et al., 2009).

Sample Analysis

Diets, ingredients, ileal samples, and fecal samples were analyzed for DM (method 930.15; AOAC Int., 2007), ash (method 942.05; AOAC Int., 2007), starch (method 76-13; AACC Int., 2000) using a modified starch assay kit (product code STA-20, Sigma, St. Louis, MO), ADF and NDF using an Ankom Technology method 12 and 13, respectively (Ankom2000 Fiber Analyzer, Ankom Technology, Macedon, NY), and acid hydrolyzed ether extract (**AEE**), which was determined by acid hydrolysis using 3*N* HCl (Sanderson, 1986) followed by crude fat extraction with petroleum ether (method 2003.06, AOAC Int., 2007) on a Soxtec 2050 automated analyzer (FOSS North America, Eden Prairie, MN). Diets and ingredients were also analyzed for water binding capacity (Robertson et al., 2000) and for P and Ca by inductively coupled plasma spectroscopy (method 975.03; AOAC Int., 2007) after wet ash sample preparation (method 975.03; AOAC Int., 2007). Diets and ileal samples were also analyzed for amino acids [method

982.30 E (a, b, c); AOAC Int., 2007] and for titanium dioxide (Myers, et al., 2004). Diets, ingredients, and ileal samples were analyzed for CP by combustion (method 999.03; AOAC Int., 2007) using a Rapid N cube (Elementar Americas Inc, Mt. Laurel, NJ). Diets, ingredients, ileals, fecal, and urine samples were analyzed for GE using an isoperibol bomb calorimetry (Model 6300, Parr Instruments, Moline, IL).

Calculations and Statistical Analysis

Energy values that were determined from the excretion of GE in the feces and urine were subtracted from the intake of GE to calculate DE and ME for each diet (Adeola, 2001). The concentration of OM in the samples was calculated as the difference between the concentration of DM and the concentration of ash. Values for the AID of DM, GE, CP, ash, OM, starch, AEE, and AA, and the ATTD of GE, starch, DM, OM, AEE, ADF, and NDF were calculated using standard procedures (Stein et al., 2007) for each diet. Hindgut fermentation of starch was calculated by subtracting the concentration of starch in the ileal digesta from the concentration of starch in the feces (Urriola and Stein, 2010). Hindgut fermentation of GE, DM, OM, and AEE was calculated using the same approach.

Data were analyzed as a 3 × 4 factorial with fiber level and post-mixing processing as factors using the Mixed Procedure of SAS (SAS Institute Inc., Cary, NC). The model included fiber level, post-mixing processing, and the fiber level × post-mixing processing interaction as fixed effects and period and pig as the random effects. However, interactions between fiber level and post-mixing processing were not significant for the response variables analyzed, except for the AID, ATTD, and hindgut fermentation (**HGF**) of AEE, and the concentrations of DE and ME. Thus, the interaction was

removed from the final model and only main effects of fiber level and post-mixing processing were included for the variables that had no interaction. Homogeneity of the variances among treatments was confirmed using the HOVTEST = BF procedure of SAS. The UNIVARIATE procedure of SAS was used to test for outliers, but no outliers were identified. The Least Squares Means statement was used to calculate treatment means. The pig was the experimental unit for all analyses and an alpha level of 0.05 was used to assess significance among means.

RESULTS

The AID of GE and DM was less ($P < 0.05$) for meal diets than for the post-mixing processed diets (Table 6.5). However, the AID of GE and DM was greater ($P < 0.05$) for extruded diets than for pelleted diets or the combination of extruded and pelleted diets. Meal diets had less ($P < 0.05$) AID of starch compared with post-mixing processed diets, but no differences were observed for the AID of starch among the post-mixing processed diets. The AID of CP and OM was greater ($P < 0.05$) for extruded diets and diets that were extruded and pelleted than for meal diets or pelleted diets, and the AID of OM was greater ($P < 0.05$) for pelleted diets than for meal diets. The AID of ash was greater ($P < 0.05$) for extruded diets than for all other diets.

For all AA except Cys, the AID was greater ($P < 0.05$) for diets that were extruded or extruded and pelleted than for the meal diets and the AID of all AA except Arg, Cys, and Gly was also greater ($P < 0.05$) for pelleted diets than for meal diets. The AID for all AA except His and Cys was also greater ($P < 0.05$) for extruded diets than for

pelleted diets, and the AID for all AA in the diets that were extruded and pelleted was intermediary between values for pelleted diets and values for extruded diets.

The AID of GE, DM, and OM was less ($P < 0.05$) for the medium fiber diets than for low fiber diets, but greater ($P < 0.05$) than for high fiber diets. The AID of starch and CP was greater ($P < 0.05$) for the low fiber diet compared with the medium and high fiber diets, but no differences were observed for the medium or high fiber diets. Medium fiber diets had greater ($P < 0.05$) AID of ash compared with the low or high fiber diets, but AID of ash was greater ($P < 0.05$) for low fiber diets than for high fiber diets. High fiber diets also had less ($P < 0.05$) AID of most AA than diets containing less fiber.

The ATTD of GE was less ($P < 0.05$) for meal diets than for pelleted diets or diets that were extruded and pelleted, but there were no differences among the post-mixing processed diets for the ATTD of starch, GE, DM, OM, ADF, or NDF (Table 6.6). The ATTD of GE, starch, DM, and OM was greater ($P < 0.05$) for medium fiber diets than for high fiber diets, but less ($P < 0.05$) than for low fiber diets. High fiber diets had greater ($P < 0.05$) ATTD of ADF than low or medium fiber diets and the AID of ADF was less ($P < 0.05$) for low fiber diets than for medium fiber diets. The ATTD of NDF was greater ($P < 0.05$) for low and high fiber diets than for medium fiber diets.

The HGF of GE, DM, and OM was greater ($P < 0.05$) for meal diets or pelleted diets than for the extruded diets or diets that were extruded and pelleted (Table 6.7), but the HGF of GE, DM, and OM was less ($P < 0.05$) for extruded diets than for the combination of extruded and pelleted diets. Meal diets had greater ($P < 0.05$) HGF of starch compared with the other diets, but there were no differences for the HGF of starch among the post-mixing processed diets. The HGF of GE, DM, and OM was greater ($P <$

0.05) for high fiber diets than for low or medium fiber diets, but the HGF of GE, DM, and OM was not different between low and medium fiber diets. Medium and high fiber diets had greater ($P < 0.05$) HGF of starch than low fiber diets.

The increase in AID and ATTD of AEE as a result of post-mixing processing was greater ($P < 0.01$) in low fiber or medium fiber diets than in high fiber diets (interaction, $P < 0.05$; Table 6.8). Likewise, the response to processing on HGF was different among fiber levels (interaction, $P < 0.05$). However, regardless of level of fiber, pelleting, extrusion or the combination of extrusion and pelleting increased ($P < 0.05$) the ATTD of AEE.

The DE and ME (DM basis) were less ($P < 0.05$) in the high fiber diets compared with the low or medium fiber diets (Table 6.9). The DE on DM basis was less ($P < 0.01$) in the meal diets compared with the pelleted diets, but this was not the case for high fiber diet. The ME on DM basis was greater ($P < 0.01$) in pelleted diet than in the meal diet for the medium fiber diets. The interaction between fiber and processing was significant ($P < 0.05$) for ME on DM basis. Diets containing low and high fiber levels processed with a combination of extrusion and pelleting increased ME on a DM basis compared with the meal diet, whereas ME on DM basis was not affected by processing with a combination of extrusion and pelleting in the medium fiber diet compared with the meal diet.

DISCUSSION

The increased AID of starch that was observed as diets were pelleted, extruded, or extruded and pelleted is consistent with data for field peas (Stein and Bohlke, 2007; Liu et al., 2015) and indicates that starch in corn will become more digestible if extruded or

pelleted. This increase in starch digestibility likely had a positive impact on energy utilization by the pigs. However, the ATTD of starch was not different among diets because the HGF of starch was greater for the meal diets indicating increased fermentation of starch in the meal diets. The increased HGF observed as the level of fiber increased in the diet is in agreement with data previously reported (Anguita et al., 2006). This supports the observation of this experiment that ME values of the diets were reduced if high fiber ingredients are included, because there is a reduction of absorption of energy and nutrients in the small intestine (Noblet and le Goff, 2001; le Gall et al., 2009), and therefore, there is an increase in HGF, which produce VFA that are absorbed as an energy source by the pig, but this will not totally compensate for the reduction of absorption of glucose in the small intestine as the level of fiber increased in the diet (Anguita et al., 2006).

The negative values observed for HGF of AEE regardless of the level of fiber in the diet are in agreement with data reported by Urriola and Stein (2012). It has been hypothesized that this is likely due to an increase in endogenous losses of fat (Kil et al., 2010) as well as synthesis of fatty acids by microbes in the hindgut if unfermented carbohydrates reach the hindgut (Dierick et al., 1990).

The increase in AID of AA that were observed as diets were pelleted or extruded also are consistent with previous research (Muley et al., 2007; Stein and Bohlke, 2007; Lundblad et al., 2012) although it has also been reported that extrusion of corn does not influence the AID of AA (Herkelman et al., 1990). The reason for the increased AID of AA in diets that are pelleted or extruded may be that processing may partly denature proteins in the diets (Svihus and Zimonja, 2011), which make them easier to digest for

the animal enzymes. The improvements obtained in the present experiment for the AID of most AA was 3 to 4 percentage units, which will add value to the diets because the inclusion of soybean meal or other protein sources potentially can be reduced if diets are pelleted, extruded, or extruded and pelleted. Thus, the costs of pelleting or extrusion may be fully or partly offset by reducing the inclusion of protein meals in the diets.

The increased DE and ME in diets that were either pelleted, extruded, or extruded and pelleted was not a result of increased fermentation of fiber. Instead, the increased ATTD of GE that was observed for pelleted diets and diets that were extruded and pelleted appeared to be a result of increased AID of AA and starch. This result is in agreement with data indicating that extrusion of field peas also results in an increase in DE (Stein and Bohlke, 2007). It also has been reported that pigs fed diets that were pelleted or extruded have increased feed conversion rates compared with pigs fed meal diets, which indicates that the DE and ME in the diets are improved by extrusion or pelleting (Sauer et al., 1990; Hongtrakul et al., 1998; Xing et al., 2004; Lundblad et al., 2011). Although G:F was not determined in the current experiment, it is, therefore, likely that the improvement in DE and ME that was determined as diets were pelleted or extruded will result in improved G:F.

The ME values that were obtained for the low fiber and medium fiber meal diets were within 25 kcal per kg from the values calculated for these diets from NRC (2012). The observation that there was no difference in the ME between the low fiber diets and the medium fiber diets is also in line with expectations because the ME for conventional DDGS is not different from the ME for corn and soybean meal (Pedersen et al., 2007; NRC, 2012). In contrast, the ME of the high fiber diet was approximately 160 kcal

greater than the value calculated from NRC, which indicates that the soybean hulls used in this experiment may have contained more ME than predicted from NRC (2012). Nevertheless, the reduction in ME in the high fiber diets compared with the low or medium fiber diets that was observed was expected because of the inclusion of soybean hulls in these diets. This reduction is a result of a linear reduction in the ATTD of GE as NDF in the diets increase (Jaworski et al., 2015). The increase in NDF from the low fiber to the high fiber diet was 10 to 12 percentage units, and the reduction in ATTD of GE was approximately 10 percentage units. This observation is in agreement with le Gall et al. (2009) who suggested that the ATTD of GE will be reduced by 1 percentage unit for each 1 percentage unit of NDF increase in the diet.

The increase in ME that was observed as a result of pelleting was not influenced by the concentration of fiber in the diet and was calculated as 2.1, 2.5, and 1.9 percent increase for the low fiber, the medium fiber, and the high fiber diets, respectively, if compared with the meal diets. These values are greater than the improvement of approximately 1.5% that was reported by le Gall et al. (2009) who also conducted a digestibility experiment using diets with different fiber levels. In agreement with the results by le Gall et al. (2009), the response to pelleting was not influenced by the level of fiber in the diets. However, the improvement in ME obtained in this experiment is less than the improvement in feed conversion rate that has been reported when pigs are offered ad libitum access to feed (Wondra et al., 1995; Xing et al., 2004; Ulens et al., 2015). However, it is possible that some of the improvement in feed conversion rate observed for pelleted diets offered to pigs on an ad libitum basis is a result of reduced feed wastage because if diets are pelleted and then ground into a meal, feed efficiency is

not different from that observed for an unpelleted meal diet (Lewis et al., 2015). With the restricted feeding regimen used in this experiment, feed wastage was less of a problem, and any wastage was carefully collected and weighed and subtracted from feed allowance to calculate feed consumption.

Feed processing may have a greater positive impact on digestibility of energy and nutrients in high fiber diets compared with low fiber diets (Fry et al., 2012). In the present experiment, there was no effect of fiber level on the increase in ME for pelleted diets, but when diets were extruded, the increase compared with the meal diets was 0.6, 2.7, and 2.9% for the low fiber, the medium fiber, and the high fiber diets, respectively. If diets were extruded and pelleted, the improvement was 3.7% for the high fiber diet vs. 2.3% improvement for the low fiber diet and no improvement for the medium fiber diet. Thus, for both extrusion and the combination of extrusion and pelleting, the greatest improvements were observed for diets with the greatest concentrations of fiber, but the differences among the 3 types of diets were relatively modest. This observation is consistent with the suggestion that effects of extrusion are influenced by the chemical characteristics that are unique to each feed ingredient (Dust et al., 2004).

In conclusion, pelleting, extrusion, or a combination of extrusion and pelleting improved the AID of starch and most AA regardless of the level of fiber in the diet. However, the ATTD of GE was only improved by pelleting and the combination of extrusion and pelleting. The increase in ATTD of GE was not a result of increased fermentation of fiber, but likely a result of the increased digestibility of starch and AA. The increase in ME that was observed for pelleting or extrusion was between 0.6 and 2.9% for the 3 types of diets. However, if diets were extruded and pelleted, ME increased

by up to 3.7% with the greatest improvement observed for the diet with the greatest concentration of fiber. This indicates that if high fiber ingredients are used in diets fed to pigs, extrusion or the combination of extrusion and pelleting may ameliorate some of the reduction of energy that is observed when those ingredients are added to the diet.

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TABLES

Table 6.1. Analyzed nutrient composition of corn, distillers dried grains with solubles (DDGS), soybean hulls, and soybean meal (SBM), as-fed basis

	Ingredient			
Item	Corn	DDGS	Soybean hulls	SBM
GE, kcal/kg	3,938	4,984	3,907	4,198
DM, %	86.57	87.13	88.30	87.50
CP, %	7.70	26.78	13.56	49.51
Ash, %	1.36	3.89	4.62	6.26
OM, %	85.21	83.24	83.69	81.24
AEE[1], %	3.79	13.17	2.43	1.72
NDF, %	7.21	25.79	51.79	9.29
ADF, %	2.12	10.38	37.60	7.64
Hemicelluloses[2], %	5.09	15.41	14.19	1.65
P, %	0.27	0.66	0.19	0.61
Ca, %	-	0.05	0.49	0.26
WBC[3], g/g	1.13	1.93	3.74	2.54
Indispensable, AA %				
Arg	0.34	1.33	0.62	3.56
His	0.24	0.91	0.34	1.38
Ile	0.26	1.02	0.47	2.26

Table 6.1. (Cont.)

Leu	0.90	3.04	0.83	3.87
Lys	0.26	1.00	0.85	3.11
Met	0.15	0.52	0.15	0.67
Phe	0.37	1.30	0.51	2.60
Thr	0.28	1.04	0.46	1.93
Trp	0.06	0.19	0.06	0.73
Val	0.36	1.35	0.54	2.29
Dispensable, AA %				
Ala	0.55	1.89	0.53	2.15
Asp	0.50	1.67	1.15	5.66
Cys	0.16	0.52	0.20	0.67
Glu	1.35	3.55	1.54	8.90
Gly	0.30	1.08	0.87	2.09
Pro	0.65	2.05	0.63	2.52
Ser	0.36	1.24	0.59	2.30
Tyr	0.23	1.04	0.45	1.87
Total AA	7.32	24.74	10.79	48.56

[1]AEE = acid hydrolyzed ether extract.

[2]Hemicelluloses were calculated as the difference between NDF and ADF.

[3]WBC = water binding capacity.

Table 6.2. Ingredient composition of experimental diets containing corn, soybean meal (SBM), distillers dried grains with solubles (DDGS), and soybean hulls, as-fed basis

Ingredient, %	Low fiber	Medium fiber	High fiber
Ground corn	69.70	47.95	29.90
SBM	27.50	24.50	22.80
DDGS	-	25.00	25.00
Soybean hulls	-	-	20.00
Dicalcium phosphate	0.75	0.15	0.25
Ground limestone	0.85	1.20	0.85
Sodium chloride	0.40	0.40	0.40
Titanium dioxide	0.50	0.50	0.50
Vitamin mineral premix[1]	0.30	0.30	0.30
Total	100.00	100.00	100.00

[1]Provided the following quantities of vitamins and micro minerals per kilogram of complete diet: vitamin A as retinyl acetate, 11,128 IU; vitamin D_3 as cholecalciferol, 2,204 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.58 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin as nicotinamide and nicotinic acid, 44 mg; folic acid, 1.58 mg; biotin, 0.44 mg; Cu, 10 mg as copper sulfate; Fe, 125 mg as iron sulfate; I, 1.26 mg as potassium iodate; Mn, 60 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; and Zn, 100 mg as zinc oxide.

Table 6.3. Analyzed nutrient composition of experimental low and medium fiber diets, as-fed basis

	Low fiber				Medium fiber			
Item	Meal	Pelleted	Ext[1]	EP[1]	Meal	Pelleted	Ext	EP
GE, kcal/kg	3,919	3,920	4,112	4,083	4,168	4,154	4,415	4,400
DM, %	85.32	85.11	89.64	88.96	87.70	87.22	92.07	92.00
CP, %	19.42	19.48	20.68	20.42	22.75	22.37	23.79	23.45
Starch, %	43.91	43.80	45.30	44.05	32.53	33.45	31.09	32.91
Ash, %	4.87	4.69	5.13	4.95	5.32	5.21	5.19	5.11
OM, %	80.45	80.42	84.51	84.02	78.91	78.78	82.35	86.72
AEE[2], %	2.33	3.26	2.84	2.76	5.63	6.02	6.19	5.77
NDF, %	7.75	6.98	7.45	7.67	11.79	11.32	12.58	10.40
ADF, %	3.65	3.00	2.82	2.68	5.69	5.16	5.17	4.37
Hemicelluloses[3] %	4.10	3.98	4.63	4.99	6.10	6.16	7.41	6.03
P, %	0.48	0.48	0.51	0.51	0.49	0.48	0.52	0.49

Table 6.3. (Cont.)

Ca, %	0.59	0.46	0.78	0.64	0.55	0.55	0.50	0.69
WBC[4], g/g	1.45	2.04	3.90	5.59	1.55	2.21	3.15	4.30
Indispensable, AA %								
Arg	1.18	1.22	1.31	1.29	1.33	1.30	1.42	1.37
His	0.54	0.56	0.59	0.58	0.61	0.65	0.69	0.67
Ile	0.81	0.83	0.89	0.87	0.91	0.90	0.96	0.94
Leu	1.73	1.77	1.88	1.83	2.10	2.09	2.23	2.21
Lys	1.03	1.06	1.14	1.10	1.10	1.09	1.13	1.13
Met	0.28	0.28	0.29	0.28	0.34	0.33	0.37	0.35
Phe	0.98	1.00	1.07	1.05	1.12	1.10	1.18	1.17
Thr	0.72	0.74	0.80	0.78	0.85	0.84	0.90	0.89
Trp	0.23	0.23	0.25	0.25	0.23	0.24	0.25	0.26
Val	0.88	0.91	0.97	0.95	1.05	1.04	1.11	1.08

Table 6.3. (Cont.)

Dispensable, AA %								
Ala	0.98	1.01	1.08	1.04	1.24	1.24	1.32	1.30
Asp	1.92	1.97	2.12	2.07	2.02	1.98	2.15	2.10
Cys	0.30	0.30	0.32	0.31	0.35	0.35	0.39	0.37
Glu	3.42	3.49	3.73	3.64	3.70	3.67	3.95	3.91
Gly	0.76	0.79	0.85	0.82	0.90	0.90	0.97	0.93
Pro	1.13	1.16	1.21	1.19	1.41	1.43	1.50	1.46
Ser	0.85	0.87	0.93	0.91	1.00	1.00	1.08	1.06
Tyr	0.66	0.69	0.73	0.73	0.79	0.79	0.84	0.83
Total AA	18.40	18.88	20.16	19.69	21.05	20.94	22.44	22.03

[1]Ext = extruded; EP = extruded and pelleted.

[2]AEE = acid hydrolyzed ether extract.

[3]Hemicelluloses were calculated as the difference between NDF and ADF.

[4]WBC = water binding capacity

Table 6.4. Analyzed nutrient composition of experimental high fiber diets, as-fed basis

	High fiber			
Item	Meal	Pelleted	Ext[1]	EP[1]
GE, kcal/kg	4,180	4,144	4,363	4,184
DM, %	88.83	87.80	92.62	88.18
CP, %	23.20	22.53	24.44	23.21
Starch, %	20.94	22.43	20.82	22.52
Ash, %	5.27	5.30	5.55	5.24
OM, %	83.56	82.50	87.07	82.94
AEE[2], %	5.59	5.84	5.49	5.52
NDF, %	20.78	19.80	19.23	20.35
ADF, %	12.60	13.24	12.12	12.89
Hemicelluloses[3] %	8.18	6.56	7.11	7.46
P, %	0.48	0.48	0.49	0.47
Ca, %	0.49	0.51	0.50	0.45
WBC[4], g/g	1.98	2.65	3.77	4.18
Indispensable, AA %				
Arg	1.30	1.27	1.40	1.35
His	0.65	0.63	0.70	0.67
Ile	0.90	0.87	1.00	0.96
Leu	2.03	1.98	2.21	2.11
Lys	1.17	1.10	1.24	1.20

Table 6.4. (Cont.)

Met	0.34	0.33	0.35	0.34
Phe	1.09	1.06	1.19	1.14
Thr	0.85	0.83	0.91	0.88
Trp	0.22	0.24	0.25	0.24
Val	1.03	0.99	1.13	1.09
Dispensable, AA %				
Ala	1.22	1.18	1.29	1.24
Asp	2.01	1.96	2.18	2.10
Cys	0.38	0.35	0.40	0.37
Glu	3.55	3.47	3.84	3.68
Gly	0.97	0.94	1.01	0.99
Pro	1.37	1.33	1.41	1.42
Ser	1.03	0.99	1.07	1.04
Tyr	0.80	0.79	0.86	0.81
Total AA	20.91	20.31	22.44	21.63

[1]Ext = extruded; EP = extruded and pelleted.

[2]AEE = acid hydrolyzed ether extract.

[3]Hemicelluloses were calculated as the difference between NDF and ADF.

[4]WBC = water binding capacity.

Table 6.5. Apparent ileal digestibility (AID, %) of GE, starch, CP, DM, ash, OM, acid hydrolyzed ether extract, and AA in experimental diets[1]

	Type of processing						Level of fiber				
Item	Meal	Pellet	Ext[2]	EP[2]	SEM	*P*-value	Low	Medium	High	SEM	*P*-value
GE	66.2^{d}	68.4^{c}	72.7^{a}	71.0^{b}	0.60	<0.01	76.6^{x}	72.5^{y}	59.5^{z}	0.52	<0.01
Starch	96.4^{b}	97.7^{a}	97.9^{a}	98.3^{a}	0.68	<0.01	98.6^{x}	97.4^{y}	96.8^{y}	0.66	<0.01
CP	72.5^{b}	73.5^{b}	77.9^{a}	76.6^{a}	0.90	<0.01	77.6^{x}	77.1^{x}	70.7^{y}	0.84	<0.01
DM	63.5^{d}	65.3^{c}	69.6^{a}	67.9^{b}	0.67	<0.01	74.7^{x}	69.2^{y}	55.8^{z}	0.60	<0.01
Ash	21.7^{c}	24.4^{bc}	32.4^{a}	27.4^{b}	1.48	<0.01	28.7^{y}	34.3^{x}	16.4^{z}	1.34	<0.01
OM	66.2^{c}	67.9^{b}	71.9^{a}	70.4^{a}	0.64	<0.01	77.4^{x}	71.5^{y}	58.4^{z}	0.57	<0.01
Indispensable, AA %											
Arg	88.3^{b}	88.6^{b}	91.6^{a}	91.1^{a}	0.57	<0.01	90.9^{x}	90.5^{x}	88.3^{y}	0.53	<0.01
His	83.1^{b}	84.9^{a}	85.8^{a}	85.6^{a}	0.61	<0.01	87.0^{x}	86.0^{x}	81.6^{y}	0.57	<0.01
Ile	78.7^{c}	81.3^{b}	84.3^{a}	83.7^{a}	0.44	<0.01	83.8^{x}	83.4^{x}	78.8^{y}	0.38	<0.01

Table 6.5. (Cont.)

Leu	82.2^{c}	84.8^{b}	87.1^{a}	86.4^{a}	0.35	<0.01	86.1^{x}	86.5^{x}	82.9^{y}	0.30	<0.01
Lys	78.0^{c}	79.6^{b}	81.8^{a}	80.9^{ab}	0.53	<0.01	83.3^{x}	81.2^{y}	75.8^{z}	0.46	<0.01
Met	83.3^{c}	86.4^{b}	87.7^{a}	86.7^{ab}	0.40	<0.01	87.1^{x}	86.8^{x}	84.2^{y}	0.35	<0.01
Phe	81.2^{c}	83.9^{b}	87.2^{a}	86.4^{a}	0.44	<0.01	85.7^{x}	86.0^{x}	82.4^{y}	0.40	<0.01
Thr	70.9^{c}	73.3^{b}	75.7^{a}	74.7^{ab}	0.62	<0.01	74.9^{x}	75.3^{x}	70.8^{y}	0.53	<0.01
Trp	78.0^{c}	80.5^{b}	83.2^{a}	83.4^{a}	0.55	<0.01	83.0^{x}	83.6^{x}	77.2^{y}	0.47	<0.01
Val	75.6^{c}	78.4^{b}	80.5^{a}	79.9^{a}	0.49	<0.01	80.6^{x}	80.5^{x}	74.7^{y}	0.42	<0.01
Mean	80.4^{c}	82.4^{b}	84.9^{a}	84.3^{a}	0.42	<0.01	84.6^{x}	84.4^{x}	80.0^{y}	0.36	<0.01
Dispensable, AA %											
Ala	74.8^{c}	77.4^{b}	80.3^{a}	79.4^{a}	0.87	<0.01	79.9^{x}	80.0^{x}	74.1^{y}	0.82	<0.01
Asp	76.6^{c}	78.2^{b}	80.3^{a}	79.3^{ab}	0.62	<0.01	81.6^{x}	79.2^{y}	75.0^{z}	0.56	<0.01
Cys	66.7	68.6	67.9	67.6	1.09	0.67	71.1^{x}	69.7^{x}	62.3^{y}	0.94	<0.01
Glu	80.2^{c}	83.1^{b}	85.4^{a}	85.6^{a}	0.70	<0.01	86.3^{x}	84.7^{y}	79.8^{z}	0.63	<0.01

Table 6.5. (Cont.)

Gly	55.6[b]	54.8[b]	62.7[a]	60.4[a]	2.26	<0.01	62.8[x]	62.9[x]	49.5[y]	2.11	<0.01
Pro	65.0[a]	53.4[b]	71.6[a]	70.6[a]	4.38	<0.01	62.9[y]	73.6[x]	58.9[y]	4.00	<0.01
Ser	79.1[c]	80.8[b]	82.9[a]	82.3[a]	0.77	<0.01	82.6[x]	82.9[x]	78.4[y]	0.74	<0.01
Tyr	83.6[c]	86.2[b]	87.9[a]	87.7[a]	0.44	<0.01	87.0[x]	87.9[x]	84.2[y]	0.38	<0.01
Mean	75.1[b]	75.1[b]	79.9[a]	79.0[a]	0.95	<0.01	79.7[x]	79.2[x]	72.9[y]	0.86	<0.01
Total AA	77.6[b]	78.7[b]	82.2[a]	81.4[a]	0.59	<0.01	82.0[x]	81.6[x]	76.4[y]	0.51	<0.01

[a-d]Means within a row a common superscript letter are different ($P < 0.05$).

[x-z]Means within a row a common superscript letter are different ($P < 0.05$).

[1]Data are means of 24 observations for processing treatments and 32 observations for fiber level.

[2]Ext = extruded; EP = extruded and pelleted.

Table 6.6. Apparent total tract digestibility (ATTD, %) of GE, starch, DM, OM, ADF, and NDF in experimental diets, as-fed basis[1]

	Type of processing						Level of fiber				
Item	Meal	Pellet	Ext[2]	EP[2]	SEM	*P*-value	Low	Medium	High	SEM	*P*-value
GE	84.7[b]	86.0[a]	85.5[ab]	86.4[a]	0.68	0.02	90.2[x]	85.7[y]	81.1[z]	0.65	<0.01
Starch	99.6	99.7	99.6	99.7	0.14	0.54	99.9[x]	99.7[y]	99.3[z]	0.14	<0.01
DM	84.9	85.6	85.4	86.2	0.67	0.14	90.0[x]	85.5[y]	81.1[z]	0.64	<0.01
OM	86.2	87.1	86.7	87.8	0.70	0.06	91.7[x]	86.6[y]	82.5[z]	0.67	<0.01
ADF	48.5	53.4	46.4	51.0	2.22	0.10	41.8[z]	46.9[y]	60.8[x]	1.96	<0.01
NDF	54.7	51.8	51.7	53.9	2.62	0.60	53.9[x]	47.1[y]	57.6[x]	2.46	<0.01

[a-b]Means within a row a common superscript letter are different ($P < 0.05$).

[x-z]Means within a row a common superscript letter are different ($P < 0.05$).

[1]Data are means of 24 observations for processing treatments and 32 observations for fiber level.

[2]Ext = extruded; EP = extruded and pelleted.

Table 6.7. Hindgut fermentation of GE, starch, DM, OM, AEE by growing pigs[1]

	Type of processing						Level of fiber				
Item	Meal	Pellet	Ext[2]	EP[2]	SEM	*P*-value	Low	Medium	High	SEM	*P*-value
GE	18.5[a]	17.5[a]	12.9[c]	15.4[b]	1.05	<0.01	13.6[y]	13.1[y]	21.6[x]	1.00	<0.01
Starch	3.2[a]	2.0[b]	1.7[b]	1.3[b]	0.70	<0.01	1.2[y]	2.3[x]	2.5[x]	0.68	<0.01
DM	21.4[a]	20.4[a]	15.8[c]	18.3[b]	1.13	<0.01	15.3[y]	16.3[y]	25.3[x]	0.64	<0.01
OM	20.0[a]	19.2[a]	14.8[c]	17.4[b]	1.12	<0.01	14.3[y]	15.2[y]	24.1[x]	1.08	<0.01

[a-c]Means within a row a common superscript letter are different ($P < 0.05$).

[x-y]Means within a row a common superscript letter are different ($P < 0.05$).

[1]Data are means of 24 observations for processing treatments and 32 observations for fiber level.

[2]Ext = extruded; EP = extruded and pelleted.

Table 6.8. Apparent ileal digestibility (AID, %), apparent total tract digestibility (ATTD, %), and hindgut fermentation (HGF, %) of acid hydrolyzed ether extract in experimental diets by growing pigs[1]

Item	Processing	AID	ATTD	HGF
Low fiber	Meal	57.2^{f}	49.1^{i}	-8.1^{ef}
	Pellet	78.5^{d}	76.6^{de}	-1.9^{abc}
	Ext[2]	72.3^{e}	66.5^{h}	-5.8^{def}
	EP[2]	74.6^{e}	73.1^{g}	-1.5^{a}
Medium fiber	Meal	79.5^{cd}	74.2^{fg}	-5.2^{cdef}
	Pellet	84.6^{ab}	82.6^{a}	-1.9^{ab}
	Ext	87.2^{a}	78.8^{bcd}	-8.4^{f}
	EP	84.4^{ab}	79.3^{bc}	-5.0^{bcde}
High fiber	Meal	79.1^{cd}	76.3^{ef}	-2.8^{abcd}
	Pellet	83.1^{b}	81.0^{ab}	-2.1^{abc}
	Ext	79.8^{cd}	77.9^{cde}	-2.0^{abc}
	EP	82.2^{bc}	79.5^{bc}	-2.7^{abcd}
SEM		1.58	0.93	1.98
P-value	Fiber	<0.01	<0.01	0.04
	Process	<0.01	<0.01	<0.01
	Fiber × process	<0.01	<0.01	<0.01

[a-i]Means within a column lacking a common superscript letter differ ($P < 0.05$).

Table 6.8. (Cont.)

[1]Data are means of 8 observations per treatment.

[2]Ext = extruded; EP = extruded and pelleted.

Table 6.9. Concentration of digestible and metabolizable energy in experimental diets[1]

Item	Processing	Gross energy[2]			Energy concentration			
		Intake	Feces	Urine	DE[3]	ME[3]	DE[4]	ME[4]
Low fiber	Meal	7,206	765.5	361.3	3,502^{ef}	3,300^{e}	4,105^{e}	3,868^{d}
	Pellet	7,196	652.4	359.3	3,561^{cd}	3,361^{de}	4,184^{bc}	3,949^{bc}
	Ext[5]	7,571	754.8	379.0	3,691^{b}	3,490^{bc}	4,117^{de}	3,893^{cd}
	EP[5]	7,542	683.0	349.9	3,708^{b}	3,520^{b}	4,168^{cd}	3,957^{bc}
Medium fiber	Meal	7,838	1189	393.2	3,532^{de}	3,325^{e}	4,192^{cde}	3,947^{cd}
	Pellet	7,835	1057	367.3	3,588^{c}	3,396^{d}	4,272^{ab}	4,044^{ab}
	Ext	8,398	1252	389.4	3,755^{ab}	3,549^{ab}	4,289^{a}	4,055^{a}
	EP	8,282	1107	377.3	3,805^{a}	3,605^{a}	4,144^{cde}	3,926^{cd}
High fiber	Meal	8,525	1670	352.5	3,343^{g}	3,172^{f}	3,777^{h}	3,583^{f}
	Pellet	8,421	1605	281.6	3,345^{g}	3,206^{f}	3,810^{gh}	3,651^{ef}
	Ext[3]	8,971	1617	320.8	3,568^{cde}	3,415^{cd}	3,853^{fg}	3,687^{e}

Table 6.9. (Cont.)

	EP[3]	8,535	1500	309.4	3,428[f]	3,278[e]	3,888[f]	3,717[e]
SEM		889	100	57	37	38	42	44
P-value	Fiber	<0.01	<0.01	0.19	<0.01	<0.01	<0.01	<0.01
	Process	<0.01	<0.01	0.54	<0.01	<0.01	<0.01	<0.01
	Fiber × process	0.64	0.27	0.96	<0.01	<0.01	<0.01	<0.01

[a-h]Means within a column lacking a common superscript letter differ ($P < 0.05$).

[1]Data are means of 8 observations per treatment.

[2]Kcal/kg.

[3]As-fed basis.

[4]As-dry matter basis.

[5]Ext = extruded; EP = extruded and pelleted.

CHAPTER 7

EFFECTS OF CHEMICAL, PHYSICAL, OR ENZYMATIC TREATMENTS ON CONCENTRATION OF DIGESTIBLE AND METABOLIZABLE ENERGY AND ON APPARENT TOTAL TRACT DIGESTIBILITY OF ENERGY, ORGANIC MATTER, AND DETERGENT FIBER IN DISTILLERS DRIED GRAINS WITH SOLUBLES FED TO GROWING PIGS

ABSTRACT: An experiment was conducted to determine the effects of chemical, physical, or enzymatic treatments on the concentration of DE and ME, and the digestibility of energy, OM, and detergent fiber in distillers dried grains with solubles (DDGS). Sixty-three barrows (initial BW: 76.1 ± 6.1 kg) were placed individually in metabolism cages and allotted to a randomized complete block design with 7 diets and 9 replicate pigs per diet. One load of DDGS was divided into 6 batches that were untreated (DDGS-CV), extruded at 120ºC with an internal pressure of 3,998 kPa by using a single screw extruder (DDGS-EX), treated with sodium hydroxide (at 1.95%; DDGS-Na) or calcium oxide (1.80%; DDGS-Ca), or treated with either cellulase (at 5%; DDGS-cellulase) or hemicellulase (at 0.4%; DDGS-hemicellulase). A 97% corn-based diet was formulated as a control diet, and 6 additional diets were formulated using 50.0% of each aforementioned source of DDGS. After a 5 d adaptation period to the diet, feces and urine samples were collected for 5 d. The apparent total tract digestibility (ATTD) of GE, OM, ADF, and NDF, and the DE and ME were calculated for each diet using the direct procedure and for each source of DDGS using the difference procedure. The ATTD of GE in corn, DDGS-CV, DDGS-EX, DDGS-Na, DDGS-Ca, DDGS-cellulase, and DDGS-

hemicellulase was 86.56, 71.75, 72.78 73.32, 70.37, 74.96, and 73.86%, respectively. The ATTD of GE was greater ($P < 0.05$) in corn than in all other ingredients. The ATTD of GE in DDGS-cellulase was greater ($P < 0.05$) than in DDGS-Ca and DDGS-CV, but the ATTD of GE was not different among DDGS-EX, DDGS-Na, DDGS-cellulase, and DDGS-hemicellulase. The ATTD of NDF was less ($P < 0.05$) in DDGS-Ca than in corn, DDGS-Na, DDGS-cellulase, and DDGS-hemicellulase. The ME was less ($P < 0.05$) in DDGS-EX (3,501 kcal/kg DM), DDGS-Na (3,458 kcal/kg DM), DDGS-Ca (3,318 kcal/kg DM), DDGS-hemicellulase (3,545 kcal/kg DM), and DDGS-CV (3,442 kcal/kg DM) than in corn (3,738 kcal/kg DM) and DDGS-cellulase (3,701 kcal/kg DM). In conclusion, in this experiment, no significant improvement in ME or ATTD of GE, OM, or ADF was observed if DDGS was extruded or treated with sodium hydroxide, calcium oxide, or hemicellulase. However, treatment of DDGS with cellulase resulted in an increase in ATTD of GE and OM and in ME compared with untreated DDGS.

Key words: calcium oxide, corn, DDGS, enzymes, pig, sodium hydroxide

INTRODUCTION

Distillers dried grains with solubles (**DDGS**) is a co-product from the dry grind industry (NRC, 2012) and has become an important ingredient in diets fed to pigs due to the relatively low cost (Stein, 2012). Most categories of pigs may be fed diets containing up to 30% DDGS (Stein and Shurson, 2009). The DE and ME in conventional DDGS are similar to that in corn even though the GE is greater in DDGS than in corn (Pedersen et al., 2007; Stein and Shurson, 2009; NRC, 2012). The reason for this is likely that the apparent total tract digestibility (**ATTD**) of energy in DDGS is less than in corn due to

the high concentration of insoluble fiber in DDGS (Pedersen et al., 2007; Stein et al., 2009). Almost 90% of the total fiber in DDGS is insoluble fiber, which is only fermented by 40% (Urriola et al., 2010). In contrast, soluble fiber in DDGS has a fermentability of more than 90% (Urriola et al., 2010; Jaworski et al., 2015). Therefore, any treatment that can solubilize some of the insoluble fiber is believed to result in increased energy contribution from the fibers in DDGS. Possible treatments that may result in increased solubility of fiber include physical, chemical, and enzymatic treatments of DDGS, but there is limited information about the effectiveness of these treatments. Therefore, the objective of this experiment was to determine effects of physical, chemical, and enzymatic pretreatments on concentrations of DE and ME and on the ATTD of GE, OM, ADF, and NDF in DDGS.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at the University of Illinois (Urbana, IL) reviewed and approved the protocol for this experiment.

Treatment of DDGS

Yellow dent corn was grown locally and obtained from the University of Illinois Feed Mill (Champaign, IL). Before conducting the animal part of the experiment, a preliminary in vitro experiment was conducted to determine the effect of different chemical and enzymatic treatments on the in vitro disappearance of NDF, ADF, and total dietary fiber. Results of the preliminary experiment indicated that incubation of DDGS with sodium hydroxide (**NaOH**), cellulase, or hemicellulase were effective in degrading some of the TDF in DDGS (data not shown). One batch of conventional low-oil DDGS

(**DDGS-CV**) was obtained from Center Ethanol (Sauget, IL). This batch was divided into 6 sub-batches (Table 7.1). One sub-batch was used without any treatment and 1 batch was extruded (**DDGS-EX**) prior to diet mixing at 120ºC and an internal pressure of 3,998 kPa by using a Model 2500 INSTA-PRO single screw extruder (Insta-Pro Int., Urbandale, IA). One batch was treated with NaOH (**DDGS-Na**) provided by AAA-Chemicals (LaMarque, TX) and 1 batch was treated with calcium oxide (**CaO**; **DDGS-Ca**) that was sourced from Mississippi Lime (St. Louis, MO). The process to treat DDGS with NaOH or CaO was described by Felix et al. (2012). Briefly, pH of an untreated sample of DDGS was determined with the objective of measuring how much NaOH or CaO are required to increase the pH of the untreated sample to pH 7. As a result, 7.3 kg of a 40% solution of water and NaOH (DDGS treated with 1.95% NaOH) was used and 7.1 kg of a 40% solution of water and CaO (DDGS treated with 1.80% CaO) was used to treat 150 kg of DDGS. This process was accomplished by mixing either of the chemical solutions with DDGS in a horizontal mixer for 15 mins. The last 2 batches of DDGS were treated with an enzyme mixture of cellulases or with an enzyme mixture of hemicellulases. Both enzyme mixtures were sourced from Novozyme (Bagsværd, Denmark). The celluase was designed to hydrolysis the cellulosic material present in plant material into glucose and cellobiose. The hemicellulase that was used was a mixture of arabinase, β-glucanase, cellulase, hemicellulase, pectinase, and xylanase. Enzyme treatment was accomplished by mixing DDGS-CV with cellulase (**DDGS-cellulase**; inclusion rate of 5%) or hemicellulase (**DDGS-hemicellulase**; inclusion rate of 0.4%) in a horizontal mixer for 15 mins. All DDGS treated with chemical or enzyme treatments was packaged and stored for 15 d before being used in the diet.

Diets, Animals, and Experimental Design

Pigs used in this experiment were the offspring of G-performer boars mated to F-25 gilts (Genetiporc, Alexandria, MN). Sixty-three growing barrows (initial BW: 76.1 ± 6.1 kg) were placed in metabolism cages and allotted to a randomized complete block design with 7 diets and 9 replicate pigs per diet. Each metabolism cage was equipped with a feeder and a nipple drinker, a slatted floor, a screen floor, and a urine pan. Seven corn-based diets were formulated (Table 7.2). The basal diet contained 97.0% corn (as-fed basis) and the remaining 6 diets contained 47.95% corn and 50.0% of each of the 6 sources of DDGS (as fed basis). Vitamins and minerals were included in the diets to meet or exceed requirements for growing pigs (NRC, 2012). The only sources of energy in the diets were corn and DDGS.

Feeding and Sample Collection

Feed was provided to the pigs in a daily amount of 3 times the maintenance energy requirement (i.e., 197 kcal of ME/kg of $BW^{0.60}$; NRC, 2012) of the smallest pig in each replicate. The total amount of feed was divided into 2 equal meals that were fed at 0800 and 1700 h. Water was available at all times.

Pigs were fed experimental diets for 12 d. The initial 5 d were considered an adaptation period to the diet. Chromic oxide and ferric oxide were added to the diet as indigestible markers in the morning meals on d 6 and on d 11, respectively. Fecal collections were initiated when chromic oxide appeared in the feces and ceased when ferric oxide appeared (Adeola, 2001). Feces were collected twice daily and stored at -20ºC immediately after collection. Urine collections started on d 6 at 0800 h and ceased on d 11 at 0800 h. Urine buckets were placed under the metabolism cages to permit total

collection. Buckets were emptied in the morning and afternoon and a preservative of 50 mL of 6*N* HCl was added to each bucket when they were emptied. The collected urine was weighed and a 20% subsample was stored at -20ºC.

Sample Analyses

After completing sample collections, fecal samples were dried at 65ºC in a forced-air oven and ground through a 1-mm screen in a Wiley mill (Model 4; Thomas Scientific, Swedesboro, NJ) before analyses. Urine samples were thawed and mixed within animal and diet, and a subsample was saved for analysis. Urine samples were lyophilized before energy analysis (Kim et al., 2009). Diets and ingredient samples were analyzed for CP by combustion (Method 999.03; AOAC Int., 2007) using a Rapid N cube (Elementar Americas Inc, Mt. Laurel, NJ) and acid hydrolyzed ether extract (**AEE**), which was determined by acid hydrolysis using 3*N* HCl (Sanderson, 1986) followed by crude fat extraction with petroleum ether (Method 2003.06, AOAC Int., 2007) on a Soxtec 2050 automated analyzer (FOSS North America, Eden Prairie, MN). Diet and ingredient samples were also analyzed for Na (Method 956.01, AOAC Int., 2007), P, and Ca by the inductively coupled plasma spectroscopy procedure (Method 985.01 A, B, and C; AOAC, 2007) after wet ash sample preparation [Method 975.03 B(b); AOAC Int., 2007].

Diets, ingredients, and fecal samples were analyzed for ash (Method 942.05; AOAC Int., 2007), DM (Method 930.15; AOAC Int., 2007), ADF (Method 973.18; AOAC Int., 2007), NDF (Holst, 1973), and ADL [Method 973.18 (a-d); AOAC Int., 2007]. Diets, ingredients, fecal samples, and urine samples were also analyzed for GE using an isoperibol bomb calorimetry (Model 6300, Parr Instruments, Moline, IL) and ingredients were analyzed for AA [Method 982.30 E (a, b, c); AOAC Int., 2007].

Calculations and Statistical Analysis

Energy values that were determined from the excretion of GE in the feces and urine were subtracted from the intake of GE to calculate DE and ME for each diet (Adeola, 2001). The DE and ME in the corn diet were divided by 0.97 to calculate the DE and ME in corn. The contributions of DE and ME from corn to the diets containing untreated or treated DDGS were then calculated and subtracted from the total DE and ME of these diets, and the concentrations of DE and ME in untreated and treated DDGS were calculated by difference (Adeola, 2001). Calculations of the DE and ME in all ingredients were completed on an as-fed basis as well as on a DM basis. Cellulose concentration was calculated in all ingredients as the difference between ADF and ADL, and hemicelluloses were calculated as the difference between NDF and ADF. The ATTD of GE, OM, ADF, NDF, hemicelluloses, and celluose was calculated for all diets and for each source of DDGS (Adeola, 2001).

Data were analyzed by ANOVA using the Mixed Procedure of SAS (SAS Institute Inc., Cary, NC). Homogeneity of variances among treatments was confirmed using the HOVTEST = BF procedure of SAS. The UNIVARIATE procedure of SAS was used to test for outliers, but no outliers were identified. Diet was the fixed effect and replicate was the random effect. The Least Significant Means statement was used to calculate treatment means and the PDIFF option was used to separate means if differences were detected. The pig was the experimental unit for all analyses and an alpha level of 0.05 was used to assess significance among means.

RESULTS

The ATTD of GE was greater ($P < 0.05$) in the DDGS-cellulase diet than in the DDGS-Ca and DDGS-CV diets, but the corn diet had greater ($P < 0.05$) ATTD of GE than all other diets (Table 7.3). The ATTD of OM was greater ($P < 0.05$) in the corn diet than in all other diets and the ATTD of OM was greater ($P < 0.05$) in the DDGS-Na and DDGS-hemicellulase diets than in the DDGS-Ca diet. The ATTD of NDF was greater ($P < 0.05$) in the DDGS-Na diet than in all other diets, but the ATTD of NDF was less ($P < 0.05$) in the DDGS-EX and DDGS-Ca diets than in the corn and DDGS-hemicellulase diets. The ATTD of ADF was greater ($P < 0.05$) in the DDGS-CV, DDGS-Na, DDGS-Ca, DDGS-cellulase, and DDGS-hemicellulase diets than in the corn and DDGS-EX diets, but the DDGS-EX diet had greater ($P < 0.05$) ATTD of ADF than corn. The ATTD of cellulose was less ($P < 0.05$) in the DDGS-EX diet than in the DDGS-CV, DDGS-Na, DDGS-cellulase, and DDGS-hemicellulase diets, but was not different from the ATTD of cellulose in the corn and DDGS-Ca diets. The ATTD of hemicellulose was less ($P < 0.05$) in the DDGS-Ca diet than in all other diets, but the ATTD of hemicellulose was greater ($P < 0.05$) in the DDGS-Na diet than in the DDGS-CV, DDGS-EX, DDGS-cellulase, and DDGS-hemicellulase diets.

The ATTD of GE was greater ($P < 0.05$) in corn than in all other ingredients, but the ATTD of GE in DDGS-cellulase was greater ($P < 0.05$) than in DDGS-Ca and DDGS-CV. The ATTD of OM was greater ($P < 0.05$) in DDGS-cellulase than in DDGS-CV and DDGS-Ca, but the ATTD of OM was not different among DDGS-EX, DDGS-Na, DDGS-cellulase, and DDGS-hemicellulase. The ATTD of OM was greater ($P < 0.05$) in corn than in all other ingredients. The ATTD of NDF was less ($P < 0.05$) in DDGS-Ca

than in corn, DDGS-Na, DDGS-cellulase, and DDGS-hemicellulase, but no differences in ATTD of NDF were observed among DDGS-CV, DDGS-EX, and DDGS-Ca. The ATTD of ADF was less ($P < 0.05$) in corn and DDGS-EX than in all other ingredients, but the ATTD of ADF was greater ($P < 0.05$) in DDGS-EX than in corn. The ATTD of cellulose was greater ($P < 0.05$) in DDGS-CV, DDGS-Na, DDGS-cellulase, and DDGS-hemicellulase than in corn and DDGS-EX, but no differences were observed in the ATTD of cellulose between DDGS-EX and DDGS-Ca. The ATTD of hemicelluloses was less ($P < 0.05$) in DDGS-CV and DDGS-cellulase than in corn, DDGS-EX, DDGS-Na, and DDGS-hemicellulase, but greater ($P < 0.05$) than the ATTD of hemicellulose in DDGS-Ca.

Pigs fed the corn diet had less ($P < 0.05$) gross energy intake than for pigs fed the other diets, except for pigs fed the DDGS-CV diet, which was not different. Gross energy intake was less ($P < 0.05$) for pigs fed the DDGS-CV diet than for pigs fed the DDGS-EX, DDGS-cellulase, or DDGS-hemicellulase diets, but no difference in GE intake were observed among pigs fed DDGS-CV, DDGS-Na, and DDGS-Ca diets (Table 7.4). Fecal excretion of GE was less ($P < 0.05$) for pigs fed the DDGS-cellulase diet than for pigs fed the DDGS-Ca diet, but greater ($P < 0.05$) than for pigs fed the corn diet. Fecal excretion of GE among DDGS-EX, DDGS-Na, DDGS-hemicellulase, and DDGS-CV diets were not different. Pigs fed the DDGS-cellulase, DDGS-hemicellulase, or DDGS-CV diets had greater ($P < 0.05$) urine excretion of GE than pigs fed the corn diet, but not different from pigs fed the DDGS-EX, DDGS-Na, or the DDGS-Ca diets. The concentration of DE (as-fed basis) was greater ($P < 0.05$) in DDGS-hemicellulase and DDGS-EX diets than in the corn, DDGS-Na, and DDGS-Ca diets, but not different from

the DDGS-CV and the DDGS-cellulase diets. The ME (as-fed basis) was greater ($P < 0.05$) in the corn, DDGS-EX, and DDGS-hemicellulase diets than in the DDGS-Na and DDGS-Ca diets, but the ME concentration was less ($P < 0.05$) in the DDGS-CV diet than in the DDGS-cellulase diet.

The DE concentration (as-fed basis) was greater ($P < 0.05$) in DDGS-cellulase than in corn, DDGS-Na, DDGS-Ca, and DDGS-CV, but DE was not different among DDGS-EX, DDGS-cellulase, and DDGS-hemicellulase. However, on a DM basis, DE in DDGS-cellulase was greater ($P < 0.05$) than in all other ingredients. Likewise, the DE (DM basis) in DDGS-CV was less ($P < 0.05$) than in corn, DDGS-EX, and DDGS-hemicellulase. The ME (as-fed basis) was greater ($P < 0.05$) in corn and DDGS-cellulase than in DDGS-EX, DDGS-Na, DDGS-Ca, and DDGS-CV, but the ME of DDGS-hemicellulase was not different from that of corn and DDGS-cellulase. On a DM basis, ME in DDGS-EX, DDGS-Na, DDGS-Ca, DDGS-hemicellulase, and DDGS-CV was not different, but less ($P < 0.05$) than in corn and DDGS-cellulase. However, DDGS-Ca had an ME value (DM basis) that was less ($P < 0.05$) than that of all other ingredients.

DISCUSSION

Chemical Ingredient Composition

Crude protein, starch, and fat are the primary sources of GE in corn, but because of fermentation of starch in the ethanol plants, there is a greater concentration of CP, fiber, and fat and less starch in DDGS compared with corn (Stein and Shurson, 2009; Anderson et al., 2012; Pedersen et al., 2014; Jaworski et al., 2015). Although DDGS contains more GE than corn (Rojas and Stein, 2013), the concentration of DE and ME in

conventional DDGS and corn are usually not different (Pedersen et al., 2007; Stein et al., 2009; NRC, 2012). The reason for this observation is that the ATTD of GE in DDGS is less than in corn (Pedersen et al., 2007; Liu et al., 2012; Rojas and Stein, 2013) due to the high concentration of insoluble fiber in DDGS (Urriola et al., 2010). The fiber in DDGS consists of almost 90% insoluble fiber, which is 40% fermentable, and 10% soluble fiber, which is 90% fermentable (Urriola et al., 2010). Thus, if chemical, physical, or enzymatic treatments can be used to solubilize some of the fiber in DDGS, it is possible that fermentation, and, as a result, energy digestibility, will increase.

The concentration of energy and nutrients in the samples of corn and DDGS-CV that were used in this experiment are close to expected values (Stein et al., 2006; Stein and Shurson, 2009; NRC, 2012). The DDGS that was used contained 6.66% AEE indicating that this source of DDGS was a low-fat DDGS (NRC, 2012). This is likely a result of oil being removed from the solubles during the production of DDGS. This observation likely is the reason for the reduced DE and ME in DDGS-CV used in this experiment compared with corn, because removal of oil from DDGS may result in reduced DE and ME (Kerr et al., 2013). The observation that the ATTD of GE increased as cellulase was added to the DDGS indicates that cellulase contributes to an increased digestibility or fermentability of cellulose in DDGS. It is believed that DDGS contains approximately 23.0% cellulose (Bach Knudsen, 2011; Jaworski et al., 2015). Because cellulose consists only of glucose, any digestion of cellulose in the small intestine will likely result in increased absorption of glucose, which will contribute to an increase in the energy digestibility of the diet. However, if the cellulase enzyme does not digest all of the β-1-4 bonds in cellulose, the resulting oligosaccharides or cellobiose will enter the large

intestine where they may be fermented, which will result in increased synthesis of VFA. These VFA will be absorbed from the hindgut of the pigs and, thereby, increase the energy contribution from DDGS. The current data do not allow us to establish the mechanism for the increase in energy digestibility that was observed when DDGS was treated with cellulase. However, the fact that the ATTD of GE was improved when cellulase was added to the diet indicates that either digestibility or fermentability of cellulose was improved.

It is possible that some of the positive effects of enzymes on energy digestibility are a result of hydrolysis of the fiber from other nutrients. Nutrients in fibrous ingredients may be bound by fiber and their digestion hindered, as a result (Bedford, 1995). However, in the present experiment, we did not attempt to determine digestibility or fermentability of nutrients other than ADF and NDF. Therefore,we do not know if absorption of CP, fat, or glucose from starch contributed to the increase in energy digestibility that we observed as a result of treatment with celullase.

In contrast to the cellulase, inclusion of hemicellulase did not improve the ATTD of GE or the ME of DDGS. This indicates that it is more challenging to develop enzyme mixtures that can improve the ATTD of hemicellulose in DDGS than it is to improve the ATTD of cellulose. This observation is in agreement with previous research that has indicated that xylanase enzymes do not always improve the ATTD of GE in corn DDGS (Yáñez et al., 2011). In contrast, pigs fed a wheat-DDGS based diet that was supplemented with a carbohydrase mixture consisting of xylanase, β-glucanase, and cellulase had greater GE digestibility compared with pigs fed diets that were not supplemented with the enzymes (Emiola et al., 2009).

Extrusion is a technology that uses high temperature and high pressure, and it may improve energy and nutrient digestibility (Hancock and Behnke, 2001). Extrusion also denatures protein and gelatinizes the starch in cereal grains, which may make these nutrients more digestible (Hancock and Behnke, 2001; Zijlstra et al., 2009). Extrusion increases the digestibility of energy in field peas (Stein and Bohlke, 2007), but results of the present experiment indicate that this is not the case for DDGS. Possible reasons for this observation include that DDGS has already been fermented, which may prevent any further improvements from extrusion. The main reason for the improved ATTD of GE in field peas is an improved ileal digestibility of starch (Stein and Bohlke, 2007), but the concentration of starch in DDGS is much less than in field peas (Stein and Shurson, 2009; NRC, 2012), which may be the reason extrusion is not effective in improving the ATTD of GE in DDGS.

To our knowledge, no previous data have been published on the effects of treatments with NaOH or CaO of DDGS, but we hypothesized that these treatments might solubilize some of the fibers in DDGS, which in turn could have resulted in improvements in the ATTD of GE. However, results indicate that the procedures we used in the present research were ineffective in obtaining this effect. Future research will need to be conducted to determine if other chemical treatments or increased dosages of NaOH or CaO may be used since treating DDGS with 1.95 or 1.80% of NaOH or CaO, respectively, were not effective concentrations to improve the ATTD of GE in DDGS by solubilizing the lignin, which may encapsulate several constituents of the plant cell wall such as amorphous hemicelluloses and crystalline cellulose (Mansfield, et al., 1999).

Sodium hydroxide is considered a hydrolytic agent that solubilizes hemicelluloses, lignin, and silica constituents of the plant cell wall (Fahey et al., 1993). The solubilization is mainly due to changes in the lignin-hemicellulose matrix that take place when the cell wall is in contact with NaOH (Fahey et al., 1993). Thus, alkaline treatments break down the hydrogen bonds in hemicelluloses, cellulose, and lignin fractions of the plant cell wall (Kahar, 2013), which results in changes in the structure of the plant cell wall. This may improve the access of microbial enzymes to the nutrients of the plant (Fahey et al., 1993), which may be the reason for the improvement in the ATTD of NDF that was observed in the DDGS that was treated with NaOH. A similar observation was reported when NaOH treated sorghum grain was fed to cows (Miron et al., 1997). However, the increased solubility of NDF that was observed in this experiment was not sufficient to improve the ATTD of GE in DDGS treated with NaOH. Sodium hydroxide has also been used to treat DDGS fed to beef cattle to ameliorate the acidity of DDGS. Heifers fed DDGS treated with NaOH, compared with heifers fed un-treated DDGS, had increased ruminal pH, which may result in a reduction in the incidence of ruminal acidosis, and increased in situ fiber disappearance (Felix et al., 2012).

Calcium oxide also may be used to solubilize fiber, and although it is less common than NaOH, it offers an inexpensive way to treat feed ingredients (Chaudhry, 1999). The reduction in ATTD of NDF that was observed when DDGS was treated with CaO was not expected because feedlot cattle fed diets containing Brix sugar cane treated with CaO had increased digestibility of NDF compared with cattle fed untreated Brix sugar cane (Magalhaes et al., 2012b). However, there is less substrate to solubilize in DDGS compared with the concentration of fiber in Brix sugar cane (Magalhaes et al.,

2012a), and growth performance was not improved in feedlot cattle fed corn stover and modified wet distillers grains with solubles that were treated with CaO compared with feedlot cattle fed untreated corn stover and modified wet distillers grains with solubles even though CaO increased digestibility of DM and fiber compared with the untreated ingredients (Duckworth, 2013). Beef cattle fed DDGS that had been treated with CaO had increased cellulase activity in the rumen after 3 h post-feeding compared with the untreated DDGS (Schroeder et al., 2014). Thus, additional research is needed to investigate if CaO can be used to improve the feeding value of high-fiber ingredients fed to pigs.

In conclusion, of the treatments investigated in this research, only cellulase treatment was effective in improving the ME of DDGS, which increases the nutritional value of DDGS when fed to pigs. In contrast, addition of hemicellulase, extrusion, or treatment with CaO or NaOH did not consistently improve the ATTD of DDGS. Additional research is required to determine if other chemical, physical, or enzyme treatments may be used to solubilize the fiber in DDGS and thereby increase the nutritional value.

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TABLES

Table 7.1. Analyzed nutrient composition of corn, untreated distiller dried grains with solubles (DDGS), and pretreated DDGS, as-fed basis

Item	Corn	DDGS-CV	Pretreated DDGS[1]				
			DDGS-EX	DDGS-Na	DDGS-Ca	DDGS-cellulase	DDGS-hemicellulase
GE, kcal/kg	3,820	4,519	4,464	4,222	4,253	4,446	4,485
DM, %	85.65	88.40	87.91	84.31	85.38	86.30	87.68
CP, %	7.68	29.31	28.86	28.52	28.07	29.86	29.93
Ash, %	1.18	5.17	5.18	7.52	6.50	5.45	5.29
OM, %	84.45	83.23	82.73	76.78	78.88	80.85	82.39
AEE[2], %	3.04	6.79	7.06	6.31	6.66	7.01	6.89
NDF, %	8.59	26.44	25.07	25.85	26.06	24.84	27.28
ADF, %	3.15	14.90	11.92	14.53	14.76	14.64	14.87

Table 7.1. (Cont.)

ADL, %	0.33	5.05	2.44	4.22	3.73	4.00	4.75
Cellulose[3], %	2.81	9.85	9.48	10.31	11.03	10.64	10.12
Hemicelluloses[4], %	5.45	11.54	13.16	11.32	11.31	10.20	12.41
Na, %	0.02	0.13	0.13	1.50	0.15	0.15	0.15
P, %	0.22	0.83	0.78	0.77	0.78	0.80	0.83
Ca, %	0.01	0.03	0.03	0.02	1.07	0.04	0.05
Indispensable, AA %							
Arg	0.39	1.43	1.44	1.26	1.43	1.45	1.46
His	0.22	0.77	0.76	0.79	0.77	0.78	0.78
Ile	0.26	1.13	1.10	1.12	1.13	1.13	1.15
Leu	0.96	3.37	3.33	3.30	3.42	3.40	3.49
Lys	0.26	0.94	0.93	0.82	0.91	0.95	0.95
Met	0.17	0.61	0.60	0.59	0.61	0.62	0.63

Table 7.1. (Cont.)

Phe	0.39	1.41	1.42	1.43	1.44	1.45	1.46
Thr	0.29	1.11	1.10	1.08	1.09	1.14	1.11
Trp	0.06	0.22	0.22	0.23	0.20	0.23	0.23
Val	0.36	1.50	1.49	1.44	1.52	1.54	1.55
Dispensable, AA %							
Ala	0.60	2.02	2.02	1.93	2.06	2.08	2.08
Asp	0.54	1.81	1.86	1.73	1.83	1.91	1.86
Cys	0.17	0.54	0.55	0.49	0.53	0.58	0.56
Glu	1.44	3.78	3.91	3.73	3.98	3.98	3.97
Gly	0.32	1.20	1.19	1.10	1.20	1.23	1.21
Pro	0.66	2.01	2.00	1.99	2.03	2.04	2.11
Ser	0.39	1.29	1.24	1.23	1.23	1.26	1.24
Tyr	0.22	1.06	1.02	1.10	1.02	1.02	1.07

Table 7.1. (Cont.)

Total AA	7.66	26.15	26.15	25.36	26.37	26.77	26.87

[1]All the pretreated DDGS was obtained from the same batch of DDGS as the untreated DDGS.

[2]AEE = acid hydrolyzed ether extract.

[3]Cellulose was calculated as the difference between ADF and ADL.

[4]Hemicelluloses were calculated as the difference between NDF and ADF.

Table 7.2. Ingredient composition of experimental diets containing corn, untreated distillers dried grains with solubles (DDGS), and pretreated DDGS, as-fed basis

	Diet						
			Pretreated DDGS[1]				
Item	Corn	DDGS-CV	DDGS-EX	DDGS-Na	DDGS-Ca	DDGS-cellulase	DDGS-hemicellulase
Ingredients, %							
Ground corn	97.00	47.95	47.95	47.95	47.95	47.95	47.95
DDGS	-	50.00	50.00	50.00	50.00	50.00	50.00
Dicalcium phosphate	1.50	-	-	-	-	-	-
Ground limestone	0.80	1.35	1.35	1.35	1.35	1.35	1.35
Sodium chloride	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin mineral premix[2]	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Analyzed composition							

Table 7.2. (Cont.)

GE, kcal/kg	3,689	4,078	4,120	3,943	3,976	4,098	4,101
DM, %	86.26	87.66	88.40	86.25	86.23	87.35	87.63
CP, %	7.69	18.16	18.86	17.77	18.17	18.32	18.56
Ash, %	4.27	4.79	5.14	6.88	6.35	4.85	4.78
OM, %	81.99	82.87	83.26	79.37	79.88	82.50	82.85
NDF, %	8.12	17.15	16.43	16.57	15.94	16.55	16.74
ADF, %	2.97	9.45	8.14	8.78	9.12	9.34	9.18
ADL, %	0.71	2.92	1.94	1.86	2.34	3.46	1.88
Cellulose[3], %	2.26	6.53	6.20	6.92	6.77	5.88	7.30
Hemicelluloses[4], %	5.16	7.70	8.29	7.79	6.82	7.22	7.56
Na, %	0.16	0.22	0.27	0.90	0.23	0.23	0.23
P, %	0.51	0.50	0.52	0.49	0.50	0.53	0.52
Ca, %	0.88	0.75	0.73	0.83	1.33	0.63	0.61

[1]All the pretreated DDGS was obtained from the same batch of DDGS as the untreated DDGS.

Table 7.2. (Cont.)

[2]Provided the following quantities of vitamins and micro minerals per kilogram of complete diet: vitamin A as retinyl acetate, 11,128 IU; vitamin D_3 as cholecalciferol, 2,204 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.58 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin as nicotinamide and nicotinic acid, 44 mg; folic acid, 1.58 mg; biotin, 0.44 mg; Cu, 10 mg as copper sulfate; Fe, 125 mg as iron sulfate; I, 1.26 mg as potassium iodate; Mn, 60 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; and Zn, 100 mg as zinc oxide.

[3]Cellulose was calculated as the difference between ADF and ADL.

[4]Hemicelluloses were calculated as the difference between NDF and ADF.

Table 7.3. Apparent total tract digestibility (ATTD) of GE, OM, NDF, ADF, cellulose and hemicelluloses in corn, untreated distillers dried grains with solubles (DDGS), and treated DDGS, as-fed basis[1]

			Pretreated DDGS						
Item, %	Corn	DDGS-CV	DDGS-EX	DDGS-Na	DDGS-Ca	DDGS-cellulase	DDGS-hemicellulase	SEM	*P*-value
Diets									
ATTD									
GE	86.6^{a}	78.9^{cd}	79.2^{bcd}	79.5^{bc}	77.9^{d}	80.4^{b}	79.7^{bc}	0.49	< 0.01
OM	89.7^{a}	80.9^{bcd}	80.7^{cd}	81.2^{bc}	80.0^{d}	81.9^{b}	81.3^{bc}	0.42	< 0.01
NDF	56.8^{ab}	53.6^{bc}	51.4^{c}	59.2^{a}	51.3^{c}	54.1^{bc}	55.3^{b}	1.23	< 0.01
ADF	57.6^{c}	71.5^{a}	66.6^{b}	72.4^{a}	71.7^{a}	71.6^{a}	71.6^{a}	1.43	< 0.01
Cellulose[2]	59.0^{c}	70.6^{a}	64.1^{bc}	74.5^{a}	69.0^{ab}	70.6^{a}	74.5^{a}	2.48	< 0.01
Hemicelluloses[3]	56.9^{a}	31.6^{d}	36.7^{c}	44.2^{b}	26.2^{e}	32.2^{cd}	37.3^{c}	2.04	< 0.01
Ingredients									

Table 7.3. (Cont.)

ATTD									
GE	86.6[a]	71.7[cd]	72.8[bcd]	73.3[bc]	70.4[d]	75.0[b]	73.9[bc]	0.86	< 0.01
OM	89.7[a]	71.1[cd]	71.4[bcd]	72.2[bc]	69.5[d]	73.7[b]	72.7[bc]	0.87	< 0.01
NDF	56.8[ab]	52.5[cde]	49.5[de]	59.9[a]	49.4[e]	53.1[bcd]	55.7[bc]	1.48	< 0.01
ADF	57.6[c]	74.3[a]	68.7[b]	75.5[a]	74.6[a]	74.4[a]	73.6[a]	1.55	< 0.01
Cellulose[2]	59.0[c]	73.0[a]	65.3[bc]	77.4[a]	71.0[ab]	73.3[a]	77.3[a]	2.83	< 0.01
Hemicelluloses[3]	56.9[a]	17.7[d]	28.7[c]	38.0[b]	9.6[e]	17.6[d]	25.3[c]	2.69	< 0.01

[a-e]Means within a row lacking a common superscript letter differ ($P < 0.05$).

[1]Data are means of 9 observations per treatment.

[2]Cellulose was calculated as the difference between ADF and ADL.

[3]Hemicelluloses were calculated as the difference between NDF and ADF.

Table 7.4. Concentration of digestible and metabolizable energy in corn, untreated distillers dried grains with solubles (DDGS), and treated DDGS, as-fed basis[1]

Item	Corn	DDGS-CV	Pretreated DDGS					SEM	*P*-value
			DDGS-EX	DDGS-Na	DDGS-Ca	DDGS-cellulase	DDGS-hemicellulase		
Diets									
GE intake, kcal	8,661^{c}	9,005^{bc}	9,576^{a}	9,268^{ab}	9,188^{ab}	9,506^{a}	9,411^{a}	150	< 0.01
GE in feces, kcal	1,161^{c}	1,896^{ab}	1,950^{ab}	1,904^{ab}	2,027^{a}	1,824^{b}	1,910^{ab}	55	< 0.01
GE in urine, kcal	206.0^{c}	356.2^{ab}	424.1^{a}	330.7^{b}	341.0^{b}	370.0^{ab}	410.0^{ab}	31	< 0.01
DE, kcal/kg	3,193^{c}	3,218^{bc}	3262^{ab}	3133^{d}	3099^{d}	3295^{a}	3267^{ab}	19	< 0.01
ME, kcal/kg	3,105^{a}	3,057^{b}	3,074^{ab}	2,993^{c}	2,951^{c}	3,132^{a}	3,089^{ab}	21	< 0.01
Ingredients									
DE, kcal/kg	3,292^{b}	3,279^{c}	3,367^{abc}	3,109^{d}	3,041^{d}	3,432^{a}	3,378^{ab}	34	< 0.01
DE, kcal/kg DM	3,844^{b}	3,709^{c}	3,830^{b}	3,688^{c}	3,561^{d}	3,977^{a}	3,852^{b}	39	< 0.01

Table 7.4. (Cont.)

ME, kcal/kg	3,201[a]	3,043[b]	3,078[b]	2,916[c]	2,833[d]	3,194[a]	3,108[ab]	38	< 0.01
ME, kcal/kg DM	3,738[a]	3,442[b]	3,501[b]	3,458[b]	3,318[c]	3,701[a]	3,545[b]	44	< 0.01

[a-d]Means within a row lacking a common superscript letter differ ($P < 0.05$).

[1]Data are means of 9 observations per treatment.

GENERAL CONCLUSIONS

Feed processing technologies other than grinding are not normally used in diets based on corn and soybean meal, which mainly are fed to pigs in the U.S. swine production system. However, if alternative feed ingredients that contain high concentrations of fiber are included in swine diets, energy and nutrient digestibilities are negatively affected, which is detrimental to pigs growth performance. Therefore, use of different feed processing technologies such as grinding, extrusion, pelleting, chemical treatments, and enzyme treatments may modify the physical and chemical composition of ingredients and thus, increase nutrient absorption by the pig.

Corn is one of the most important ingredients used in diets fed to pigs. Results of the present research demonstrate that the apparent ileal digestibility (AID) of starch and GE and the concentration of DE and ME linearly increased when corn particle size was reduced from 869 to 339 μm. In contrast, the standardized total tract digestibility (STTD) of P and the standardized ileal digestibility (SID) of CP and indispensable AA, with the exception of Trp, were not influenced by reducing the particle size. However, the increased DE and ME in finely ground corn compared with more coarsely ground corn can be taken advantage in diet formulations by reducing the inclusion of added fat without reducing he energy concentration in the diets. This concept was demonstrated in an experiment with growing-finishing pigs in which growth performance was not influenced by the reduction of fat inclusion in diets containing finely ground corn. This indicates that pigs can utilize the extra ME in the finely ground corn compared with coarser corn. It was also demonstrated that pigs fed diets containing the finely ground corn had lower concentrations of volatile fatty acids in the hindgut and greater pH

compared with pigs fed diets containing more coarsely ground corn. This is likely the result of less starch being fermented in the hindgut of pigs fed diets containing finely ground corn because of the increased small intestinal digestibility of starch in finely ground corn compared with coarsely ground corn. Dressing percentage was also improved when diets containing corn ground to a lower particle size were used, which may increase the amount of saleable meat from the pigs. However, pigs fed diets containing finely ground corn may develop gastric parakeratosis, but no pigs in this research developed gastric ulcers.

By feeding diets containing corn ground to different particle sizes to weanling pigs, it was demonstrated that the caloric utilization of corn also is increased by weanling pigs if the particle size of corn is reduced. As was the case for growing-finishing pigs, the inclusion of lipids in diets for weanling pigs may be reduced if corn is ground to a finer particle size, without impacting pig growth performance.

The negative effects on energy and nutrient digestibility when high fiber ingredients are included in swine diets may be ameliorated if diets are extruded or processed using a combination of extrusion and pelleting. It was demonstrated that pelleting or extrusion may increase the ME of diets by 0.6 to 2.9%, but if diets were both extruded and pelleted, ME increased by up to 3.7%. It was also observed that the response to extrusion and pelleting was greater in diets with greater concentrations of fiber compared with diets containing less fiber.

Distillers dried grains with soubles (DDGS) has greater concentration of GE than corn, but the DE in DDGS is similar to corn because of a reduced energy digestibility. However, extrusion of DDGS prior to diet mixing, addition of hemicellulase, or treatment

with calcium oxide or sodium hydroxide did not improve energy utilization of DDGS by pigs. In contrast, treatment with cellulase was effective in improving the ME of DDGS, which increases the nutritional value of DDGS when fed to pigs.

In conclusion, results from these experiments indicate that feed technology may be used to improve energy and nutrient digestibility and enhance absorption of nutrients. This may fully or partly ameliorate the negative effects of fiber on energy and nutrient utilization in diets fed to pigs and it is possible that effects of feed technology are greater in diets containing high fiber ingredients than in diets with lower levels of fiber. Thus, results of the present research indicate that processing of diets or ingredients can positively impact profits of pig production.