USE OF FEED TECHNOLOGY TO IMPROVE NUTRITIONAL VALUE OF FEED INGREDIENTS FED TO PIGS

BY

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THESIS

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ABSTRACT

Four studies were conducted to determine nutrient digestibility of feed ingredients and the effect of feed technology on the nutritional value of feed ingredients or diets fed to pigs. In study 1, two experiments were conducted to determine the digestibility of AA and concentrations of DE and ME in 2 sources of distillers dried grains with solubles (DDGS) that have different oil contents. Dakota Gold DDGS that was low in fat and a conventional DDGS were evaluated as feed ingredients for growing pigs. Results of this study indicated that Dakota Gold DDGS had greater ($P < 0.05$) standardized ileal digestibility (SID) of CP and Lys compared with conventional DDGS. The SID of most other AA was also greater ($P < 0.05$) or tended to be greater ($P < 0.10$) in Dakota Gold than in conventional DDGS with the exception of Trp, Cys, Pro, and Ser. The ATTD of NDF, ADF, and AEE was greater ($P < 0.01$) in conventional DDGS than in Dakota Gold DDGS, but there was no difference in the ATTD of GE between the 2 sources of DDGS. Study 2, was conducted to determine the effects of including Dakota Gold or conventional DDGS in diets that were fed in meal form or in a pelleted form to pigs from weaning to market on growth performance and carcass characteristics. Diets were formulated based on digestibly values for AA and energy obtained from the previous study. Results for this study indicated that for the overall nursery phase, feeding meal diets instead of pelleted diets increased ($P < 0.001$) ADFI and decreased ($P < 0.05$) G:F. However, no difference between the 2 sources of DDGS were observed on average daily gain of weanling pigs. For the entire growing-finishing period, the source of DDGS did not affect average daily gain of pigs, but pigs fed meal diets had reduced ($P < 0.001$) G:F compared with pigs fed the pelleted diets. There were no differences in carcass characteristics between pigs fed diets containing Dakota Gold DDGS or conventional DDGS. However, 10^{th} rib back fat was greater ($P = 0.018$) for pigs fed pelleted diets than for pigs fed meal diets. There were also tendencies for lower HCW (*P* = 0.091) and greater fat-free lean percentage (*P* = 0.064) for pigs fed meal diets compared with pigs fed pelleted diets. In study 3, two experiments were conducted to determine effects of extrusion on energy and nutrient digestibility in yellow dent corn, wheat, and sorghum fed to growing pigs. Results for this study indicated that extruded grains had greater ($P < 0.001$) apparent ileal digestibility (AID) of starch than non-extruded grains. Extrusion also increased SID of CP and all AA except Pro in corn, but the SID of CP and AA in wheat and sorghum was not affected by extrusion (interaction, $P < 0.05$). The ATTD of GE was increased by extrusion of corn or sorghum, but that was not the case for wheat (interaction, $P < 0.001$). The ATTD of NDF in wheat was reduced by extrusion, but that was not the case for corn and sorghum (interaction, $P < 0.001$), but extrusion reduced ($P < 0.05$) the ATTD of ADF in all grains. Extrusion increased DE and ME in corn and sorghum compared with non-extruded grains, but there was no increase in DE and ME when wheat was extruded (interaction, $P < 0.001$). In study 4, two experiments were conducted to determine effects of extrusion on energy and AA digestibility in soybean hulls fed to growing pigs. Results for this study indicated that extrusion of soybean hulls did not change AID or SID of CP and most AA with the exception that the AID for Leu, Phe, Asp, Ser, and Tyr in the non-extruded soybean hulls was less than in extruded soybean hulls. The ATTD of GE and values for DE and ME in soybean hulls were not improved by extrusion. Likewise, extrusion did not change the concentration of total dietary fiber in soybean hulls. In conclusion, use of pelleting or extrusion in feed ingredients or diets may be used to improve nutrient and energy digestibility by pigs, but effects are not consistent across all feed ingredients.

Key words: pigs, feed technology, extrusion, pelleting

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“Familia, este logro es para ustedes, LOS AMO PROFUNDAMENTE!”

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CHAPTER 1: INTRODUCTION

Feed technology is commonly to enhance nutrient digestibility and improve handling properties of feed ingredients. Technologies such as pelleting or extrusion of feed ingredients or diets may be used, and the aim of these practices are to change the primarily structure of the ingredient with the purpose of increasing nutrient availability and handling properties (Hancock and Behnke, 2001; Rojas and Stein, 2016). Corn distiller dried grains with solubles (DDGS) is a co-product that is obtained from ethanol production and it is commonly included in swine diets (Robinson et al., 2008; Stein et al., 2009; Stein and Shurson, 2009; Gutierrez et al., 2014). However, depending on the technique used for oil extraction, nutrient composition of DDGS may change among sources, and DDGS is often classified according to oil concentration (Sauvant et al., 2004; NRC, 2012). There is, however, limited information about comparing the effects of inclusion of DDGS in diets that were fed in a meal form or a pelleted form on nutrient digestibility, growth performance, and carcass characteristic in pigs from weaning to finishing.

Cereal grains are usually the main source of energy and fiber is frequently formulated in diets fed to pigs. Nutrient composition varies among cereal grains and effects of extrusion on nutrient digestibility also varies among different cereal grains (Barneveld et al., 2005; Rodrigues et al., 2016). There is, therefore, a need for research to establish the effects of extrusion on each individual cereal grain.

Therefore, the overall objectives of this work was to determine effects of pelleting diets that contain DDGS on energy and nutrient digestibility, growth performance, and carcass characteristics of pigs, and to determine the effects of extrusion of feed ingredients on energy and nutrient digestibility by growing pigs.

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CHAPTER 2: EFFECTS OF EXTRUSION AND PELLETING ON NUTRIENT DIGESTIBILITY IN DIETS AND GROWTH PERFORMANCE BY PIGS

INTRODUCTION

Feed cost-effectiveness is a significant consideration in the swine industry and many studies have been conducted with the aim of improving feed efficiency and economic benefits. Feed efficiency is calculated as the weight gained by pigs divided by the amount of feed the animal consume. Different feed technologies may be used to improve feed efficiency. New feed technologies and alternative feed ingredients have been used to formulate diets. The use of feed technology is increasing in the global feed industry with the purpose of improvement of nutrient utilization and achieve growth performance parameters with high cost-efficiency. Most of the ingredients or diets that are used in the livestock industry are processed before being fed to the animals. The main feed processing technique used in the feed industry is grinding to reduce the particle size of ingredients. The aim of this process is to maximize nutritional values in feed ingredients because an increase in the surface area of a particle allows for better access of digestive enzymes, which results in increased digestibility of nutrients (Wondra et al., 1995b; Rojas and Stein, 2015). The feed industry has developed other technologies that have been implemented to increase nutritional values of feed ingredients. Pelleting and extrusion are two technologies that are commonly used for ingredients or complete diets. In the U.S., more than 80% of the diets fed to monogastric animals are pelleted (Department of Grain Science and Industry, Kansas State University). It has been demonstrated that the improvements in growth performance attributed to the pelleting process are due to a decrease in feed wastage, decreased ingredient segregation, which additionally reduce selective feeding, increase in bulk density, and increased handling properties (Hancock and Behnke, 2001). One of the steps that happens during extrusion or pelleting of feed ingredients is that heat is applied. Applying heat to feedstuffs, destroys pathogenic organisms, and results in modifications in the natural structure of nutrients, which can affect nutrient digestibility (Wondra et al., 1995a; Hancock and Behnke, 2001; Sun et al., 2006; Stein and Bohlke, 2007). Extrusion is a technology that is extensively used in the pet food and aqua feed industry, and more than 95% of the pet food is extruded (Behnke, 1996). In the swine industry, extrusion of feed ingredients or diets is not used extensively, due to the high cost of extrusion, but positive effects of extrusion on nutrient digestibility of cereal grains have been reported (Barneveld et al., 2005; Liu et al., 2016; Rodrigues et al., 2016). It is therefore, of interest to further investigate if pelleting or extrusion can be used to increase the nutritional value of feed ingredients or diets used for pigs.

PELLETING

Effects on Handling Properties

The main purpose of pelleting is to compact ground feed ingredients. By the use of steam, heat, pressure, moisturize, and compacting forces, pellets are formed, which improve handling properties (Behnke, 1996; Muramatsu et al., 2015). Beneficial handling properties of pelleted diets include increased bulk density, improved dust control, reduced ingredient segregation, and reduced feed wastage, when diets are fed to pigs. (Thomas and van der Poel, 1996; Muramatsu et al., 2015). By using a reduced particle size during conditioning, particles will have an increased surface area, and the time of exposure to moisture and heat may be reduced (Muramatsu et al., 2015). The length of time and the steaming used during conditioning of feed ingredients determine the quality of the pellet. The longer time a feed ingredient is exposed to steam, the more starch is gelatinized and the more protein is denatured (Hancock and Behnke, 2001). Wondra et al. (1995a) reported that by reducing the particle size from 1,000 to 400μm in a corn-soybean meal diet, pellet durability increased by 8%. Measuring the quality of a pellet is a good indicator of controlling the process and achieving the improvements that are intended by pelleting. Pellet durability index (PDI), which indicate the percentage of pellets that remain intact after being exposed to external forces such as transportation and storage, is the parameter most often used to determine pellet quality (Muramatsu et al., 2015).

Diet formulation plays an important role in pellet quality. Thomas and van der Poel (1996) reported that addition of fiber and protein into the diet may increase pellet quality, because high fiber ingredients may facilitate the compaction process during the pellet formation (Traylor et al., 1999). However, high inclusion of fat in diets may result in less durability, because fat affects the contact of the meal with the die-hole walls, which increase the passage of the meal through the die and thus reducing feed compaction (Briggs et al., 1999).

Effects on Nutrient Digestibility

The main affect that pelleting has on protein is that the thermal process during pelleting may denature the structure of proteins, causing a reduction in digestibility (Svihus and Zimonja, 2011). However during the process of pelleting, the temperature used is generally low, and denaturation of protein starts around 60 to 70ºC (Ludikhuyze et al., 2003). Rojas et al. (2016) reported an increase of apparent ileal digestibility (**AID**) of AA when diets with different levels of fiber were pelleted at temperature of 85ºC, which indicates that the thermal process during formation of the pellet was not high enough to denaturalize the structure of the protein.

Effects on Growth Performance

The pellet size that optimizes production may depend on the physiological stage of the pigs. Hancock and Behnke (2001) reported that pigs are able to utilize different pellet diameters without affecting growth performance. However nursery pigs have the greatest growth performance if the diameter of the pellet is around 3 to 4 mm in diameter, and during the grower-finisher phase of pigs and in diets for sows, the best results are obtained if the pellets are 4 to 5 mm in diameter (Richert and DeRouchey, 2010). Pelleting of diets fed during the nursery phase may increase G:F by up to 12% (Stark, 1994). Pelleting of corn-soybean meal diets fed to finishing pigs increased ADG and G:F ratio by 5 and 7% respectively, and the reason for this effect most likely is an increase in bulk density, and a reduction of dust which make the diet more palatable (Wondra et al., 1995a). Including distillers dried grains with solubles (**DDGS**) in corn-soybean meal diets to reduce cost of diet formulation is commonly used by feed mills. By pelleting corn-soybean meal diets containing 30% DDGS increased ADG and G:F of growing to finishing pigs by 5 to 8% (Overholt et al., 2016). However, there is lack of information about the effect on growth performance of inclusion of DDGS in pelleted diets fed to wean to finish pigs.

EXTRUSION

Effects on Handling Properties

Extrusion is a technology that may be applied to cereal grains with the purpose of increasing absorption of nutrients by the animals. The process uses moisture, pressure, friction, and heat, which results in an expansion of the raw materials (Rojas and Stein, 2016). Conditioning of feed prior to extrusion consist of adding moisture and heat to the feed before it is exposed to pressure. Particle size and composition of particles are changed during conditioning. Reduced particle size of feed ingredients may be facilitated by addition of steam during conditioning, which results in increased surface area of the particle (Ruiz et al., 2018). Extrusion, therefore, results in a change in the physicochemical characteristic of the feed ingredient. Increase in starch gelatinization, increase in denaturation of proteins, reduced concentration of microorganisms, and dehydration of feed ingredients are usually observed as a result of extrusion (Hancock and Behnke, 2001; Barneveld et al., 2005). Gelatinization of starch in wheat increased when the extrusion temperature increased from 65 to 110ºC (Chiang and Johnson, 1977). Similar observations were made when corn and waxy corn were extruded at temperatures between 120 and 164ºC, but the responses in waxy corn were greater than in normal corn due to the higher amylopectin concentration in the starch granule in waxy corn (Bhattacharya and Hanna, 1987). Extrusion also reduces bulk density of ingredients, which may be a negative characteristic of the process, due to a reduction on feed storage efficiency (Rojas and Stein, 2016).

Effects on Nutrient Digestibility

The main objective of extrusion is to increase energy and nutrient digestibility. The increased energy utilization is primarily due to increased starch gelatinization in cereal grains (Rojas and Stein, 2017). Starch is a polysaccharide and the major energy reserve in plants and grains. It is composed of polymers of D-glucose units bound together to form amylose or amylopectin (Ai, 2013). During extrusion, starch granules lose their structure, and consequently become easier to hydrolyze by amylolytic enzymes in the digestive tract, which results in increased absorption of glucose (Ai, 2013). Increased digestibility of starch in field peas and in corn-soybean meal diets have been reported (Stein and Bohlke, 2007; Rojas et al., 2016). Veum et al. (2017) also reported that concentration of gelatinized starch in corn increased by more than 3 fold after extrusion, but the total starch concentration does not change. Digestibility of starch was also increased when barley, peas, and potato starch were extruded (Sun et al., 2006).

The effect of extrusion on digestibility of CP and AA is not always consistent, and may be influenced by nutrient composition of the ingredients. Chae et al. (1997) reported that ileal digestibility of CP and AA increased in corn and soybean meal after extrusion, and the ileal digestibility of AA increased after extrusion of field peas (Stein and Bohlke, 2007) and complete diets (Rojas et al., 2016). However, thermal processing of feed ingredients may result in heat damage of protein, especially Lys (Fontaine et al., 2007; Stein et al., 2009; González-Vega et al., 2011). Maillard reaction may occur during thermal processing because of condensation of the NH_2 group of an AA with a reducing sugar, which makes the AA unavailable for protein synthesis. Lysine is the AA that is most susceptible to this reaction because of the epsilon amino group in the side chain, which allows it to react with the carbonyl group of the reducing sugar (Pahm et al., 2008). After extrusion of a flaxseed-field pea diet, the total tract digestibility of CP did not change (Htoo et al., 2008).

Non-digestible carbohydrates are known as the carbohydrates that are not digested by endogenous enzymes in the small intestine, but they maybe fermented by microorganism in the hindgut to produce energy by synthesis of short chain fatty acids (Abelilla, 2018). The carbohydrate composition of cereal grains varies and that may affect the response of feed technology on nutrient digestibility depending on the concentration of starch and Non-digestible carbohydrates in the ingredients (Jaworski et al., 2015). The effect of extrusion on fiber digestibility it is not clear, but may be affected by the nutrient composition of each ingredient. Rojas et al. (2016) reported no effects of extrusion on the apparent total tract digestibility of fiber in diets containing different levels of fiber, but a decrease in energy digestibility when the concentration of fiber increased in diets fed to pigs was observed. Similar results were reported for apparent total tract digestibility of fiber when different cereal grains were extruded and fed to weanling pigs (Rodrigues et al., 2016).

Effects on Growth Performance

Adequate use of conditioning, pressure, and heat during extrusion may increase utilization and access to nutrient by digestive enzymes because of change in the structure of the grain particle (NRC, 2012). Therefore, the increase in nutrient availability may influence growth performance. Rodrigues et al. (2016) reported an increased in digestibility of GE in different cereal grains after extrusion, however this improvement was not reflected in improved growth performance parameters such as ADG, feed intake, and G:F in weanling pigs. Amornthewaphat and Attamangkune (2008) also observed no increase in growth performance of weanling pigs fed extruded corn, but linear reduction in feed intake and ADG of pigs was observed if the bulk density of extruded material was reduced. Thus, extrusion of ingredients on diets fed to pigs has resulted in contradictory effects on growth performance and further research is needed to determine the impact of extrusion of diets.

CONCLUSIONS

The use of feed technology to increase the nutritional value of diets fed to pigs is a common practice. Increased feed efficiency is usually observed if diets area pelleted and this may be a result of a combination of reduced feed wastage, increased nutrient digestibility, and other factors. There is, however, a lack of information about the effects of pelleting diets for wean to finish pigs containing DDGS. Likewise, the effect of extruding cereal grains or other ingredients on nutrient digestibility is not always predictable, which may be a result of variations in nutrient composition of feed ingredients. There is, however, a need for further research on the effects of extrusion on the nutritional value of diets fed to pigs.

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CHAPTER 3: DIGESTIBILITY OF AMINO ACIDS, FIBER, AND FAT AND CONCENTRATIONS OF DIGESTIBLE AND METABOLIZABLE ENERGY IN TWO SOURCES OF DISTILLERS DRIED GRAINS WITH SOLUBLES FED TO GROWING PIGS

ABSTRACT

Two experiments were conducted to test the hypothesis that the digestibility of AA, GE, NDF, ADF, acid hydrolyzed ether extract (AEE), and the DE and ME in 2 sources of distillers dried grains and solubles (DDGS) are not different each other despite of different oil contents. Dakota Gold DDGS that is low in fat and a conventional DDGS were evaluated as a feed ingredient for growing pigs. In Exp. 1, twelve growing barrows (initial BW = 55.2 ± 3.6 kg) that had a T-cannula installed in the distal ileum were used. Pigs were allotted to a 2-period cross-over design with 3 diets and 4 replicate pigs in each period. Two diets contained either Dakota Gold or conventional DDGS as the sole source of CP and AA. The third diet was an N-free diet that was used to determine the basal endogenous losses of AA from the pigs. Each experimental period lasted 7 d with the initial 5 d being the adaptation period and ileal digesta were collected on d 6 and 7 for 8 h. Greater ($P < 0.05$) standardized ileal digestibility (SID) of CP and Lys were observed in pigs fed Dakota Gold DDGS compared with pigs fed conventional DDGS. The SID of most other AA were also greater ($P < 0.05$) or tended to be greater ($P < 0.10$) in Dakota Gold than in conventional DDGS with the exception of Trp, Cys, Pro, and Ser. In Exp. 2, twenty-four barrows (initial BW = 17.3 ± 1.3 kg) were randomly allotted to the three diets with 8 replicate pigs per diet. A corn-based basal diet and 2 diets containing either Dakota Gold DDGS or conventional DDGS were formulated. Pigs were housed individually in metabolism crates and the feces and urine samples were collected separately for 5 d followed by the 7 d adaptation period. The ATTD of NDF, ADF, and AEE was greater ($P < 0.01$) in conventional DDGS than in Dakota Gold DDGS, but there was no difference in the ATTD of GE between the 2 sources of DDGS. The conventional DDGS contained more ($P < 0.001$) DE and ME than the Dakota Gold DDGS. In conclusion, the digestibility of AA, GE, NDF, ADF, and AEE and energy concentrations of DE and ME were different between 2 sources of DDGS fed to growing pigs.

Key words: amino acids, energy, digestibility, distillers dried grains with solubles, fat, fiber

INTRODUCTION

Corn distillers dried grains with solubles (**DDGS**), a co-product of ethanol production, is often included in diets for pigs (Stein and Shurson, 2009). As more corn oil has been extracted from the solubles at the ethanol plants, the oil content in DDGS is reduced. Conventional DDGS usually contains at least 10% crude fat whereas low-oil DDGS contain, 6 to 9% crude fat (NRC, 2012) resulting in other nutrients being more concentrated. Addition of fat to diets fed to pigs increases the digestibility of AA (Cervantes-Pahm and Stein, 2008; Kil and Stein, 2011) and it is, therefore, possible that AA digestibility is affected by the reduced oil concentration in DDGS. It has been demonstrated that DE and ME in the low-oil DDGS are reduced compared with conventional DDGS (NRC, 2012; Kerr et al., 2013; Curry et al., 2016), but there is limited information about how oil concentration in DDGS influences the apparent total tract digestibility (**ATTD**) of NDF, ADF, and acid hydrolyzed ether extract (**AEE**). Dakota Gold is a low-oil DDGS that is produced by Poet (Sioux Falls, SD). The process that is used to obtain Dakota Gold DDGS is a heat-free process using a cold fermentation technic and it is possible that this technique will positively influence nutrient digestibility. This technique, which is called the BPX technology, usually results in a final product that contains less AEE than conventional DDGS. However, there is limited information about how this process affects the digestibility of energy and nutrients in growing pigs. Therefore, the objective of this experiments was to test the hypothesis that the digestibility of AA, GE, NDF, ADF, acid hydrolyzed ether extract (AEE), and the DE and ME in 2 sources of distillers dried grains and solubles (DDGS) are not different each other despite of different oil contents.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocol for 2 experiments. Pigs were the offspring of Line 359 boars and Camborough females (Pig Improvement Company, Hendersonville, TN). The same batches of conventional DDGS and Dakota Gold DDGS were used in the two experiments (Tables 3.1 and 3.2).

Exp. 1. Digestibility of CP and AA

Diets, Animals, and Housing. Three diets were formulated (Table 3.2). Two diets contained either Dakota Gold or conventional DDGS as the sole source of CP and AA. The third diet was the N-free diet that was used to determine the basal endogenous losses of AA from the pigs. Vitamins and minerals were included in all diets to meet or exceed current requirement estimates (NRC, 2012). All diets also contained 0.40% chromic oxide as an indigestible marker.

Twelve growing barrows that had a T-cannula installed in the distal ileum were used (initial BW = 55.2 ± 3.6 kg). Pigs were housed in individual pens (1.2 × 1.5 m) in an environmentally controlled room. Pens had smooth sides and fully slatted T-bar floors. A feeder and a nipple drinker were installed in each pen. Pigs were allotted to a 2-period cross-over design with 3 diets and 4 replicate pigs in each period. Therefore, there were 8 replicate pigs per treatment.

Feeding and sample collection. Pigs were fed at a level of 3 times the maintenance energy requirement (i.e., 197 kcal ME per kg $^{0.60}$; NRC, 2012). Water was available at all times. Each experimental period lasted 7 d with the initial 5 d being the adaptation period and ileal digesta were collected on d 6 and 7 for 8 h using standard procedures (Stein et al., 1998).

Chemical Analyses, Calculations, and Statistical Analyses. At the conclusion of the experiment, ileal digesta samples were thawed, pooled within animal and diet, and sub-samples were collected for chemical analysis. Digesta samples were lyophilized and finely ground through a 1-mm screen in a Wiley mill (Model 4; Thomas Scientific, Swedesboro, NJ). Samples of diets, each source of DDGS, and ileal digesta were analyzed for DM (method 930.15; AOAC Int., 2007), CP (method 990.03; AOAC Int., 2007), and AA by a Hitachi Amino Acid Analyzer, Model No. L8800 (Hitachi High Technologies America, Inc; Pleasanton, CA) using ninhydrin for postcolum derivatization and norleucine as the internal standard. Prior to analysis, samples were hydrolyzed with 6*N* HCl for 24 h at 110°C (method 982.30 E(a); AOAC Int., 2007). Methionine and Cys were determined as Met sulfone and cysteic acid after cold performic acid oxidation overnight before hydrolysis (method 982.30 E(b); AOAC Int., 2007). Tryptophan was determined after NaOH hydrolysis for 22 h at 110°C (method 982.30 E(c); AOAC Int., 2007). Diets and ileal digesta samples were also analyzed for chromium using Inductive Coupled Plasma Atomic Emission Spectrometric method (method 990.08; AOAC Int., 2007) after digestion using nitric acid-perchloric acid (method 968.08D(b); AOAC Int., 2007).

The apparent ileal digestibility (**AID**) of CP and AA was calculated in the 2 diets containing Dakota Gold or conventional DDGS (Stein et al., 2007). The basal endogenous losses of CP and AA were calculated from pigs fed the N-free diet as previously described (Stein et al., 2007) and these values were used to correct AID values for basal endogenous losses to calculate SID of CP and AA (Stein et al., 2007). Data were analyzed using the PROC MIXED procedure (SAS Inst. Inc., Cary, NC). An ANOVA was conducted, and the model included diet as fixed effect and pig and period as random effects. Mean values were calculated using the LSMeans statement, and pig was the experimental unit. Results were considered significant at $P < 0.05$ and considered a trend at $P < 0.10$.

Exp. 2. Digestibility of NDF, ADF, AEE, and Energy

Diets, Animals, and Housing. A corn-based basal diet and 2 diets containing either Dakota Gold DDGS or conventional DDGS were formulated (Table 3.3). Vitamins and minerals were included in all diets to meet or exceed current requirement estimates (NRC, 2012).

Twenty four barrows (initial BW = 17.3 ± 1.3 kg) were randomly allotted to the 3 diets with 8 replicate pigs per diet. Pigs were housed individually in metabolism crates that were equipped with a feeder, a nipple waterer, and a slatted floor. A screen and a urine pan were placed under the slatted floor to allow for the total, but separate, collection of urine and fecal materials.

Feeding and Sample Collection. Pigs were fed at 3 times the energy requirement for maintenance, and diets were provided each day at 0800 and 1600 h in 2 equal meals. Pigs had ad libitum access to water throughout the 14-d experiment. The initial 7 d were considered the adaptation period to the diet, whereas urine and fecal materials were collected from the feed provided during the following 5 d according to standard procedures for the marker to marker approach (Adeola, 2001). Urine was collected in urine buckets over a preservative of 50 mL of 6*N* HCl. Fecal samples and 20% of the collected urine were stored at −20°C immediately after collection.

Chemical Analyses, Calculations, and Statistical Analyses. At the conclusion of the experiment, fecal samples were thawed and pooled for each pig and then dried in a 50°C forced air drying oven and ground through a 1-mm screen using a Wiley mill (Model 4; Thomas Scientific, Swedesboro, NJ). Urine samples were also mixed for each pig and a subsample was dripped onto cotton balls that were placed in a plastic bag and lyophilized (Kim et al., 2009). Ingredients (corn and the 2 sources of DDGS), diets, ground fecal samples, and lyophilized urine samples were analyzed for GE using bomb calorimetry (Model 6300; Parr Instruments, Moline, IL). Ingredients, diets, and fecal samples were also analyzed for DM (Method 930.15; AOAC Int., 2007), CP (method 990.03; AOAC Int., 2007), ADF and NDF (Ankom 2000 Fiber Analyzer, Ankom Technology, Macedon, NY). Acid hydrolyzed ether extract was also analyzed in these samples using the acid hydrolysis filter bag technique (Ankom HCl Hydrolysis System, Ankom Technology, Macedon, NY) followed by fat extraction (Ankom XT-15 Extractor, Ankom Technology, Macedon, NY). Bulk density were analyzed for the 2 sources of DDGS (Cromwell et al., 2000). Color of the 2 sources of DDGS were measured using a Minolta CR-400 apparatus (Minolta, Camera Company Osaka, Japan) and particle sizes of the DDGS sources were also measured (ASABE, 2008)

Following chemical analysis, the ATTD of GE, DM, ADF, NDF, and AEE were calculated for each diet and the DE and ME in each diet were calculated as well. The DE and ME of corn was then calculated by dividing the DE and ME of the corn diet by the inclusion rate of corn in that diet (i.e., 97.0%). The contribution of DE and ME from corn to the DE and ME in the diets containing each source of DDGS were then subtracted from the DE and ME of these diets and the DE and ME of Dakota Gold and conventional DDGS were calculated by difference (Adeola, 2001). The ATTD of ADF, NDF, and AEE in the 2 sources of DDGS were also calculated by proportional contribution from each source to the diets.

Homogeneity of the variances was confirmed using the UNIVARIATE procedure in SAS (SAS Institute Inc., Cary, NC) and data were analyzed by ANOVA using the PROC MIXED in SAS. Diet or ingredient was the fixed effect and replicate was the random effect. Mean values were calculated using the LSMeans statement and pig was the experimental unit. A contrast statement was also used to compare the diets (i.e., basal vs. DDGS diets; Dakota Gold vs. conventional DDGS diets) and ingredients (i.e., corn vs. the 2 DDGS sources; Dakota Gold vs. conventional DDGS). Results were considered significant at $P < 0.05$ and considered a trend at $P < 0.10$.

RESULTS AND DISCUSSION

The CP in Dakota Gold and conventional DDGS were 27.99 and 26.23%, respectively, and Lys concentrations were 0.96 and 0.84% in the 2 sources of DDGS (Table 3.1). As a consequence, the Lys:CP ratio was 3.43 in Dakota Gold DDGS and 3.20 in conventional DDGS. The Lys:CP ratios obtained in this experiment are greater than observed in previous experiments (Stein and Shurson, 2009; Kim et al., 2012), which indicates that samples used in this experiment were less heat damaged compared with DDGS used previously. It was expected that the Dakota Gold DDGS would have less heat damage because of the cold-processing technique, but the high Lys:CP ratio in the conventional DDGS, although less than Dakota Gold DDGS, indicates that this source of DDGS was also of high quality. The conventional DDGS had a lighter (greater L*) and more yellow (greater b*), but less redder (less a*) color than the Dakota Gold DDGS, but color measurements also indicate that samples were not heat damaged compared to previously reported data (Almeida et al., 2013). The GE in the Dakota Gold DDGS was 4,442 kcal/kg, and in the conventional DDGS, GE was 4,831 kcal/kg. The reason for the increased GE in the conventional DDGS compared with the Dakota Gold DDGS is most likely that the concentration of AEE as expected was reduced in Dakota Gold DDGS. The Dakota Gold DDGS had smaller particle size and less dense than the conventional DDGS.

Exp. 1. Digestibility of CP and AA

Pigs remained healthy during the experimental period and very little feed refusals were observed. Greater ($P < 0.05$) AID and SID of CP and Lys were observed in pigs fed Dakota Gold DDGS compared with pigs fed conventional DDGS (Table 3.4). The AID and SID of most other AA were also greater ($P < 0.05$) or tended to be greater ($P < 0.10$) in Dakota Gold than in conventional DDGS with the exception that there was no difference between the 2 sources of DDGS for the SID of Trp, Cys, Pro, and Ser.

The SID values for AA in conventional DDGS that were calculated in this experiment are in agreement with values for the SID of AA in low-oil DDGS (Kim et al., 2009; NRC, 2012). However, the values for Dakota Gold were greater than average values for low-oil DDGS, but were mostly within the range of previously published values (Stein et al., 2016). The basal endogenous losses of AA were also close to expected values predicted using equations by (Park et al., 2013).

It is not clear why the digestibility of AA in Dakota Gold DDGS is greater than in conventional DDGS. Reduced AID and SID of AA were reported for low-fat DDGS than for conventional DDGS (Curry et al., 2014) and this may be explained by data that supplemental oil increased the AA digestibility in diets fed to growing pigs (Cervantes-Pahm and Stein, 2008). However, it is possible that the fact that Dakota Gold DDGS is produced using the BPX technology that does not include cooking of the grain (Robinson et al., 2008; Gutierrez et al., 2014) results in reduced heat damage and therefore increased SID of AA. Furthermore, it seemed that the reduction of fat in DDGS used in this experiment was not enough to make a difference. Further research is needed to determine if the SID of AA always is greater in Dakota Gold DDGS compared with conventional DDGS.

Exp. 2. Digestibility of NDF, ADF, AEE, and Energy

Pigs remained healthy during the experiment and only little feed refusals were observed. The feed intake of pigs fed the basal diet tended to be greater ($P = 0.079$) than in pigs fed DDGS diets (Table 3.5), but daily GE intake did not differ between basal and DDGS diets. However, the intake of NDF, ADF, and AEE was greater ($P < 0.001$) for pigs fed DDGS diets than for pigs fed the basal diet reflecting the greater concentrations of these nutrients in DDGS than in corn. Pigs fed the basal diet had less ($P < 0.01$) excretion of GE, NDF, ADF, and AEE and also less ($P < 0.01$) excretion of GE in the urine than pigs fed the 2 DDGS diets. The ATTD of DM, GE, NDF, ADF, and AEE for the basal diet was greater ($P < 0.05$) than for the 2 DDGS diets.

The GE, NDF, ADF, and daily feed intake did not differ between pigs fed the 2 DDGS diets, but AEE intake was greater ($P < 0.05$) for pigs fed the diet with conventional DDGS compared with pigs fed the diet containing Dakota Gold DDGS. Fecal and urine excretion and ATTD of DM and GE did not differ between the 2 DDGS diets. However, the ATTD of NDF, ADF, and AEE was greater ($P < 0.001$) in pigs fed the diet containing conventional DDGS than in the diet containing Dakota Gold DDGS, but there was no difference in DE and ME between the 2 diets containing Dakota Gold DDGS and conventional DDGS.

The ATTD of GE, NDF, ADF, and AEE was greater ($P < 0.05$) in corn than in 2 sources of DDGS. The ATTD of NDF, ADF, and AEE was greater ($P < 0.01$) in conventional DDGS than in Dakota Gold DDGS, but there was no difference in the ATTD of GE between the 2 sources of DDGS (Table 3.6). The DE and ME of corn that were obtained in this experiment were close to expected values (NRC, 2012). When energy concentrations were adjusted to 88% DM, the DE and ME in corn were greater ($P < 0.001$) than in the 2 sources of DDGS, and conventional DDGS contained more ($P < 0.001$) DE and ME than Dakota Gold DDGS.

The DE and ME in conventional DDGS that were determined in this experiment are less than values previously reported for conventional DDGS (Stein et al., 2006; NRC, 2012). However, it has been demonstrated that low oil DDGS contains less DE and ME than DDGS with greater concentrations of fat (Curry et al., 2016) and the values for conventional low-oil DDGS obtained in this experiment are in agreement with the average DE and ME recently reported for 20 sources of low-oil DDGS (Curry et al., 2016).

The reduced DE and ME in Dakota Gold DDGS compared with conventional DDGS is in agreement with previous data (Anderson et al., 2012; Gutierrez et al., 2014). It is possible that part of the reason for this difference is that the concentration of AEE was less in Dakota Gold DDGS than in conventional DDGS although it has been reported that fat concentration is not always related with DE and ME in DDGS (Kerr et al., 2013). The ATTD of ADF and NDF obtained in this experiment for conventional DDGS is in agreement with previous data (Stein and Shurson, 2009; Urriola et al., 2010). However, it is not clear why the ATTD of ADF and NDF was less in Dakota Gold DDGS than in conventional DDGS, but it is possible that the BPX technology that is used in the production of Dakota Gold DDGS results in more of the fermentable fibers being fermented in the ethanol plant with a resulting lower concentration of these fractions in the DDGS that is produced.

CONCLUSION

Values for SID of most AA were greater in Dakota Gold DDGS with greater concentrations of AA than in conventional DDGS. However, ATTD of NDF, ADF, and AEE and energy concentrations of DE and ME were less in the Dakota Gold DDGS than in the conventional DDGS fed to growing pigs.

TABLES

Table 3.1. Chemical composition of corn and 2 sources of distillers dried grains with solubles (DDGS)[1], Exp. 1 and 2

Item, %	Corn	Dakota Gold DDGS	Conventional DDGS
DM	84.90	87.77	82.26
GE, kcal/kg	3,962	4,442	4,831
AEE[2]	3.44	6.82	9.54
Ash	0.95	5.35	5.92
CP	6.93	27.99	26.23
Lys:CP ratio	-	3.43	3.20
Indispensable AA			
Arg	-	1.28	1.23
His	-	0.78	0.71
Ile	-	1.14	1.14
Leu	-	3.31	3.16
Lys	-	0.96	0.84
Met	-	0.53	0.51
Phe	-	1.42	1.42
Thr	-	1.09	1.04
Trp	-	0.17	0.21
Val	-	1.44	1.42
Dispensable AA			

Table 3.1. (Cont.)

Ala	-	2.07	1.89
Asp	-	1.87	1.75
Cys	-	0.53	1.48
Glu	-	4.65	3.70
Gly	-	1.21	1.10
Pro	-	2.31	2.03
Ser	-	1.25	1.20
Tyr	-	1.04	1.01
Carbohydrates			
Starch	59.58	6.60	2.82
Glucose	0.55	0.21	0.26
Fructose	0.33	0.25	0.21
Maltose	ND[3]	ND	ND
Sucrose	0.80	ND	ND
Stachyose	ND	ND	ND
Raffinose	0.19	ND	ND
Fructo-oligosaccharides	0.10	0.13	0.10
NDF	10.28	29.40	37.59
ADF	3.24	12.47	16.50
Physical characteristics			
Objective Color[4]			

Table 3.1. (Cont.)

L*	-	59.67	66.95
a*	-	10.45	9.70
b*	-	18.10	23.70
Bulk density, g/L	-	437	429
Particle size, μm	-	410	367

[1]All values except DM and physical characteristics were adjusted to 88% DM.

[2]AEE = acid hydrolyzed ether extract.

[3]ND = not detected.

[4]L* = greater value indicates a lighter color; a* = greater value indicates a redder color; b* = greater value indicates a more yellow color.

Table 3.2. Ingredient composition and analyzed nutrient composition of experimental diets containing distillers dried grains with solubles (DDGS), Exp. 1

Item, %	Diet		
	Dakota Gold DDGS	Conventional DDGS	N-free
Ingredient composition, as-fed basis			
Dakota Gold DDGS	50.00	-	-
Conventional DDGS	-	50.00	-
Soybean oil	2.00	2.00	4.00
Ground limestone	0.80	0.80	0.45
Dicalcium phosphate	0.90	0.90	2.15
Sucrose	-	-	20.00
Cornstarch	45.20	45.20	67.80
Solka floc[1]	-	-	4.00
Magnesium oxide	-	-	0.10
Potassium carbonate	-	-	0.40
Sodium chloride	0.40	0.40	0.40
Chromic oxide	0.40	0.40	0.40
Vitamin-mineral premix[2]	0.30	0.30	0.30
Analyzed nutrient composition, 88% DM basis			
DM	93.2	93.8	96.4
CP	13.36	11.53	0.31
Indispensable AA			

Table 3.2. (Cont.)

Arg	0.64	0.56	ND[3]
His	0.40	0.33	ND
Ile	0.58	0.51	0.01
Leu	1.68	1.46	0.03
Lys	0.50	0.40	0.01
Met	0.26	0.23	ND
Phe	0.72	0.64	0.01
Thr	0.55	0.48	ND
Trp	0.10	0.09	0.02
Val	0.75	0.66	0.01
Dispensable AA			
Ala	1.06	0.88	0.01
Asp	0.97	0.84	0.01
Cys	0.26	0.23	ND
Glu	2.49	1.98	0.03
Gly	0.62	0.51	0.01
Pro	1.22	1.00	0.01
Ser	0.62	0.54	0.01
Tyr	0.53	0.46	0.01

[1]Fiber Sales and Development Corp., Urbana, OH.

[2]Provide the following quantities of vitamins and micro minerals per kg of complete diet: Vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 as cholecalciferol, 2,208 IU; vitamin E as DL-

Table 3.2. (Cont.)

alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 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, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper sulfate and copper chloride; Fe, 126 mg as ferrous sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese sulfate; Se, 0.3 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc sulfate.

[3]ND = not detected.

Table 3.3. Ingredient composition and analyzed nutrient composition of experimental diets containing distillers dried grains with solubles (DDGS), Exp. 2

Item, %	Diet		
	Basal	Dakota Gold DDGS	Conventional DDGS
Ingredient composition, as-fed basis			
Corn	97.0	47.4	47.4
Dakota Gold DDGS	-	50.0	-
Conventional DDGS	-	-	50.0
Ground limestone	0.8	1.3	1.3
Dicalcium phosphate	1.5	0.6	0.6
Sodium chloride	0.4	0.4	0.4
Vit-Min premix[1]	0.3	0.3	0.3
Analyzed nutrient composition, 88% DM basis			
DM	84.96	86.43	84.92
GE, kcal/kg	3,833	4,094	4,200
CP	7.27	18.42	17.07
NDF	10.09	19.86	23.42
ADF	4.83	7.39	9.00
AEE[2]	3.34	5.32	7.22

[1]Provide the following quantities of vitamins and micro minerals per kg of complete diet: Vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 as cholecalciferol, 2,208 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg;

Table 3.3. (Cont.)

thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 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, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper sulfate and copper chloride; Fe, 126 mg as ferrous sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese sulfate; Se, 0.3 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc sulfate.

[2]AEE = acid hydrolyzed ether extract.

Table 3.4. Apparent ileal digestibility (AID) and standardized ileal digestibility (SID) of CP and AA in DDGS[1,2,3], Exp. 1

	AID				SID			
Item, %	Dakota Gold DDGS	Conventional DDGS	SEM	*P*-value	Dakota Gold DDGS	Conventional DDGS	SEM	*P*-value
CP	67.0	54.6	2.5	0.021	84.6	74.8	2.5	0.031
Indispensable AA								
Arg	85.9	78.8	1.2	0.010	93.3	87.2	1.2	0.013
His	82.2	76.8	1.1	0.030	86.6	82.1	1.1	0.043
Ile	78.4	72.6	1.4	0.033	84.7	79.8	1.4	0.051
Leu	86.8	82.7	1.2	0.061	90.5	86.9	1.2	0.075
Lys	47.4	27.6	4.6	0.003	68.1	53.0	4.6	0.007
Met	85.9	81.5	0.9	0.004	89.3	85.4	0.9	0.007
Phe	82.9	78.1	1.1	0.008	88.4	84.2	1.1	0.017
Thr	70.2	65.3	1.1	0.009	80.8	77.4	1.1	0.052
Trp	72.3	69.1	2.7	0.489	79.1	76.7	2.7	0.582
Val	74.8	68.1	1.5	0.015	83.2	77.6	1.5	0.026

Table 3.4. (Cont.)

Dispensable AA								
Ala	80.3	72.0	1.9	0.003	87.2	80.2	1.9	0.004
Asp	72.7	67.4	1.1	0.006	81.6	77.6	1.1	0.027
Cys	73.9	71.0	1.4	0.147	81.8	79.9	1.4	0.301
Glu	83.8	78.1	1.5	0.015	88.5	84.0	1.5	0.045
Gly	57.9	36.8	5.6	0.018	88.5	74.2	5.6	0.051
Pro	66.7	33.7	10.1	0.034	118.3	95.9	10.1	0.106
Ser	78.6	74.4	1.0	0.057	86.5	83.4	1.0	0.110
Tyr	85.4	82.4	0.7	0.012	90.8	88.5	0.7	0.048

[1]Each least squares mean represents 8 observations.

[2]DDGS = distillers dried grains with solubles.

[3]Standardized ileal digestibility of CP and AA was calculated by correcting values for AID for basal endogenous losses. Basal endogenous losses (g/kg DMI) were determined from pigs fed the N-free diet: CP, 25.7; Arg, 0.52; His, 0.19; Ile, 0.40; Leu, 0.69; Lys, 1.13; Met, 0.10; Phe, 0.43; Thr, 0.64; Trp, 0.08; Val, 0.69; Ala, 0.80; Asp, 0.95; Cys, 0.23; Glu, 1.28; Gly, 2.10; Pro, 6.90; Ser, 0.54; Tyr, 0.31.

Table 3.5. Apparent total tract digestibility (ATTD) of nutrients and energy concentrations of DE and ME in experimental diets[1] (as-fed basis), Exp. 2

Item	Diet[2]			SEM	Contrast *P*-value	
	Basal	Dakota Gold DDGS	Conventional DDGS		Basal vs. DDGS	DDGS source
Intake						
Feed intake, kg/d	0.70	0.63	0.57	0.05	0.079	0.332
GE, kcal/d	2,584	2,530	2,301	206	0.426	0.349
NDF, g/d	69	123	128	9	< 0.001	0.606
ADF, g/d	33	46	49	4	< 0.001	0.391
AEE[3], g/d	23	33	40	3	< 0.001	0.043
Fecal excretion						
Dry feces output, kg/d	0.06	0.12	0.11	0.01	< 0.001	0.169
Fecal GE, kcal/d	278	569	524	41	< 0.001	0.383
NDF, g/d	26	58	51	5	< 0.001	0.174
ADF, g/d	9	20	17	2	< 0.001	0.097

Table 3.5. (Cont.)

AEE[3], g/d	7	15	13	1	0.001	0.179
Urinary excretion						
Urine output, kg/d	2	3	2	0	0.036	0.541
Urinary GE, kcal/d	56	113	97	8	< 0.001	0.193
ATTD						
DM, %	91.5	80.3	80.8	0.4	< 0.001	0.410
GE, %	89.2	77.6	77.2	0.5	< 0.001	0.623
NDF, %	61.7	52.7	60.8	1.9	0.046	0.007
ADF, %	73.1	57.5	66.6	1.6	< 0.001	< 0.001
AEE[3], %	69.6	53.6	68.5	2.9	0.026	0.002
Energy in diets, kcal/kg						
DE	3,303	3,119	3,130	19	< 0.001	0.671
ME	3,221	2,940	2,958	24	< 0.001	0.548

[1]Each least squares mean represents 8 observations.

[2]DDGS = distillers dried grains with solubles.

Table 3.5. (Cont.)

[3]AEE = acid hydrolyzed ether extract.

Table 3.6. Concentrations of DE and ME and apparent total tract digestibility (ATTD) of nutrients in corn and 2 sources of distillers dried grains with solubles (DDGS)[1,2], Exp. 2

Item	Ingredient			SEM	Contrast *P*-value	
	Corn	Dakota Gold DDGS	Conventional DDGS		Corn vs. DDGS	DDGS source
ATTD, %						
GE	89.2	67.9	67.2	0.8	< 0.001	0.505
NDF	61.7	49.9	60.6	2.2	0.025	0.002
ADF	73.1	56.0	66.1	1.7	< 0.001	< 0.001
AEE[3]	69.6	51.9	68.4	3.1	0.023	0.001
Energy, kcal/kg						
GE	3,962	4,442	4,831	-	-	-
DE	3,529	3,017	3,244	36	< 0.001	< 0.001
ME	3,446	2,743	2,965	50	< 0.001	0.001

[1]Each least squares mean represents 8 observations.

[2]All values were adjusted to 88% DM.

[3]AEE = acid hydrolyzed ether extract.

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CHAPTER 4: EFFECTS OF DAKOTA GOLD DDGS AND CONVENTIONAL DDGS ON WEAN TO FINISH GROWTH PERFORMANCE AND CARCASS QUALITY OF PIGS FED DIETS THAT WERE PELLETED OR PROVIDED IN A MEAL FORM

ABSTRACT

The objective of this research was to determine the effects of including Dakota Gold or conventional distillers dried grains and solubles (DDGS) in diets that were fed in a meal form or a pelleted form to pigs from weaning to market on growth performance and carcass characteristics. A total of 160 barrows and gilts were used in this experiment. There were 4 diets and 10 pens per diet and 4 pigs per each pen. Pigs were weaned at 21 d of age and fed a common phase 1 diet that did not contain DDGS during the initial 7 d post-weaning. Pigs were then allotted to the 4 diets that were arranged in a 2 × 2 factorial design with 2 sources of DDGS (Dakota Gold and conventional DDGS) and 2 diet forms (meal and pellets). Pigs were fed phase 2 diet from d 7 to d 21 and phase 3 diets from d 21 to d 43 post weaning. All diets were based on corn and soybean meal, but phase 2 diets also contained 15% DDGS and phase 3 diets contained 30% DDGS. From d 43, pigs were fed grower diets for 38 d, early finisher diets for 38 d, and late finisher diets for 18 d. All diets for growing-finishing period contained 30% of DDGS. Feed was provided on an ad libitum basis and water was available at all times. Pigs were weighed at the beginning of each phase and at the conclusion of experiment. Daily feed allotments were recorded as well. On the last day of the experiment, the pig in each pen that had a BW that was closest to the pen average was euthanized and standard carcass measurements were determined. The interaction between source of DDGS and diet form was not significant for any response variables and was, therefore, eliminated from the final model. Combined for the 2 nursery phases, feeding meal diets instead of pelleted diets increased ($P < 0.001$) ADFI and decreased ($P < 0.05$) G:F. However, no differences between the 2 sources of DDGS were observed for the overall growth performance of weanling pigs. For the entire growing-finishing period, the source of DDGS did not affect growth performance of pigs, but pigs fed meal diets had reduced ($P < 0.001$) G:F compared with pigs fed the pelleted diets. There were no differences among pigs fed diets containing Dakota Gold DDGS and pigs fed diets containing conventional DDGS in any of the carcass characteristics measured. However, 10th rib back fat was greater ($P = 0.018$) for pigs fed pelleted diets than for pigs fed meal diets. There were also tendencies for lower HCW ($P = 0.091$) and greater fat-free lean percentage ($P = 0.064$) in pigs fed meal diets compared with pigs fed pelleted diets. In conclusion, use of different sources of DDGS in diets fed to weaning to market did not affect growth performance and carcass characteristics. However, pigs fed diets in the pelleted form had greater G:F ratio than in the meal form during the whole periods and had greater backfat than in the meal form.

Key words: carcass characteristics, distillers dried grains and solubles, growth performance, pellet, meal, wean to market

INTRODUCTION

Corn distillers dried grains with solubles (**DDGS**), a co-product of dry-mill ethanol production, is commonly included in diets for pigs (Stein and Shurson, 2009). Recently, ethanol plants have introduced technology to remove oil from the solubles resulting in less oil in DDGS. Conventional DDGS usually contains 10% crude fat whereas low-oil DDGS contains only 6 to 9% fat (NRC, 2012). It has been demonstrated that up to 30% DDGS may be used in diets for growing-finishing pigs (Stein and Shurson, 2009) and in some studies, the effects of feeding

DDGS with different oil concentrations on growth performance, carcass traits including fat quality, and nutrient digestibility were determined (Graham et al., 2014; Wu et al., 2016). However, growth performance and carcass quality of pigs fed either conventional DDGS or Dakota Gold have not been compared.

Dakota Gold is a low-oil DDGS that is produced by Poet (Sioux Falls, SD). This ingredient is produced using a cold-fermentation process and results of recent research indicate that the digestibility of AA in Dakota Gold is greater than in conventional DDGS (Rodriguez et al., 2018). However, because of the reduced oil, the ME in Dakota Gold is less than in conventional DDGS. It is, however, not known how this will affect growth performance or carcass quality of pigs.

Pelleting is one of the technologies that are used to improve growth performance of weanling and growing-finishing pigs (Rojas and Stein, 2017), but there is limited information about effects of pelleting diets that contain conventional DDGS or low-oil DDGS. Therefore, the objective of this research was to determine the effects of including Dakota Gold or conventional DDGS in diets that were fed in a meal form or a pelleted form to pigs from weaning to market.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocol for the experiment. Pigs used in this experiment were the offspring of PIC 359 boars and Camborough females (Pig Improvement Company, Hendersonville, TN).

Animals, Housing, Diets, and Feeding

A total of 160 barrows and gilts were used in this experiment. There were 4 diets and 10 pens per diet (i.e., a total of 40 pens) and 4 pigs were housed in each pen. Pigs were weaned at 21 d of age and fed a common phase 1 diet during the initial 7 d post-weaning. The phase 1 diet did not contain DDGS. Pigs were then allotted to the 4 experimental diets that were arranged in a 2 × 2 factorial design with 2 sources of DDGS (Dakota Gold and conventional DDGS; Table 4.1) and 2 diet forms (meal and pellets). Pigs were fed phase 2 diets from d 7 to d 21 post-weaning and phase 3 diets from d 21 to d 43 post weaning (Table 4.2). All diets were based on corn and soybean meal, but phase 2 diets also contained 15% DDGS and phase 3 diets contained 30% DDGS. Concentrations of standardize ileal digestible (**SID**) AA in diets were calculated based on data for the 2 sources of DDGS that were obtained in a previous experiment. All diets were formulated to meet current requirement estimates for weanling pigs (NRC, 2012), but no attempt to equalize ME was made. As a consequence, the calculated ME in diets containing conventional DDGS was slightly greater than for diets containing Dakota Gold. Feed was provided on an ad libitum basis and water was available at all times. Pigs were weighed at the beginning of phase 2 and at the conclusion of phases 2 and 3. Daily feed allotments were recorded as well.

On d 43, pigs were moved to a growing-finishing facility. Pigs stayed in their respective pens and they were fed grower diets for 38 d, early finisher diets for 38 d and late finisher diets for 18 d. The dietary treatments from the nursery were continued in the growing-finishing period with inclusion of 30% DDGS in all diets (Table 4.4). Diets for the growing-finishing period were formulated as outlined for the nursery phase with SID AA being equal among diets within each phase, whereas ME in diets was allowed to vary based on the source of DDGS that was used. Daily feed allotments were recorded and individual pig weights were recorded on the last day of each phase.

On the last day of the experiment, the pig in each pen that had a BW that was closest to the pen average was transported to the Meats Science Laboratory at the University of Illinois and euthanized. Standard carcass measurements (i.e., hot carcass weight, dressing percentage, backfat thickness, and loin eye area) were determined after slaughter.

Data for pig weights and feed consumption were summarized at the conclusion of the experiment and ADG, ADFI, and G:F ratio were calculated for each treatment group and summarized within phase. Data for carcass characteristics were also summarized within treatment and average carcass fat-free leanness was calculated for each treatment group based on NPPC (1999).

Chemical Analysis

Ingredients and diet samples were analyzed for GE using bomb calorimetry (Model 6300, Parr Instruments, Moline, IL), DM (Method 930.15; AOAC, 2007), CP (method 990.03; AOAC, 2007), and acid hydrolyzed ether extract using the acid hydrolysis filter bag technique (Ankom HCl Hydrolysis System, Ankom Technology, Macedon, NY) followed by fat extraction (Ankom XT-15 Extractor, Ankom Technology, Macedon, NY). Diet samples also were analyzed for ash (method 942.05; AOAC, 2007), insoluble and soluble dietary fiber (method 991.43; AOAC, 2007) using the Ankom Dietary Fiber Analyzer (Ankom Technology, Macedon, NY). Ether extract without acid hydrolysis and ADF and NDF (Ankom 2000 Fiber Analyzer, Ankom Technology, Macedon, NY) also were analyzed for the 2 sources of DDGS.

Amino acids in the 2 sources of DDGS and all diets were analyzed on a Hitachi Amino Acid Analyzer, Model No. L8800 (Hitachi High Technologies America, Inc; Pleasanton, CA) using ninhydrin for postcolum derivatization and norleucine as the internal standard. Prior to analysis, samples were hydrolyzed with 6*N* HCl for 24 h at 110°C [method 982.30 E(a); AOAC, 2007]. Methionine and Cys were determined as Met sulfone and cysteic acid after cold performic acid oxidation overnight before hydrolysis [method 982.30 E(b); AOAC, 2007]. Tryptophan was determined after NaOH hydrolysis for 22 h at 110°C [method 982.30 E(c); AOAC, 2007].

Statistical Analyses

Data were analyzed as a 2 × 2 factorial using the PROC MIXED procedure in SAS. The statistical model included the fixed effect of source of DDGS, diet form, and the interaction between source of DDGS and diet form. However, the interaction between source of DDGS and diet form was not significant for any response variables and was, therefore, eliminated from the final model. The pen was the experimental unit. Least square means were calculated for each independent variable. Results were considered significant at $P < 0.05$ and considered a trend at $P < 0.10$.

RESULTS AND DISCUSSION

Pigs remained healthy and consumed their diets without apparent problems. Overall, 2 pigs died during the experiment; these pigs were fed the Dakota Gold DDGS diet in meal form (phase 2 of the nursery period) and the conventional DDGS in the pelleted form early finishing period), respectively. Two additional pigs fed the pelleted conventional DDGS diet (early finishing period) and the pelleted Dakota Gold diet (late finishing period), respectively, were removed from the study because of leg problems. Data for the pens where these 4 pigs were housed were adjusted using a partitioning method (Lindemann and Kim, 2007).

Growth Performance

During phase 2 of the nursery period, feeding diets containing conventional DDGS instead of Dakota Gold tended ($P = 0.076$) to increase ADG and final BW and increased ($P < 0.05$) G:F (Table 4.6). This may be because of the greater ME in the conventional DDGS. Pigs fed meal diets had greater ($P < 0.01$) ADG, ADFI, and final BW than pigs fed the pelleted diets during this phase, but there was no difference in G:F between pigs fed pelleted and meal diets. In phase 3, no differences between the 2 sources of DDGS were observed for ADG, ADFI, G:F, or final BW, but pigs fed meal diets had greater (P < 0.001) ADFI and reduced (P < 0.05) G:F compared with pigs fed pelleted diets. Combined for the 2 nursery phases from d 7 to 43 post-weaning, feeding meal diets instead of pelleted diets increased (P < 0.001) ADFI and decreased (P < 0.05) G:F. However, no differences between the 2 sources of DDGS were observed for the overall growth performance of weanling pigs during this period indicating that the values for SID of AA used in diet formulations likely were accurate.

In the grower phase, pigs fed diets containing conventional DDGS had greater (P < 0.05) ADG and ADFI and tended (P = 0.057) to have greater final BW than pigs fed Dakota Gold DDGS (Table 4.7). Pigs fed meal diets also had greater (P < 0.01) ADG, ADFI, and final BW compared with pigs fed pelleted diets, but the G:F was reduced (P = 0.032) for pigs fed the meal diets compared with pigs fed diets that were pelleted.

In the early finishing period, there were no differences between pigs fed the 2 DDGS sources, but ADG and G:F of pigs fed pelleted diets were greater (P < 0.01) than for pigs fed meal diets. In late finishing, the source of DDGS in the diet did not influence pig growth performance, but pigs fed pelleted diets had greater (P < 0.05) G:F than pigs fed meal diets. For the entire growing-finishing period, the source of DDGS did not affect ADG, ADFI, or G:F of pigs, but pigs fed meal diets had reduced (P < 0.001) G:F compared with pigs fed the pelleted diets.

The overall growth performance of all pigs was excellent during the growing-finishing period indicating that if diets are formulated on measured values for SID AA in DDGS, acceptable growth performance of pigs may be obtained even if there is 30% DDGS in the diets. This observation is in agreement with results of numerous previous experiments (Stein and Shurson, 2009; Cromwell et al., 2011), but it has also been reported that inclusion of DDGS may reduce growth performance of pigs (Whitney et al., 2006; Kim et al., 2012; Graham et al., 2014).

The reason for these different outcomes is most likely that differences in AA digestibility among different sources of DDGS have been reported (Stein et al., 2006; Pahm et al., 2008). However, results of this research indicate that if diets containing DDGS are formulated based on measured values for the digestibility of AA, this variability may be minimized or eliminated.

Because Dakota Gold had a greater digestibility of AA including Lys than conventional DDGS, the inclusion of crystalline Lys was reduced in the diets containing Dakota Gold compared with conventional DDGS. The observation that this did not reduce growth performance of pigs indicate that the values used in diet formulations were correct. The implication of this observation is that the costs of formulating diets were reduced if Dakota Gold was used instead of conventional DDGS because less crystalline Lys was needed in diets containing Dakota Gold DDGS.

The reduced ME that was determined in Dakota Gold compared with conventional DDGS did not result in a reduced G:F for the overall nursery period or for the growing-finishing period. This observation may indicate that the reduction in ME that was measured for Dakota Gold DDGS is not big enough to have a measurable impact on G:F.

The improved G:F of pigs fed pelleted diets compared with pigs fed the meal diets during the nursery phases, as well as the growing-finishing phases is in agreement with previous data (Steidinger et al., 2000; Rojas and Stein, 2016). The increase in G:F that was observed in the growing-finishing period (approximately 5%) is also in line with previous data and may be a result of increased ileal digestibility of starch and AA and increased total tract digestibility of GE by pigs fed pelleted diets compared with pigs fed diets in meal form (Rojas et al., 2016). Thus, pelleting of DDGS-containing diets appears to be an effective way of increasing ME of the diets and thereby improving G:F.

Inclusion of DDGS in diets for weanling pigs has been reported in a limited number of experiments, and it has been concluded that 15 to 30% DDGS may be used in diets for weanling pigs without reducing growth performance (Whitney and Shurson, 2004; Linneen et al., 2006). Results of this experiment demonstrating that 15% low-oil DDGS from d 7 to 21 and 30% low-oil DDGS during the remaining nursery period does not compromise pig growth performance compared with pigs fed conventional DDGS, and this indicates that pig responses to low-oil DDGS is similar to that of conventional DDGS. We are not aware of previous data for weanling pigs fed diets containing low-oil DDGS, but the current results indicate that reducing the oil in DDGS does not have a negative impact on growth performance of weanling pigs.

To our knowledge, there are no previous data for pigs fed diets containing DDGS from 7 d post-weaning to market. However, the overall excellent growth performance that was observed in the experiment, in the nursery as well as the growing-finishing phase, indicates that feeding DDGS diets from 7 d post-weaning to market does not compromise pig growth performance. However, because no diets without DDGS were included in this experiment, it is not known if DDGS increased or reduced performance compared with pigs fed diets without DDGS.

Carcass Characteristic

There were no differences among pigs fed diets containing Dakota Gold DDGS and pigs fed diets containing conventional DDGS in any of the carcass characteristics measured (Table 4.8). However, 10^{th} rib back fat was greater (P = 0.018) for pigs fed pelleted diets than for pigs fed meal diets. There were also tendencies for lower HCW (P = 0.091) and greater fat-free lean percentage (P = 0.064) in pigs fed meal diets compared with pigs fed pelleted diets.

We are not aware of previous research in which effects of low-oil DDGS and conventional DDGS on carcass quality were compared, but the present data indicate that there were no negative effects of using the low-oil Dakota Gold DDGS on HCW, dressing percentage, 10^{th} rib back fat, or lean percentage. It is possible that low-oil DDGS will have a positive impact on fat iodine values, but iodine values were not determined in this experiment.

The increased back fat and the tendency for increased HCW that were observed for pigs fed pelleted diets compared with pigs fed meal diets is likely a result of the increased ME in pelleted diets (Rojas et al., 2016). The increased back fat resulted in the reduced lean percentage that was observed for the pigs fed pelleted diets compared with pigs fed meal diets. The observation that there was no difference in the amount of fat-free lean that was deposited between pigs fed pelleted and meal diets indicate that pelleting diets did not compromise protein synthesis and the increased backfat in pigs fed pelleted diets was only a result of the increased ME in the diets.

CONCLUSION

In conclusion, use of different sources of DDGS in diets fed to weaning to market did not affect growth performance and carcass characteristics. However, pigs fed diets in the pelleted form had greater G:F ratio than in the meal form during the whole periods and had greater back fat than in the meal form.

TABLES

Table 4.1. Analyzed nutrient composition of distillers Dakota Gold and conventional dried grains with solubles (DDGS)[1]

	DDGS	
Item, %	Dakota Gold	Conventional
GE, kcal/kg	4,442	4,831
DM	87.77	82.26
CP	29.50	28.67
Ether extract	4.49	7.91
Acid hydrolyzed ether extract	6.82	9.54
NDF	29.40	37.59
ADF	12.47	16.50
Indispensable AA		
Arg	1.28	1.23
His	0.78	0.71
Ile	1.14	1.14
Leu	3.31	3.16
Lys	0.96	0.84
Met	0.53	0.51
Phe	1.42	1.42
Thr	1.09	1.04
Trp	0.17	0.21
Val	1.44	1.42

Table 4.1. (Cont.)

Dispensable AA		
Ala	2.07	1.89
Asp	1.87	1.75
Cys	0.53	0.48
Glu	4.65	3.70
Gly	1.21	1.10
Pro	2.31	2.03
Ser	1.25	1.20
Tyr	1.04	1.01

[1]All values except DM were adjusted to 88% DM.

Table 4.2. Composition of experimental diets for weanling pigs (as-fed basis)

Ingredient, %	Phase 2		Phase 3	
DDGS[1]	Dakota Gold	Conventional	Dakota Gold	Conventional
Corn	36.50	36.43	43.40	43.25
Whey, dried	20.00	20.00	-	-
Soybean meal, 48% CP	14.00	14.00	20.00	20.00
Dakota Gold DDGS	15.00	-	30.00	-
Conventional DDGS	-	15.00	-	30.00
Fish meal	6.00	6.00	-	-
Blood plasma	3.00	3.00	-	-
Soybean oil	3.50	3.50	3.50	3.50
L-Lys·HCl	0.30	0.35	0.55	0.65
DL-Met	0.05	0.05	0.05	0.05
L-Thr	-	0.02	0.05	0.10
L-Trp	-	-	0.05	0.05
Ground limestone	0.95	0.95	1.30	1.30
Dicalcium phosphate	-	-	0.40	0.40
Salt	0.40	0.40	0.40	0.40
Vit-Min premix[1]	0.30	0.30	0.30	0.30

[1]DDGS = distillers dried grains with solubles.

[2]The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kg of complete diet: Vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 as cholecalciferol, 2,208 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as

Table 4.2. (Cont.)

menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 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, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper sulfate and copper chloride; Fe, 126 mg as ferrous sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese sulfate; Se, 0.3 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc sulfate.

Table 4.3. Chemical composition of experimental diets containing corn distillers dried grains with solubles (**DDGS**) for weanling pigs (as-fed basis)

Item, %	Phase 2				Phase 3			
DDGS	Dakota Gold		Conventional		Dakota Gold		Conventional	
Diet form	Meal	Pellet	Meal	Pellet	Meal	Pellet	Meal	Pellet
GE, kcal/kg	4,202	4,107	4,173	4,118	4,221	4,082	4,229	3,960
ME[1], kcal/kg	3,441	3,441	3,447	3,447	3,283	3,283	3,295	3,295
DM	91.00	89.64	91.22	90.17	91.21	88.35	87.21	86.27
CP	22.61	22.71	22.20	21.72	20.75	22.19	22.02	21.29
Ash	5.94	6.11	6.59	6.28	5.98	5.85	5.62	5.44
AEE[2]	4.20	4.10	4.34	3.91	4.13	6.11	7.27	5.91
Indispensable AA								
Arg	1.25	1.14	1.22	1.15	1.16	1.21	1.22	1.14
His	0.58	0.54	0.57	0.54	0.56	0.58	0.57	0.54
Ile	0.98	0.92	0.96	0.92	0.95	0.98	0.96	0.91
Leu	2.03	1.94	1.99	1.89	2.09	2.12	2.06	2.00
Lys	1.62	1.49	1.61	1.49	1.44	1.46	1.53	1.41
Met	0.43	0.40	0.42	0.40	0.38	0.39	0.37	0.37
Phe	1.08	1.02	1.05	0.99	1.06	1.09	1.00	0.96
Thr	0.99	0.94	0.99	0.93	0.90	0.91	0.91	0.89
Trp	0.29	0.29	0.31	0.28	0.27	0.28	0.29	0.29
Val	1.18	1.10	1.16	1.11	1.09	1.12	1.11	1.06
Dispensable AA								

Table 4.3. (Cont.)

Ala	1.26	1.20	1.23	1.18	1.26	1.26	1.23	1.21
Asp	2.08	1.94	2.04	1.93	1.86	1.93	1.94	1.82
Cys	0.42	0.40	0.39	0.39	0.39	0.41	0.38	0.38
Glu	3.62	3.40	3.46	3.30	3.62	3.69	3.54	3.44
Gly	0.98	0.96	0.98	0.93	0.86	0.90	0.89	0.86
Pro	1.32	1.27	1.27	1.24	1.43	1.42	1.36	1.32
Ser	0.97	0.91	0.95	0.89	0.89	0.92	0.93	0.89
Tyr	0.76	0.71	0.73	0.69	0.74	0.76	0.68	0.67

[1]ME was calculated based on the results from the previous experiment for 2 sources of DDGS and on the values in NRC (2012) for corn.

[2]AEE = acid hydrolyzed ether extract.

Table 4.4. Composition of experimental diets (as-fed basis)

Ingredient, %	Grower		Early Finishing		Late Finishing	
DDGS[1]	Dakota	Conventional	Dakota	Conventional	Dakota	Conventional
Corn	49.48	49.37	54.85	54.76	57.12	57.03
Soybean meal,	17.00	17.00	12.00	12.00	10.00	10.00
Dakota Gold	30.00	-	30.00	-	30.00	-
Conventional	-	30.00	-	30.00	-	30.00
Choice White	1.00	1.00	1.00	1.00	1.00	1.00
$_{L}$-Lys·HCl	0.31	0.40	0.22	0.31	0.13	0.22
Ground	1.36	1.38	1.23	1.23	1.05	1.05
Dicalcium	0.15	0.15	-	-	-	-
Salt	0.40	0.40	0.40	0.40	0.40	0.40
Vit-Min premix[2]	0.30	0.30	0.30	0.30	0.30	0.30

[1]DDGS = distillers dried grains with solubles.

[2]The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kg of complete diet: Vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 as cholecalciferol, 2,208 IU; vitamin E as $_{DL}$-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 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, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper sulfate and copper chloride; Fe, 126 mg as ferrous sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese sulfate; Se, 0.3 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc sulfate.

Table 4.5. Chemical composition of experimental diets containing corn distillers dried grains with solubles (DDGS) for growing and finishing pigs (as-fed basis)

Item, %	Growing				Early finishing				Late finishing			
DDGS	Dakota Gold		Conventional		Dakota Gold		Conventional		Dakota Gold		Conventional	
Diet form	Meal	Pellet	Meal	Pellet	Meal	Pellet	Meal	Pellet	Meal	Pellet	Meal	Pellet
DM	90.20	87.56	89.22	87.72	89.79	87.42	89.01	86.95	88.91	87.65	88.37	86.51
GE, kcal/kg	4,085	3,981	4,043	3,990	4,012	3,969	4,074	3,942	4,014	3,955	4,028	3,965
ME, kcal/kg	3,154	3,154	3,165	3,165	3,167	3,167	3,179	3,179	3,175	3,175	3,186	3,186
CP	21.33	20.86	20.21	19.96	18.98	18.54	17.97	18.03	17.34	18.04	16.83	16.20
Ash	5.60	4.74	5.06	5.60	4.78	4.67	4.47	4.53	4.44	4.19	4.52	4.16
AEE	5.18	4.69	5.24	5.42	5.14	5.79	5.69	5.92	5.45	4.92	5.21	5.49
Indispensable AA												
Arg	1.15	1.15	1.18	1.12	1.07	1.06	1.03	1.00	0.88	0.91	0.85	0.82
His	0.57	0.56	0.55	0.53	0.53	0.52	0.50	0.49	0.47	0.47	0.43	0.42
Ile	0.90	0.88	0.88	0.85	0.81	0.83	0.79	0.77	0.71	0.72	0.70	0.70
Leu	2.05	2.01	1.98	1.93	1.93	1.91	1.85	1.80	1.78	1.80	1.69	1.69

Table 4.5. (Cont.)

Lys	1.26	1.19	1.29	1.19	1.05	1.04	1.07	1.06	0.85	0.83	0.86	0.85
Met	0.33	0.33	0.34	0.33	0.34	0.33	0.32	0.31	0.30	0.28	0.30	0.27
Phe	1.05	1.03	1.05	1.01	0.98	0.98	0.88	0.86	0.86	0.88	0.85	0.85
Thr	0.78	0.79	0.80	0.77	0.75	0.73	0.69	0.69	0.65	0.66	0.65	0.64
Trp	0.23	0.25	0.24	0.22	0.21	0.21	0.22	0.22	0.18	0.22	0.19	0.18
Val	1.04	1.02	1.04	0.99	0.96	0.98	0.96	0.93	0.85	0.85	0.83	0.86
Dispensable AA												
Ala	1.27	1.23	1.21	1.16	1.21	1.18	1.14	1.11	1.11	1.11	1.03	1.03
Asp	1.75	1.77	1.79	1.74	1.61	1.62	1.53	1.51	1.35	1.37	1.39	1.36
Cys	0.37	0.39	0.38	0.35	0.39	0.37	0.33	0.34	0.33	0.32	0.35	0.29
Glu	3.59	3.54	3.38	3.30	3.31	3.30	3.07	3.07	2.92	2.96	2.76	2.76
Gly	0.87	0.85	0.87	0.83	0.82	0.81	0.80	0.78	0.74	0.74	0.70	0.70
Pro	1.41	1.39	1.36	1.31	1.37	1.37	1.24	1.23	1.26	1.24	1.18	1.14
Ser	0.89	0.88	0.89	0.87	0.84	0.78	0.76	0.78	0.70	0.73	0.71	0.72
Tyr	0.69	0.71	0.72	0.68	0.67	0.66	0.59	0.57	0.59	0.63	0.59	0.53

[1]ME was calculated based on the results from the previous experiment for 2 sources of DDGS and on the values in NRC

Table 4.5. (Cont.)

(2012) for corn.

[2]AEE = acid hydrolyzed ether extract.

Table 4.6. Growth performance of weanling pigs fed experimental diets[1]

Item	DDGS	Dakota Gold		Conventional			*P*-value	
	Diet form	Meal	Pellet	Meal	Pellet	SEM	DDGS	Diet form
Nursery phase 2 (d 7 - 21)								
Initial BW, kg		7.84	7.89	7.89	7.87	-	-	-
ADG, kg/d		0.39	0.34	0.41	0.37	0.01	0.076	0.002
ADFI, kg/d		0.53	0.48	0.53	0.49	0.02	0.967	0.002
G:F ratio		0.73	0.71	0.77	0.75	0.02	0.020	0.366
Final BW, kg		13.25	12.72	13.59	13.02	0.46	0.076	0.003
Nursery phase 3 (d 21 - 43)								
ADG, kg/d		0.64	0.65	0.64	0.63	0.02	0.568	0.964
ADFI, kg/d		1.08	1.03	1.12	1.03	0.03	0.178	< 0.001
G:F ratio		0.59	0.63	0.57	0.61	0.01	0.142	0.011
Final BW, kg		27.31	27.06	27.75	26.86	0.79	0.757	0.146
Overall (d 7 - 43)								
ADG, kg/d		0.54	0.53	0.55	0.53	0.01	0.771	0.131

Table 4.6. (Cont.)

ADFI, kg/d	0.87	0.82	0.89	0.82	0.02	0.279	< 0.001
G:F ratio	0.63	0.65	0.62	0.64	0.01	0.547	0.030

[1]Each least squares mean represents 10 observations.

Table 4.7. Growth performance of growing to finishing pigs fed experimental diets[1]

Item	DDGS	Dakota Gold		Conventional			*P*-value	
	Diet form	Meal	Pellet	Meal	Pellet	SEM	DDGS	Diet form
Growing (d 0 - 38)								
Initial BW, kg		27.31	27.06	27.75	26.86	0.79	0.757	0.146
ADG, kg/d		0.89	0.85	0.93	0.88	0.02	0.040	0.009
ADFI, kg/d		1.91	1.79	2.00	1.84	0.04	0.026	< 0.001
G:F ratio		0.47	0.48	0.46	0.48	0.01	0.986	0.032
Final BW, kg		61.13	59.41	62.97	60.30	1.29	0.057	0.003
Early finishing (d 38 - 76)								
ADG, kg/d		0.97	1.03	0.95	1.04	0.02	0.832	0.002
ADFI, kg/d		2.84	2.77	2.83	2.86	0.06	0.517	0.747
G:F ratio		0.34	0.37	0.34	0.36	0.01	0.154	< 0.001
Final BW, kg		98.06	98.45	99.05	99.80	1.66	0.396	0.680
Late finishing (d 76 - 94)								
ADG, kg/d		1.01	1.03	1.03	1.06	0.04	0.505	0.411

Table 4.7. (Cont.)

ADFI, kg/d	3.34	3.13	3.34	3.33	0.10	0.297	0.268
G:F ratio	0.30	0.33	0.31	0.32	0.01	0.719	0.026
Final BW, kg	116.16	116.51	117.51	118.85	1.72	0.218	0.567
Overall (d 0 - 94)							
ADG, kg/d	0.95	0.95	0.95	0.98	0.02	0.223	0.315
ADFI, kg/d	2.56	2.44	2.59	2.54	0.05	0.167	0.067
G:F ratio	0.37	0.39	0.37	0.39	0.003	0.526	< 0.001

[1]Each least squares mean represents 10 observations.

Table 4.8. Carcass characteristics of pigs fed experimental diets[1]

Item	DDGS	Dakota Gold		Conventional			*P*-value	
	Diet form	Meal	Pellet	Meal	Pellet	SEM	DDGS	Diet form
HCW, kg		84.84	88.13	84.32	85.59	1.39	0.250	0.091
Dressing, %		76.80	77.58	76.59	77.00	0.41	0.328	0.149
10^{th} rib backfat, cm		1.10	1.52	1.31	1.44	0.11	0.602	0.018
Longissimus muscle area, sq. cm		50.85	52.14	48.99	50.66	1.56	0.155	0.204
Fat-free lean[2], kg		49.77	49.93	48.34	48.79	0.97	0.142	0.723
Fat-free lean[3], %		58.65	56.66	57.32	57.03	0.65	0.426	0.064

[1]Each least squares mean represents 10 observation.

[2]Calculated from NPPC (1999): pounds fat-free lean = 8.588 – 21.896 * 10^{th} rib backfat (in.) + 0.465 * HCW (lbs.) + 3.005 * *Longissimus* muscle area (sq. in.).

[3]Fat-free lean, % = (Fat-free lean / HCW) * 100 = % fat-free lean.

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CHAPTER 5: DIGESTIBILITY OF AMINO ACIDS, FIBER, AND ENERGY, AND CONCENTRATIONS OF DIGESTIBLE AND METABOLIZABLE ENERGY IN CONVENTIONAL AND EXTRUDED YELLOW DENT CORN, WHEAT, AND SORGHUM FED TO GROWING PIGS

ABSTRACT

Two experiments were conducted to determine effects of extrusion on energy and nutrient digestibility in cereal grains fed to growing pigs. One source of yellow dent corn, one source of wheat, and one source of sorghum were ground to approximately 500 microns and each source of grain was divided into 2 batches. One batch of each grain was extruded, whereas the other batch was used without further processing. In Exp. 1, 7 diets were formulated to determine starch and AA digestibility in the grains. Three diets contained the non-extruded grains and 3 diets contained the extruded grains. The last diet was an N-free diet that was used to determine basal endogenous losses of AA from the pigs. Seven growing barrows (initial BW = 14.2 ± 0.9 kg) had a T-cannula installed in the distal ileum and were allotted to a 7 × 7 Latin square. Each experimental period lasted 7 d with the initial 5 d being the adaptation period and ileal digesta were collected on d 6 and 7 for 8 h. Results indicated that extruded grains had greater ($P < 0.001$) apparent ileal digestibility (AID) of starch than non-extruded grains. Extrusion also increased standardized ileal digestibility (SID) of CP and all AA except Pro in corn, but the SID of CP and AA in wheat and sorghum was not affected by extrusion. In Exp. 2, 6 diets were used. Three diets contained the non-extruded corn, wheat, or sorghum, and 3 diets contained the extruded grains. Forty eight growing barrows (initial BW = 15.1 ± 3.7 kg) were allotted to a randomized complete block design. Pigs were housed individually in metabolism crates and

feces and urine were collected separately for 5 d after 5 d of adaptation. The ATTD of GE was increased by extrusion of corn or sorghum, but that was not the case for wheat (interaction, $P < 0.001$). The ATTD of NDF in wheat was reduced by extrusion, but that was not the case for corn and sorghum (interaction, $P < 0.001$), but extrusion reduced ($P < 0.05$) the ATTD of ADF in all grains. Extrusion increased the digestible energy (DE) and metabolizable energy (ME) in corn and sorghum compared with non-extruded grains, but there was no increase in DE and ME when wheat was extruded (interaction, $P < 0.001$). The DE and ME in non-extruded corn was greater ($P < 0.05$) than in non-extruded sorghum and the DE and ME in extruded corn was greater ($P < 0.05$) than in extruded wheat. In conclusion, nutrient composition in grains changed after extrusion with a reduction in ADF and NDF, but the AID of starch and the ATTD of energy in all grains increased by extrusion. The SID of AA in corn and the ME of corn and sorghum were increased by extrusion.

Key words: extrusion, gelatinization, feed processing, grains, starch, swine

INTRODUCTION

Extrusion of cereal grains may be used to improve growth performance of weanling pigs (Hancock and Behnke, 2001) because the heat and pressure in combination with addition of moisture that is applied during extrusion may gelatinize the starch in the grains. Extrusion may also improve the digestibility of starch and amino acids (**AA**) in field peas (Sun et al., 2006; Stein and Bohlke, 2007), and extrusion of corn in combination with other ingredients improves energy and AA digestibility (Liu et al., 2015; Rojas et al., 2016). Extrusion of mixed diets may also increase the concentration of digestible energy (**DE**) and of metabolizable energy (**ME**) and the response seems to be more pronounced in high fiber diets than in low fiber diets indicating that extrusion may increase the solubility of dietary fiber (Rojas et al., 2016).

Although cereal grains generally have low concentrations of dietary fiber it is possible that if extrusion results in increased digestibility of starch or AA, the digestibility of energy may also increase, but data to verify this hypothesis have not been published. Therefore, the objective of these experiments was to test the hypothesis that the ileal digestibility of AA and starch, and the apparent total tract digestibility (**ATTD**) of ADF, NDF, and GE as well as the DE and ME in corn, wheat, and sorghum may be increased by extrusion.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocol for 2 experiments. Pigs were the offspring of Line 359 boars and Camborough females (Pig Improvement Company, Hendersonville, TN).

One source of yellow dent corn, one source of wheat, and one source of sorghum were ground to approximately 500 microns and divided into 2 batches. One batch of each grain was used without further processing, whereas the other batch was extruded (Table 5.1). Therefore, a total of 6 batches of grain were used. Grinding and extrusion of the grains took place at Kansas State University, Manhattan, KS. Both batches of each grain were transported to the University of Illinois where diets for both experiments were prepared.

Exp. 1. Ileal Digestibility of Starch and Amino Acids

Diets and Animals. Seven diets were formulated (Tables, 5.2 and 5.3). Three diets contained the non-extruded corn, wheat, or sorghum and 3 additional diets contained the extruded grains. The last diet was an N-free diet that was used to determine endogenous losses of

AA from the pigs. Vitamins and minerals were included in all diets to meet or exceed current requirement estimates (NRC, 2012). All diets also contained 0.40% chromic oxide as an indigestible marker.

Seven growing barrows (initial BW = 14.2 ± 0.9 kg) were equipped with a T-cannula in the distal ileum (Stein et al., 1998) and allotted to a 7 × 7 Latin square design with 7 diets and 7 replicate pigs in each period. Therefore, there were 7 observations per treatment.

Housing, Feeding, and Sample Collection. Pigs were housed in individual pens (1.2 × 1.5 m) in an environmentally controlled room. Pens had smooth sides and fully slatted T-bar floors. Each pen was equipped with a feeder and a nipple drinker. Pigs were fed their diets in an amount equivalent to 3.4 times the maintenance energy requirement (i.e., 197 kcal per kg $BW^{0.6}$; NRC, 2012) and water was available at all times. Pig weights were recorded at the beginning of each period and at the conclusion of the experiment. An AA mixture was provided to all pigs during the initial 5 d of each period, but not on d 6 and 7 (Table 5.4). The initial 5 d of each period was considered the adaptation period to the diet, but ileal digesta were collected for 8 h on d 6 and 7 using standard procedures (Stein et al., 1998). In short, a plastic bag was attached to the cannula barrel and digesta flowing into the bag were collected. Bags were removed whenever filled or at least once every 30 min. Digesta sample was immediately frozen at -20^{o}C to prevent bacterial degradation of AA in the digesta. On the completion of one experimental period, animals were deprived of feed overnight and the following morning, a new experimental diet was offered.

Chemical Analysis. At the conclusion of the experiment, ileal digesta samples were thawed and mixed within animal and diet, and a sub-sample was collected for analysis. Digesta samples were lyophilized and finely ground. A sample of each source of grain and of each diet was collected at the time of diet mixing. All samples including each source of grain, diets, and ileal digesta were analyzed for dry matter (**DM**; method 930.15; AOAC Int., 2007) and crude protein (**CP**; method 990.03; AOAC Int., 2007). Amino acids were analyzed by ion-exchange chromatography with ninhydrin used for postcolumn derivatization. Methionine and Cys were analyzed after oxidation with performic acid, which was neutralized with Na metabisulfite (Llames and Fontaine, 1994; Directive, 1998). Samples were hydrolyzed with 6*N* HCl for 24 h at 110°C and AA were quantified using the internal standard by measuring the absorption of reaction products with ninhydrin at 570 nm. Tryptophan was determined by HPLC with fluorescence detection (extinction 280 nm and emission 356 nm) after alkaline hydrolysis with barium hydroxide octahydrate for 20 h at 110°C (Directive, 2000). The chromium concentration in the 7 diets and all ileal digesta samples was determined using Inductive Coupled Plasma Atomic Emission Spectrometry (method 990.08; AOAC Int., 2007). Samples were prepared using nitric acid-perchloric acid (method 968.08D(b); AOAC Int., 2007). All samples of diets, the 6 sources of cereal grains, and ileal digesta samples from pigs fed the 6 cereal-containing diets (but not digesta from pigs fed the N-free diet) were also analyzed for starch, using the glucoamylase procedure (method 979.10; AOAC Int., 2007). The cereal grains were also analyzed for ash (method 942.05; AOAC Int., 2007), and ADF and NDF were analyzed using Ankom Technology method 12 and 13, respectively (Ankom 2000 Fiber Analyzer, Ankom Technology, Macedon, NY). Sorghum was analyzed for tannic acid as described by Taylor et al. (2007).

Calculations and Statistical Analysis. Apparent ileal digestibility values for AA in each cereal grain were calculated using equation [1]:

$$\mathrm{AID_{AA}}, \% = 100 - [\left(\frac{\mathrm{AA_{digesta}}}{\mathrm{AA_{feed}}}\right) \times \left(\frac{\mathrm{Cr_{feed}}}{\mathrm{Cr_{digesta}}}\right)] \times 100 \qquad \textbf{[1]}$$

where AID_{AA} is the apparent ileal digestibility of an AA (%), $AA_{digesta}$ is the concentration of that AA in the ileal digesta DM, AA_{feed} is the AA concentration of that AA in the feed DM, Cr_{feed} is the Cr concentration in the feed DM, and $Cr_{digesta}$ is the Cr concentration in the ileal digesta DM. The AID for CP and starch were also calculated using this equation.

The basal endogenous flow to the distal ileum of each AA were determined based on the flow obtained after feeding the N-free diet using equation [2] (Stein et al., 2007):

$$\mathrm{IAA_{end}} = [\mathrm{AA_{digesta}} \times \left(\frac{\mathrm{Cr_{feed}}}{\mathrm{Cr_{digesta}}}\right)] \qquad \textbf{[2]}$$

where IAA_{end} is the basal ileal endogenous loss of an AA (mg per kg DM intake). The basal ileal endogenous loss of CP was determined using the same equation.

By correcting the AID for the IAA_{end} of each AA, SID values of AA were calculated using equation [3] (Stein et al., 2007):

$$\mathrm{SID_{AA}} = [\frac{\mathrm{AID+IAA_{end}}}{\mathrm{AA_{feed}}}] \qquad \textbf{[3]}$$

where SID_{AA} is the SID value (%) of each AA. The SID for CP was also calculated using the same equation.

Data were analyzed to verify normal distribution using PROC UNIVARIETE of SAS (SAS Institute Inc., Cary, NC) and 4 outliers were identified and removed from the original data using the PROC BOXPLOT of SAS. Data were analyzed using the PROC MIXED of SAS. The model included source of grain, processing, and the interaction between source of grain and processing as main effects and pig and period as random effects. Least squares means were calculated and means were separated using the PDIFF statement with Tukey's adjustment. Results were considered significant at $P \leq 0.05$ and considered a trend at $P \leq 0.10$.

Exp. 2. Digestibility of Fiber and Energy and Energy Concentrations

Animals, Housings, and Diets. Forty eight growing barrows (initial BW = 15.1 ± 3.7 kg) were allotted to a randomized complete block design with 2 blocks of 24 pigs, 6 diets, and 4 pigs per diet in each block, for a total of 8 replicate pigs per diet. Pigs were placed in individual metabolism crates that were equipped with a self-feeder, a nipple drinker, a slatted floor and a urine tray to allow for the total, but separate, collection of urine and fecal materials. Three diets that contained the non-extruded corn, wheat, or sorghum, and 3 diets that contained the extruded grains were formulated (Table 5.5). Vitamins and minerals were included in all diets to meet or exceed the estimated nutrient requirements for growing pigs (NRC, 2012).

Feeding and Sample Collection. Pigs were fed at 3.2 times the energy requirement for maintenance (i.e., 197 kcal/kg × $BW^{0.60}$; NRC, 2012), and feed was provided each day in 2 equal meals at 0700 and 1500 h. Throughout the study, pigs had free access to water. Feed consumption was recorded daily and diets were fed for 12 d. The initial 5 d were considered the adaptation period to the diet, whereas urine and fecal materials were collected from the feed provided during the following 5 d according to standard procedures using the marker to marker approach (Adeola, 2001). Urine was collected in buckets over a preservative of 50 ml of 6*N* HCl. Fecal samples and 20% of the collected urine were stored at -20°C immediately after collection.

Chemical Analysis. At the conclusion of the experiment, urine samples were thawed and mixed within animal and diet, and a sub-sample was lyophilized before analysis. Fecal samples were thawed and mixed within pig and diet, and then dried in a 50°C forced air drying oven prior to analysis.

Fecal samples were ground through a 1-mm screen using a Wiley mill (Model 4; Thomas Scientific, Swedesboro, NJ). Urine samples were also mixed and a subsample was dripped onto cotton balls that were placed in a plastic bag and lyophilized (Kim et al., 2009). Diets, ingredients, ground fecal samples, and lyophilized urine samples were analyzed for GE using bomb calorimetry (Model 6400; Parr Instruments, Moline, IL). Diets, ingredients, and fecal samples were also analyzed for DM, CP, ADF, and NDF.

Calculations and Statistical Analysis. Following analysis, ATTD of GE, ADF, and NDF was calculated for each diet and the DE and ME in each diet were calculated as well (NRC, 2012). By dividing the DE and ME of each diet by the inclusion rate of the cereal grain in the diet, the DE and ME in both extruded and non-extruded corn, sorghum, and wheat were calculated.

Data were analyzed as a randomized complete block design with the pig as the experimental unit using the PROC MIXED of SAS (SAS Institute Inc., Cary, NC). Normality of data was confirmed using the PROC UNIVARIATE of SAS. Grain source (corn, wheat, or sorghum), processing (extruded or non-extruded), and the interaction between grain source and processing were the fixed effects, and pig, block, and replicate within block were random effects. Least squares means were calculated and separated using the PDIFF statement with Tukey's adjustment in PROC MIXED. Results were considered significant at $P \leq 0.05$ and considered a trend at $P \leq 0.10$.

RESULTS

All pigs remained healthy and consumed their diets with little feed refusals during both experiments.

Exp. 1. Ileal Digestibility of Starch and Amino Acids

There was no interaction between source of grain and processing for the AID of starch (Table 5.6). However, the extruded grains had greater ($P < 0.001$) AID of starch than non-extruded grains. The AID of CP and AA in wheat and sorghum was not affected by extrusion, but extruded corn had greater AID of CP and all AA except Pro than non-extruded corn (interaction, $P < 0.05$). For some, but not all AA, wheat had greater ($P < 0.05$) AID than corn and sorghum, whereas only a few differences between corn and sorghum were observed.

The SID of CP in corn was increased by extrusion, but that was not the case for wheat and sorghum (interaction, $P < 0.01$; Table 5.7). The SID of AA in wheat and sorghum was not affected by extrusion, but extruded corn had greater SID of all AA except Pro compared with non-extruded corn (interaction, $P < 0.05$). The SID of Ile, Phe, Cys, and Glu in wheat was greater ($P < 0.05$) compared with values in corn and sorghum.

Exp. 2. Digestibility of Fiber and Energy and Energy Concentrations

There were no differences among grains for feed intake and GE intake (Table 5.8). The intake of NDF decreased ($P < 0.05$) if pigs were fed extruded grains compared with non-extruded grains. The intake of ADF was reduced by extrusion of sorghum, but extrusion did not affect ADF intake if pigs were fed corn or wheat (interaction, $P < 0.05$).

Pigs fed the diet containing extruded sorghum had reduced fecal GE compared with pigs fed the diet containing non-extruded sorghum, but the fecal GE was not affected by extrusion of corn or wheat (interaction, $P < 0.05$). There was no interaction between the source of grain and extrusion of ingredients for fecal NDF output, but the effect of extrusion on fecal output of ADF was different among grains (interaction, $P < 0.05$). However, there were no interactions between the source of grain and extrusion for total urine output and urinary output of GE. The ATTD of

GE was increased by extrusion of corn or sorghum, but that was not the case for wheat (interaction, $P < 0.001$). The ATTD of NDF in diets containing wheat was reduced by extrusion, but the ATTD of NDF in corn and sorghum was not affected by extrusion (interaction, $P < 0.001$). Extrusion reduced ($P < 0.05$) the ATTD of ADF in all grains. The DE and ME in all diets containing the 3 sources of extruded grain were improved compared with the non-extruded grain, but the increase was greater for diets containing sorghum than for the wheat or corn diets (interaction, $P < 0.001$).

Extrusion also increased the DE and ME in corn and sorghum compared with non-extruded grains, but there was no increase in DE and ME when wheat was extruded (interaction, $P < 0.001$; Table 5.9). The DE in non-extruded corn was greater ($P < 0.05$) than in non-extruded sorghum and the DE in extruded corn was greater ($P < 0.05$) than in extruded wheat. Likewise, the ME in non-extruded corn was greater ($P < 0.05$) than in non-extruded wheat and sorghum and the ME in extruded corn was greater ($P < 0.05$) than in extruded wheat.

DISCUSSION

Effects of Extrusion on Nutrient Composition of Grains

Concentrations of CP, AA, fiber components, AEE, and GE in the un-extruded corn, wheat, and sorghum were generally in agreement with reported values (Sauvant et al., 2004; NRC, 2012; Stein et al., 2016). Starch concentrations in corn and wheat were also within the range of reported values (NRC, 2012; Stein et al., 2016), but the starch in sorghum was about 10% units less than previously reported (NRC, 2012; Stein et al., 2016). It is not clear why the sorghum used in this experiment contained less starch compared with sorghum used in previous studies.

The increased DM in the extruded cereal grains compared with the un-extruded grains is likely a result of the thermal processing and the subsequent drying that is used in extrusion (Hancock and Behnke, 2001). There was also an increase in DM if feed ingredients or diets containing multiple feed ingredients were extruded (Skoch et al., 1983; Rojas et al., 2016). In contrast, extrusion reduced NDF and ADF in all the grains, indicating that some of the NDF or ADF in the original grains may have become solubilized during extrusion.

Any thermal treatment of feed ingredients may result in heat damage of proteins and subsequently reduction in the concentration of Lys (Fontaine et al., 2007; Rutherfurd and Moughan, 2007; Pahm et al., 2008). However, the observation that the concentration of Lys, both as analyzed and as a percentage of CP did not change after extrusion indicates that proteins were not damaged during extrusion because heat damage results in a reduction in Lys as a percentage of CP (Stein et al., 2009; González-Vega et al., 2011).

Effects of Extrusion on Digestibility of Amino Acids and Starch

Values for the SID of AA in un-extruded corn and wheat were within the range pf reported values (Stein et al., 2006; Widyaratne and Zijlstra, 2007; NRC, 2012) and that was also the case for the SID of AA in sorghum (NRC, 2012; Stein et al., 2016).

When grains are processed with appropriate moisture, pressure, and heat during extrusion, the shape of grain particles are destroyed and more nutrients can be accessed by digestive enzymes (Amornthewaphat and Attamangkune, 2008; NRC, 2012). Therefore, the change in anatomy of the grains during extrusion may increase digestibility of AA, fiber, and energy. The observed increase in the AID of starch in corn, wheat, and sorghum indicates that extrusion improves small intestinal starch absorption, which is in agreement with results observed for field peas and mixed diets (Stein and Bohlke, 2007; Rojas et al., 2016). This increase is most likely a result of the observed increase in gelatinization of starch, which is a process in which the intermolecular bonds in the starch granule are broken, and thus allowing more space between molecules to hold water (Ai, 2013). Therefore, gelatinized starch is more available for intestinal enzymes. The concentration of gelatinized starch in corn may increase by more than 3 fold during extrusion, but total starch concentration does not change (Veum et al., 2017). Extrusion also increased rapidly digestible starch and decreased resistant starch in barley, field peas, and in a diet containing potato starch and wheat bran, which resulted in increased AID of starch by pigs (Sun et al., 2006). Thus, increased gelatinization of starch is the most likely reason for the increased AID of starch that was observed in the extruded grains compared with the non-extruded grains.

The increase in the AID and SID of AA that was observed as corn was extruded is in agreement with data from experiments where the AID of AA was increased by extrusion of feed ingredients or complete diets (Chae et al., 1997; Stein and Bohlke, 2007; Htoo et al., 2008; Rojas et al., 2016). The reason for this increase may be that heat from extrusion changes the 3-dimensional structure of protein, and thus increases access of digestive enzymes to the peptide bonds (Duodu et al., 2003). However, it is not clear why this effect was observed only in corn and not in wheat and sorghum.

Effects of Extrusion on ATTD of NDF and ADF

Values for the ATTD of NDF and ADF in non-extruded that were obtained in the present experiment were comparable with values observed previously (Herkelman et al., 1990; Navarro et al., 2018) but the extruded corn had greater ATTD of NDF compared with previous data (Herkelman et al., 1990). To our knowledge, effects of extrusion on the ATTD of NDF and ADF in wheat and sorghum have not been reported.

The interaction that was observed for the ATTD of NDF was a result of reduced ATTD in corn and increased ATTD of NDF in sorghum. The reduced ATTD of NDF in extruded corn indicates that the lower concentrations of NDF and ADF in extruded corn compared with non-extruded corn most likely is a result of the most fermentable parts of the fiber in the grains being solubilized during extrusion. This likely left the most insoluble fiber in the extruded grains, which resulted in reduced fermentation by the pigs. The increased ATTD of NDF in sorghum after extrusion may have been a result of changes in the tannins in sorghum. Procyanidins in sorghum, one of the tannins, easily bind to fiber, protein, and minerals, and there is a negative correlation between procyanidins concentrations and ATTD of NDF in birds (Reed, 1987). However, by extrusion, the procyanidins may be depolymerized, which results in degradation of the bond between procyanidins and fiber (Gu et al., 2008) with a subsequent increase in the ATTD of NDF. However, extrusion did not reduce the total amount of tannin in sorghum indicating that even if the procyanidins were depolymerized they were analyzed as tannins.

Effects of Extrusion on ATTD of Energy and DE and ME

The ATTD of GE and DE and ME in non-extruded corn and wheat were within the range of reported values, but the ATTD of GE and DE and ME in non-extruded sorghum were less than values previously observed (Sauvant et al., 2004; NRC, 2012; Stein et al., 2016), which may be a result of the lower starch concentration in the sorghum used in this experiment. The DE and ME in extruded corn (Herkelman et al., 1990; Liu et al., 2016) and in extruded wheat were also within the range of published values (Barneveld et al., 2005). In contrast, the DE in extruded sorghum that was obtained in this experiment was greater than values reported by Barneveld et al. (2005).

The observation that the ATTD of GE and DE and ME increased if corn or sorghum was extruded is in agreement with observations indicating that the ATTD of GE in corn, wheat, and sorghum and DE or ME in field peas and soybean meal increased by extrusion (Marty and Chavez, 1993; Stein and Bohlke, 2007; Rodrigues et al., 2016). The increased ME is likely a result of the increased AID of starch and AA that were observed in Exp. 1 and possibly greater solubilization of fiber. The ATTD of NDF and ADF in wheat were less compared with corn and sorghum, but it is not clear if that is the reason for a lack of response to extrusion in wheat. It is also possible that because wheat had the greatest AID of starch among the un-extruded grains, the increase in AID of starch that was observed as a consequence of extrusion was not large enough to significantly increase ME of the extruded wheat.

CONCLUSION

Nutrient composition in grains changed after extrusion with a reduction in ADF and NDF. Extrusion increased AID of starch and the SID of AA in corn, wheat, and sorghum fed to growing pigs, and as a result, the ATTD of energy was also increased by extrusion. The ME of corn and sorghum was also increased by extrusion, but that was not the case for wheat.

TABLES

Table 5.1. Chemical composition of non-extruded and extruded cereal grains[1]

Item, %	Corn		Wheat		Sorghum	
Extruded	-	+	-	+	-	+
Dry matter	88.69	91.08	88.62	90.67	88.23	91.07
Gross energy, kcal/kg	3,838	3,905	3,837	3,848	3,813	3,913
Acid-hydrolyzed ether extract	3.41	3.74	2.01	2.57	3.13	3.73
Ash	1.23	1.11	1.60	1.68	1.15	1.21
Neutral detergent fiber	8.61	6.37	11.78	9.89	8.36	6.18
Acid detergent fiber	2.77	1.93	3.67	3.16	3.65	2.37
Tannic acid, %	-	-	-	-	0.16	0.15
Total starch	59.07	66.91	54.75	58.48	59.23	63.97
Gelatinized starch	6.04	60.73	6.75	54.68	6.34	56.38
Gelatinized starch, % of total	10.22	90.76	12.33	93.50	10.71	88.13
Crude protein	7.80	7.60	13.31	13.44	9.49	9.27
Lys to crude protein, %	3.21	3.21	2.70	2.75	2.11	2.05
Indispensable amino acids						
Arg	0.36	0.37	0.63	0.64	0.34	0.31
His	0.21	0.21	0.30	0.30	0.20	0.18
Ile	0.26	0.25	0.45	0.45	0.35	0.31
Leu	0.86	0.84	0.85	0.85	1.20	1.00
Lys	0.25	0.25	0.36	0.37	0.20	0.19
Met	0.18	0.16	0.21	0.20	0.16	0.14

Table 5.1. (Cont.)

Phe	0.35	0.37	0.60	0.60	0.45	0.42
Thr	0.28	0.27	0.37	0.37	0.29	0.26
Trp	0.06	0.06	0.16	0.16	0.10	0.09
Val	0.36	0.35	0.56	0.55	0.45	0.40
Total	3.16	3.12	4.48	4.49	3.74	3.30
Dispensable amino acids						
Ala	0.55	0.53	0.45	0.47	0.84	0.70
Asp	0.53	0.52	0.65	0.67	0.60	0.53
Cys	0.16	0.16	0.30	0.29	0.17	0.15
Glu	1.38	1.33	3.68	3.63	1.91	1.61
Gly	0.30	0.30	0.53	0.53	0.29	0.27
Pro	0.61	0.61	1.31	1.30	0.79	0.65
Ser	0.36	0.35	0.59	0.58	0.40	0.36
Total	3.87	3.80	7.51	7.46	4.98	4.27

[1]All values except DM were adjusted to 88% DM.

Table 5.2. Composition of experimental diets (as-is basis, Exp. 1)

Item	Corn		Wheat		Sorghum		N-free
Extruded	-	+	-	+	-	+	-
Grain	93.50	93.50	93.85	93.85	93.55	93.55	-
Soybean oil	3.00	3.00	3.00	3.00	3.00	3.00	4.00
Solka floc	-	-	-	-	-	-	4.00
Dicalcium phosphate	1.60	1.60	0.80	0.80	1.50	1.50	2.15
Limestone	0.80	0.80	1.25	1.25	0.85	0.85	0.45
Cornstarch	-	-	-	-	-	-	52.80
Lactose	-	-	-	-	-	-	20.00
Sucrose	-	-	-	-	-	-	15.00
Chromic oxide	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Magnesium oxide	-	-	-	-	-	-	0.10
Potassium carbonate	-	-	-	-	-	-	0.40
Sodium cloride	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
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00

[1]The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kg of complete diet: vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 as cholecalciferol, 2,208 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 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, 44.1 mg; folic acid, 1.59 mg; biotin,

Table 5.2. (Cont.)

0.44 mg; Cu, 20 mg as copper sulfate and copper chloride; Fe, 126 mg as ferrous sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese sulfate; Se, 0.3 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc sulfate.

Table 5.3. Chemical compositions of experimental diets[1] (Exp. 1)

Item	Corn		Wheat		Sorghum		N-free
Extruded	-	+	-	+	-	+	-
Dry matter	89.66	91.48	89.50	90.94	89.10	91.45	93.54
Starch	54.66	55.15	53.29	51.95	54.93	63.80	44.56
Crude protein	7.13	7.21	12.30	12.26	8.90	7.62	0.90
Indispensable amino acids							
Arg	0.34	0.35	0.59	0.59	0.33	0.30	0.01
His	0.20	0.19	0.28	0.27	0.19	0.17	0.01
Ile	0.25	0.24	0.41	0.41	0.34	0.29	0.01
Leu	0.82	0.81	0.80	0.80	1.15	0.94	0.02
Lys	0.24	0.23	0.32	0.34	0.18	0.17	0.02
Met	0.17	0.15	0.19	0.18	0.15	0.13	0.01
Phe	0.36	0.36	0.57	0.56	0.46	0.38	0.02
Thr	0.27	0.25	0.34	0.35	0.28	0.24	0.01
Trp	0.06	0.06	0.15	0.15	0.10	0.09	0.02
Val	0.33	0.33	0.52	0.51	0.42	0.38	0.02
Dispensable amino acids							
Ala	0.51	0.51	0.42	0.44	0.79	0.65	0.01
Asp	0.51	0.50	0.61	0.62	0.57	0.50	0.01
Cys	0.16	0.15	0.28	0.27	0.16	0.14	0.01
Glu	1.33	1.27	3.42	3.38	1.81	1.52	0.03
Gly	0.28	0.28	0.49	0.49	0.28	0.26	0.01

Table 5.3. (Cont.)

Pro	0.61	0.59	1.16	1.10	0.71	0.62	0.01
Ser	0.35	0.34	0.54	0.54	0.39	0.34	0.01

[1]All values except DM were adjusted to 88% DM.

Table 5.4. Composition of amino acids mixture[1] (Exp. 1)

Amino acid	%
Gly	57.92
L-His	2.12
L-Ile	4.25
L-Lys·HCl	13.51
DL-Met	4.44
L-Phe	5.79
L-Thr	5.79
L-Trp	1.35
L-Val	4.83
Total	100.00

[1]One hundred grams of the mixture were fed daily to each pig during adaptation periods.

Table 5.5. Ingredient composition and analyzed nutrient composition of experimental diets (Exp. 2)

Item, %	Corn		Wheat		Sorghum	
Extruded	-	+	-	+	-	+
Ingredient composition, as-fed basis						
Grain	96.90	96.90	97.25	97.25	96.95	96.95
Dicalcium phosphate	1.60	1.60	0.80	0.80	1.50	1.50
Ground limestone	0.80	0.80	1.25	1.25	0.85	0.85
Sodium chloride	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
Total	100.00	100.00	100.00	100.00	100.00	100.00
Analyzed nutrient composition, 88% dry matter basis						
Dry matter	87.87	91.10	88.04	90.14	86.64	91.44
Gross energy, kcal/kg	3,746	3,789	3,731	3,764	3,792	3,747
Crude protein	7.45	7.95	12.95	13.35	9.20	8.39
Neutral detergent fiber	9.27	6.96	10.40	8.02	8.43	6.53
Acid detergent fiber	2.23	1.54	2.44	2.05	3.24	1.70

[1]The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kg of complete diet: vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 as cholecalciferol, 2,208 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 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, 44.1 mg; folic acid, 1.59 mg; biotin,

Table 5.5. (Cont.)

0.44 mg; Cu, 20 mg as copper sulfate and copper chloride; Fe, 126 mg as ferrous sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese sulfate; Se, 0.3 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc sulfate.

Table 5.6. Apparent ileal digestibility of starch, crude protein (CP), and amino acids (AA) in non-extruded and extruded cereal grains fed to growing pigs (Exp. 1)

Item, %	Corn		Wheat		Sorghum		SEM	*P*-value		
Extruded	-	+	-	+	-	+		Grain	Extrusion	Grain × extrusion
Starch	90.7	99.2	94.1	98.8	93.2	99.0	1.3	0.419	< 0.001	0.277
CP	55.5^{c}	75.8^{ab}	76.5^{ab}	80.9^{a}	66.8^{b}	69.7^{b}	2.5	< 0.001	< 0.001	0.003
Indispensable AA										
Arg	70.2^{c}	84.3^{a}	79.3^{abc}	80.8^{ab}	71.7^{bc}	75.1^{abc}	2.4	0.037	0.003	0.027
His	72.7^{b}	82.2^{a}	81.0^{a}	82.6^{a}	69.4^{b}	68.4^{b}	1.6	< 0.001	0.013	0.006
Ile	66.0^{c}	80.7^{ab}	79.2^{ab}	83.7^{a}	73.8^{b}	75.6^{b}	1.7	< 0.001	< 0.001	0.002
Leu	77.7^{c}	87.8^{a}	81.0^{bc}	84.9^{ab}	80.9^{bc}	81.9^{bc}	1.3	0.454	< 0.001	0.005
Lys	60.0	77.5	69.4	74.2	58.8	67.7	2.9	0.018	< 0.001	0.059
Met	81.1^{c}	89.7^{a}	82.7^{bc}	86.5^{ab}	79.3^{c}	81.5^{c}	1.2	0.001	< 0.001	0.025
Phe	76.8^{d}	86.5^{ab}	85.0^{abc}	87.6^{a}	80.4^{cd}	81.3^{bcd}	1.3	0.001	< 0.001	0.006
Thr	49.8^{c}	65.7^{ab}	64.4^{ab}	71.6^{a}	58.3^{bc}	59.4^{bc}	2.7	0.001	0.001	0.035
Trp	43.6^{c}	60.6^{b}	74.0^{a}	78.2^{a}	67.0^{ab}	66.2^{ab}	2.9	< 0.001	0.007	0.014

Table 5.6. (Cont.)

Val	65.0^{c}	78.5^{ab}	76.1^{ab}	80.2^{a}	72.2^{bc}	73.1^{ab}	1.8	0.004	0.001	0.006
Total	69.8^{c}	82.1^{a}	78.0^{ab}	81.7^{a}	74.4^{bc}	75.8^{abc}	1.7	0.017	< 0.001	0.006
Dispensable AA										
Ala	70.4^{cd}	84.0^{a}	67.5^{d}	73.9^{bcd}	77.8^{abc}	79.1^{ab}	1.9	0.001	< 0.001	0.009
Asp	63.3^{b}	78.2^{a}	68.9^{ab}	73.6^{a}	69.6^{ab}	71.9^{ab}	2.1	0.958	< 0.001	0.013
Cys	65.2^{b}	76.0^{a}	82.4^{a}	83.5^{a}	66.6^{b}	64.5^{b}	1.9	< 0.001	0.046	0.008
Glu	76.6^{e}	87.6^{bc}	91.0^{ab}	93.2^{a}	80.1^{de}	82.2^{cd}	1.3	< 0.001	< 0.001	0.001
Gly	28.9^{c}	55.1^{ab}	61.2^{a}	64.0^{a}	34.0^{bc}	33.0^{bc}	5.5	< 0.001	0.045	0.038
Pro	28.4	71.8	81.8	86.8	52.0	53.3	12.0	0.012	0.088	0.138
Ser	63.8^{d}	77.1^{abc}	78.8^{ab}	81.6^{a}	69.4^{cd}	70.6^{bcd}	1.9	< 0.001	0.001	0.007
Total	60.8^{c}	79.5^{ab}	83.0^{ab}	85.8^{a}	69.7^{bc}	71.9^{bc}	3.0	< 0.001	0.003	0.012

$^{a\text{-}e}$Within a row, means without a common superscript differ ($P < 0.05$).

Table 5.7. Standardized ileal digestibility (SID) of crude protein (CP), and amino acids (AA) in non-extruded and extruded cereal grains fed to growing pigs[1] (Exp. 1)

Item, %	Corn		Wheat		Sorghum		SEM	*P*-value		
Extruded	-	+	-	+	-	+		Grain	Extrusion	Grain × Extrusion
CP	74.8^{c}	94.9^{a}	87.7^{ab}	92.1^{ab}	82.2^{bc}	87.7^{ab}	2.5	0.094	< 0.001	0.007
Indispensable AA										
Arg	83.0^{b}	97.1^{a}	86.8^{ab}	88.2^{ab}	85.4^{b}	89.8^{ab}	2.4	0.504	0.002	0.031
His	79.5^{bc}	89.1^{a}	86.0^{ab}	87.5^{a}	76.6^{c}	76.2^{c}	1.6	< 0.001	0.009	0.008
Ile	73.4^{c}	88.2^{a}	83.6^{ab}	88.2^{a}	79.2^{bc}	82.0^{ab}	1.7	0.006	< 0.001	0.003
Leu	81.4^{c}	91.7^{a}	84.9^{bc}	88.8^{ab}	83.6^{bc}	85.1^{bc}	1.3	0.154	< 0.001	0.007
Lys	67.4	84.9	74.7	79.4	68.6	77.6	2.9	0.341	< 0.001	0.056
Met	84.0^{c}	92.9^{a}	85.4^{bc}	89.2^{ab}	82.5^{c}	85.1^{bc}	1.2	0.002	< 0.001	0.025
Phe	80.5^{c}	90.3^{a}	87.3^{ab}	90.0^{a}	83.3^{bc}	84.7^{abc}	1.3	0.006	< 0.001	0.007
Thr	66.4^{b}	83.2^{a}	77.3^{ab}	84.4^{a}	74.4^{ab}	77.5^{ab}	2.7	0.067	< 0.001	0.048
Trp	61.2^{b}	78.0^{a}	80.7^{a}	84.8^{a}	77.3^{a}	77.7^{a}	2.9	< 0.001	0.006	0.021
Val	73.5^{b}	87.1^{a}	81.6^{a}	85.7^{a}	78.9^{ab}	80.7^{ab}	1.8	0.091	< 0.001	0.008

Table 5.7. (Cont.)

Total	77.2^{c}	89.7^{a}	83.4^{abc}	87.1^{ab}	80.7^{bc}	83.0^{abc}	1.7	0.145	< 0.001	0.008
Dispensable AA										
Ala	77.9^{b}	91.6^{a}	76.5^{b}	82.7^{b}	82.6^{b}	85.0^{ab}	1.9	0.020	< 0.001	0.015
Asp	74.0^{c}	89.1^{a}	77.7^{bc}	82.3^{ab}	79.0^{bc}	82.6^{abc}	2.1	0.767	< 0.001	0.018
Cys	75.7^{b}	86.6^{a}	88.2^{a}	89.5^{a}	76.9^{b}	75.6^{b}	1.9	< 0.001	0.029	0.010
Glu	81.4^{b}	92.6^{a}	92.9^{a}	95.1^{a}	83.6^{b}	86.4^{b}	1.3	< 0.001	< 0.001	0.002
Gly	79.0^{b}	105.9^{a}	90.2^{ab}	93.1^{ab}	86.7^{ab}	88.7^{ab}	5.5	0.666	0.025	0.047
Pro	119.8	166.9	129.7	137.3	130.4	143.5	12.0	0.655	0.025	0.177
Ser	77.1^{c}	90.9^{a}	87.3^{ab}	90.1^{a}	81.4^{bc}	84.4^{abc}	1.9	0.011	< 0.001	0.009
Total	85.3^{c}	104.8^{a}	96.2^{abc}	99.2^{ab}	89.3^{bc}	94.7^{abc}	3.0	0.179	0.001	0.017

[a-c]Within a row, means without a common superscript differ ($P < 0.05$).

[1]Values for SID were calculated by correcting the values for apparent ileal digestibility for basal ileal endogenous losses. Basal ileal endogenous losses (g/kg of dry matter intake) were determined as: CP, 15.64; Arg, 0.50; His, 0.15; Ile, 0.21; Leu, 0.35; Lys, 0.20; Met, 0.06; Phe, 0.15; Thr, 0.50; Trp, 0.11; Val, 0.32; Ala, 0.44; Asp, 0.61; Cys, 0.19; Glu, 0.72; Gly, 1.63; Pro, 6.33; and Ser, 0.52.

Table 5.8. Apparent total tract digestibility (ATTD) of nutrients and concentrations of digestible energy (DE) and metabolizable energy (ME) in diets containing non-extruded or extruded cereal grains, as-fed basis (Exp. 2)

Item[1], %	Corn		Wheat		Sorghum		SEM	*P*-value		
Extruded	-	+	-	+	-	+		Grain	Extrusion	Grain × Extrusion
Intake										
Feed intake, g/d	723	722	609	694	610	615	57	0.160	0.521	0.698
GE, kcal/d	2,705	2,832	2,274	2,677	2,276	2,395	215	0.139	0.225	0.754
NDF, g/d	67	52	63	57	51	42	5	0.009	0.016	0.669
ADF, g/d	16^{ab}	12^{bc}	15^{abc}	15^{abc}	19^{a}	11^{c}	1	0.553	< 0.001	0.007
Fecal excretion										
Dry feces output, g/d	68^{ab}	51^{ab}	67^{ab}	73^{a}	72^{ab}	46^{b}	6	0.179	0.019	0.037
GE, kcal/d	318^{ab}	214^{b}	297^{ab}	313^{ab}	348^{a}	205^{b}	28	0.373	0.002	0.019
NDF, g/d	25	23	27	31	18	12	2	< 0.001	0.650	0.084
ADF, g/d	7^{b}	7^{b}	12^{a}	14^{a}	8^{b}	5^{b}	1	< 0.001	0.626	0.031
Urinary excretion										

Table 5.8. (Cont.)

Urine output, g/d	1,462	2,883	1,955	1,898	1,103	1,772	679	0.550	0.229	0.562
GE, kcal/d	48	83	70	88	43	70	10	0.083	0.002	0.707
ATTD										
GE, %	88.2^{b}	92.4^{a}	86.9^{bc}	88.3^{b}	84.8^{c}	91.5^{a}	0.6	< 0.001	< 0.001	< 0.001
NDF, %	63.1^{bc}	55.0^{c}	58.1^{bc}	45.0^{d}	64.6^{ab}	71.2^{a}	1.9	< 0.001	0.003	< 0.001
ADF, %	55.8	42.8	20.7	4.6	60.5	51.8	2.7	< 0.001	< 0.001	0.392
Energy values, kcal/kg										
DE	$3,300^{c}$	$3,624^{a}$	$3,246^{cd}$	$3,403^{b}$	$3,167^{d}$	$3,562^{a}$	21	< 0.001	< 0.001	< 0.001
ME	$3,232^{b}$	$3,514^{a}$	$3,132^{c}$	$3,273^{b}$	$3,096^{c}$	$3,449^{a}$	24	< 0.001	< 0.001	< 0.001

[a-d]Within a row, means without a common superscript differ ($P < 0.05$).

[1]GE = gross energy; NDF = neutral detergent fiber; ADF = acid detergent fiber.

Table 5.9. Concentrations of digestible energy (DE) and metabolizable energy (ME) in non-extruded and extruded cereal grains fed to pigs (Exp. 2)

Item, kcal/kg	Corn		Wheat		Sorghum		SEM	*P*-value		
Extruded	-	+	-	+	-	+		Grain	Extrusion	Grain × Extrusion
As-fed basis										
DE	3,405[c]	3,740[a]	3,338[cd]	3,499[b]	3,267[d]	3,674[a]	22	< 0.001	< 0.001	< 0.001
ME	3,335[b]	3,626[a]	3,220[c]	3,365[b]	3,194[c]	3,557[a]	24	< 0.001	< 0.001	< 0.001
Dry matter basis										
DE	3,874[b]	4,098[a]	3,794[b]	3,848[b]	3,773[b]	4,002[a]	25	< 0.001	< 0.001	0.001
ME	3,794[bc]	3,972[a]	3,660[d]	3,701[cd]	3,689[cd]	3,875[ab]	28	< 0.001	< 0.001	0.018

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CHAPTER 6: EFFECTS OF EXTRUSION ON DIGESTIBILITY OF AMINO ACIDS AND ENERGY, AND CONCENTRATION OF DIGESTIBLE AND METABOLIZABLE ENERGY IN SOYBEAN HULLS FED TO GROWING PIGS

ABSTRACT

Two experiments were conducted to determine effects of extrusion on energy and nutrient digestibility in soybean hulls. One source of soybean hulls was ground and divided into 2 batches. One batch was used without further processing, whereas the other batch was extruded. In Exp. 1, 4 diets were formulated to determine CP and AA digestibility in soybean hulls. One diet was a soybean meal-based diet in which soybean meal provided all the CP and AA. Two diets were formulated to contain 30% non-extruded or extruded soybean hulls and 18% soybean meal. An N-free diet that was used to determine the endogenous losses of CP and AA was also formulated. Eight growing barrows (initial BW = 36.98 ± 3.86 kg) had a T-cannula installed in the distal ileum and were allotted to a replicated 4 × 4 Latin square. Each experimental period lasted 7 d with the initial 5 d being the adaptation period and ileal digesta were collected for 8h on d 6 and 7. Results indicated that extrusion of soybean hulls did not change the apparent ileal digestibility (AID) and the standardize ileal digestibility (SID) of CP and most AA with the exception that the AID of Leu, Phe, Asp, Ser, and Tyr in the non-extruded soybean hulls diet was less than in the diet with extruded soybean hulls. In Exp. 2, 3 diets were formulated to determine energy and nutrient digestibility in soybean hulls. One corn-soybean meal based basal diet, and 2 diets in which 32% of the basal diet was replaced by either extruded or non-extruded soybean hulls were formulated. Twenty four growing barrows (initial BW = 59.88 ± 3.37 kg) were allotted to a randomized complete block design. Pigs were housed individually in metabolism crates and feces and urine were collected separately for 4 d after 5 d of adaptation. The ATTD of GE, DE, and ME were reduced (P < 0.05) in diets containing non-extruded or extruded soybean hulls compared with the basal diet. However, the ATTD of GE and values for DE and ME in soybean hulls were not improved by extrusion. Likewise, extrusion did not change the concentration of total dietary fiber in soybean hulls. In conclusion, there were no effects of extrusion on AID and SID of AA, energy digestibility, and ME concentration in soybean hulls.

Key words: extrusion, feed processing, fiber, soybean hulls, swine

INTRODUCTION

Extrusion is commonly used as a technology in the feed industry because it may increase the nutritional value of feed ingredients (Liu et al., 2015; Rojas et al., 2016). The use of a combination of heat, pressure, and moisture that is applied to the feed during extrusion may gelatinize the starch, and improve the apparent ileal digestibility **(AID)** of starch in feed ingredients (Sun et al., 2006; Stein and Bohlke, 2007; Rodriguez et al., 2019). Extrusion may also increase the apparent total tract digestibility (**ATTD**) of energy in high fiber diets (Rojas et al., 2016), indicating that the increase in energy digestibility may be caused not only by increased starch digestibility but also by solubilization of fiber. Extrusion of cereal grains may increase concentration of metabolizable energy **(ME)** in corn, wheat, and sorghum (Rodriguez et al., 2019).

Soybean hulls is not an ingredient that is commonly used in swine diets, because the high content of fiber results in low energy digestibility, but if extrusion increases energy release from fiber, it is possible that soybean hulls can be used in diets for pigs. There are, however, no data to demonstrate the effects of extruding soybean hulls on energy and nutrient utilization when fed to pigs. Therefore, the objectives of these experiments were to test the hypothesis that standardized ileal digestibility (**SID**) of AA and the apparent total tract digestibility (**ATTD**) of GE and concentrations of DE and ME in soybean hulls may be increased by extrusion.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocol for 2 experiments. Pigs were the offspring of Line 359 boars and Camborough females (Pig Improvement Company, Hendersonville, TN). One source of soybean hulls was ground and divided into 2 batches. One batch was used without further processing, whereas the other batch was extruded (Table 6.1).

Exp. 1. Ileal Digestibility of Amino Acids

Diets, Animals, and Housing. Four diets were formulated (Tables 6.2 and 6.3). One diet was a soybean meal-based diet in which soybean meal provided all the CP and AA. Two diets were formulated to contain 30% non-extruded or extruded soybean hulls and 18% soybean meal. An N-free diet that was used to determine the endogenous losses of CP and AA was also formulated. All diets contained vitamins and minerals to meet or exceed current requirement estimates (NRC, 2012). All diets also contained 0.40% chromic oxide as an indigestible marker. Eight growing barrows (initial BW = 36.98 ± 3.86 kg) were equipped with a T-cannula in the distal ileum (Stein et al., 1998) and allotted to a replicated 4 × 4 Latin square design with 4 diets and 4 periods. There were 2 pigs per diet in each period and for a total of 8 observations per treatment. Pigs were housed in individual pens (1.2 × 1.5 m) in an environmentally controlled room. Pens had smooth sides and fully slatted T-bar floors. Each pen was equipped with a feeder and a nipple drinker.

Feeding and Sample Collection. Pigs were fed diets in an amount equivalent to 3 times the maintenance energy requirement (i.e., 197 kcal per kg $BW^{0.6}$; NRC, 2012) and water was available at all times. Pig weights were recorded at the beginning of each period and at the conclusion of the experiment. The initial 5 d of each period was considered an adaptation period to the diet. On d 6 and 7, ileal digesta were collected for 8 h using standard procedures (Stein et al., 1998). In short, a plastic bag was attached to the cannula barrel and digesta flowing into the bag were collected. Bags were removed whenever filled or at least once every 30 min. Digesta samples were immediately frozen at -20ºC to prevent bacterial degradation of AA in the digesta. On the completion of one experimental period, animals were deprived of feed overnight and the following morning, a new experimental diet was offered.

Chemical Analyses, Calculations, and Statistical Analysis. At the conclusion of the experiment, ileal digesta samples were thawed and mixed within animal and diet, and a sub-sample was collected for analyses. Digesta samples were lyophilized and finely ground. A sample of each ingredient and each diet was collected at the time of diet mixing. Diets and soybean hulls were analyzed for ash (method 942.05; AOAC Int., 2007). All samples including soybean meal, soybean hulls, diets, and ileal digesta were analyzed for DM (method 930.15; AOAC Int., 2007). Diets and ingredients were analyzed for ash (method 942.05; AOAC Int., 2007). The concentration of CP was calculated as N × 6.25 and N was measured using the combustion procedure (method 990.03; AOAC Int., 2007) using a LECO FP628 (LECO Corp., Saint Joseph, MI). Amino acids were analyzed on a Hitachi Amino Acid Analyzer, Model No. L8800 (Hitachi High Technologies America, Inc; Pleasanton, CA) using ninhydrin for postcolumn derivatization and norleucine as the internal standard. Prior to analysis, samples were hydrolyzed with 6*N* HCl for 24 h at 110°C (method 982.30 E(a); AOAC Int., 2007). Methionine and Cys were determined as Met sulfone and cysteic acid after cold performic acid oxidation overnight before hydrolysis (method 982.30 E(b); AOAC Int., 2007). Tryptophan was determined after NaOH hydrolysis for 22 h at 110°C (method 982.30 E(c); AOAC Int., 2007). Diets and ileal digesta samples were also analyzed for Cr using Inductive Coupled Plasma Atomic Emission Spectrometric method (method 990.08; AOAC Int., 2007) after digestion using nitric acid-perchloric acid (method 968.08D(b); AOAC Int., 2007).

The non-extruded and extruded soybean hulls and the soybean meal were also analyzed for insoluble and soluble dietary fiber according to method 991.43; AOAC Int., 2007) using the Ankom Dietary Fiber Analyzer (Ankom Technology, Macedon, NY). Diets were analyzed for ADF and NDF were analyzed using Ankom Technology method 12 and 13, respectively (Ankom 2000 Fiber Analyzer, Ankom Technology, Macedon, NY). Total fat was analyzed in soybean meal and the 2 sources of soybean hulls by acid hydrolysis using 3N HCl (AnkomHCl, Ankom Technology, Macedon, NY) followed by crude fat extraction using petroleum ether (AnkomXT15, Ankom Technology, Macedon, NY).

Values for AID and SID of CP and AA were calculated for all diets and the AID and SID for CP and AA in soybean hulls and extruded soybean hulls were calculated by difference by subtracting the contribution of CP and AA from soybean meal to the diets containing soybean hulls and soybean meal (Widmer et al., 2007). Data were analyzed using the PROC MIXED (SAS Inst. Inc., Cary, NC). The model included diet or extrusion as fixed effect and pig, replicate, and period as random effects, pig was the experimental unit. Least Significant Means were calculated and if significant differences were detected, means were separated using the PDIFF option with Tukey adjustment. Results were considered significant at $P \leq 0.05$ and a trend at $P \leq 0.10$.

Exp. 2. Digestibility of Nutrients and DE and ME

Diets, Animals, and Housing. A corn-soybean meal based basal diet, and 2 diets in which 32% of the basal diet was replaced by either extruded or non-extruded soybean hulls were formulated (Table 6.4). Vitamins and minerals were included in all diets to meet or exceed current requirements estimates (NRC, 2012). A total of 24 barrows (initial BW = 59.88 ± 3.37 kg) were allotted to the 3 diets in a randomized complete block design, with 3 diets and 8 replicate pigs per diet. Pigs were housed individually in metabolism crates that were equipped with a slatted floor, a self-feeder, and a nipple waterer. A screen and a urine pan were placed under the slatted floor of each crate to allow for the total, but separate, collection of urine and fecal materials.

Feeding and Sample Collection. Pigs were fed at 3 times the energy requirement for maintenance (i.e., 197 kcal/kg × $BW^{0.6}$; NRC, 2012). Diets were provided every day in 2 equal meals at 0800 and 1600 h. Throughout the study, pigs had ad libitum access to water. Diets were fed for 12 d, where the initial 5 d were considered the adaptation period to the diet, whereas urine and fecal material were collected during the following 4 d according to standard procedures using the marker to marker approach (Adeola, 2001). Urine was collected in buckets over a preservative of 50 mL of *6N* hydrochloric acid. Fecal samples and 20% of the collected urine were stored at -20ºC immediately after collection.

Chemical Analyses, Calculation, and Statistical Analysis. At the conclusion of the experiment, urine and fecal samples were thawed and mixed within animal and diet, and a subsample of urine was lyophilized before analyses (Kim et al., 2009). Fecal samples were dried at 50°C in a forced air drying oven, and dried samples were ground through a 1-mm screen using a Wiley mill (Model 4; Thomas Scientific, Swedesboro, NJ). Urine samples were mixed and a subsample was dripped onto cotton balls that were placed in a plastic bag and lyophilized (Kim et al., 2009). Ingredients, diets, ground fecal samples, and lyophilized urine samples were analyzed for GE using bomb calorimetry (Model 6400; Parr Instruments, Moline, IL). Ingredients and diets were analyzed for DM and ingredients for CP as explained for Exp. 1. Diets were also analyzed for ash as explained for Exp. 1. Following analysis, the ATTD of energy was calculated for each diet and the DE and ME in each diet was calculated as well. By dividing the DE and ME in each diet by the inclusion rate of the basal diet in the soybean hull containing diets, the DE and ME in soybean hulls were calculated by difference (Adeola, 2001).

Data were analyzed as a randomized complete block design with the pig as the experimental unit. The PROC MIXED in SAS (SAS Institute Inc., Cary, NC) was used. Homogeneity of the variances was confirmed using the UNIVARIATE procedure in SAS. The statistical model included diet or extrusion as fixed effect and replication as random effect. Least squares means were calculated and separated using the PDIFF option with Tukey's adjustment. Results were considered significant at $P < 0.05$ and considered a trend at $P < 0.10$.

RESULTS AND DISCUSSION

Values obtained for the nutrient composition of soybean meal and soybean hulls used in these experiments are in agreement with values reported previously (Sauvant et al., 2004; NRC, 2012). However, concentration of acid-hydrolyzed ether extract in soybean hulls was greater compared with published values.

Exp. 1. Ileal Digestibility of Amino Acids

Values for AID and SID of all AA in the diet containing soybean meal were greater ($P < 0.05$) compared with the 2 diets containing 30% soybean hulls. However, extrusion did not change the AID or SID of most AA with the exception that the AID for Leu, Phe, Asp, Ser, and Tyr in the non-extruded soybean hulls diet was less than in the diet with extruded soybean hulls (Table 6.5). Likewise, when AID and SID of CP and AA in non-extruded and extruded soybean hulls were calculated, no effects of extrusion were observed (Table 6.6).

The values for SID of AA in SBM that were observed in this experiment are in agreement with published data, but the SID for most AA in soybean hulls is greater than published data (Sauvant et al., 2004; NRC, 2012). Use of soybean oil increases AA digestibility (Cervantes-Pahm and Stein, 2008) and the diet containing the soybean hulls contained 4% soybean oil, which may have contributed to an increased AA digestibility. Furthermore, the soybean hulls used in this experiment had greater concentration of acid-hydrolyzed ether extract compared with published values (NRC, 2012).

The lack of an effect of extrusion of soybean hulls on SID of AA is in contrast with observations indicating that values for AID and SID of AA increased if field peas were extruded (Stein and Bohlke, 2007). Likewise the AID and SID of most AA also increased if diets containing corn and SBM, corn, SBM, and DDGS, or corn, SBM, DDGS, and soybean hulls were extruded (Rojas et al., 2016). By extrusion, greater digestibility of protein is expected because of the structural changes in the proteins, which results in increased access to the protein by gastrointestinal enzymes (Freire et al., 1991; Ai, 2013). It is possible that because soybean hulls do not contain starch, the SID of AA in soybean hulls were not affected by extrusion.

Exp. 2. Digestibility of Nutrients and DE and ME

Feed intake and GE intake were not affected by dietary treatments (Table 6.7). Dry feces output was increased ($P < 0.05$), but ATTD of GE, DE, and ME were reduced ($P < 0.05$) in diets containing non-extruded or extruded soybean hulls compared with the basal diet. However, the

ATTD of GE, DE, and ME were not different between the 2 diets containing non-extruded or extruded soybean hulls. Likewise, the ATTD of GE, and values for DE and ME in soybean hulls were not improved by extrusion (Table 6.8).

The values for DE and ME in the basal diets were in agreement with calculated values for DE and ME in a corn-soybean meal diet (NRC, 2012). Digestibility of energy and energy concentrations in feed ingredients may increase because extrusion gelatinizes starch in cereal grains, which results in an improvement of starch digestibility (Ai, 2013; Rodriguez et al., 2019). It is also possible that increase in ileal starch digestibility increases the energy utilization by animals because the energy obtained from microbial fermentation in the hindgut is less compared with the energy obtained from absorption of starch in the small intestine. However, the observation that there was no effect of extrusion on energy digestibility in soybean hulls may be a result of the low concentration of starch in soybean hulls compared with cereal grains (Sauvant et al., 2004; NRC, 2012).

Extrusion did not change the concentration of total dietary fiber in soybean hulls, but there was a small increase in soluble dietary fiber and a corresponding reduction in insoluble dietary fiber in the extruded soybean hulls compared with the non-extruded soybean hulls. Although soluble dietary fiber has a greater ATTD than insoluble dietary fiber (Urriola et al., 2010; Navarro et al., 2018), the increase in soluble dietary fiber that was observed as a result of extrusion of the soybean hulls likely was too small to result in a measurable effect on DE and ME.

In conclusion, there were not effects of extrusion on AID and SID of AA, energy digestibility, or ME concentration in soybean hulls.

TABLES

Table 6.1. Nutrient composition of soybean meal, non-extruded, and extruded soybean hulls

		Soybean hulls	
Item, %	Soybean Meal	Non-extruded	Extruded
DM	89.0	93.1	91.9
GE, kcal/kg	4,173	3,915	3,892
CP	43.60	9.81	9.67
Acid-hydrolyzed ether extract	2.12	4.84	4.12
Ash	6.27	4.57	4.58
Insoluble dietary fiber	13.5	68.0	63.4
Soluble dietary fiber	0.7	3.9	7.7
Total dietary fiber	14.2	71.9	71.1
Indispensable AA			
Arg	3.38	0.47	0.46
His	1.20	0.26	0.26
Ile	2.23	0.42	0.42
Leu	3.55	0.69	0.69
Lys	2.98	0.74	0.70
Met	0.63	0.11	0.11
Phe	2.41	0.40	0.41
Thr	1.81	0.39	0.39
Trp	0.66	0.06	0.10
Val	2.29	0.47	0.47

Table 6.1. (Cont.)

Dispensable AA			
Ala	2.00	0.43	0.43
Asp	5.10	0.97	0.98
Cys	0.63	0.20	0.20
Glu	8.37	1.09	1.11
Gly	1.96	0.84	0.86
Pro	2.44	0.56	0.57
Ser	2.14	0.56	0.58
Tyr	1.74	0.41	0.39

Table 6.2. Composition of experimental diets (as-is basis, Exp. 1)

	Diet			
Item, %	Soybean meal	Non-extruded soybean hulls	Extruded soybean hulls	N-free
Corn starch	53.00	30.35	30.35	68.10
Soybean meal, 43% CP	25.00	18.00	18.00	-
Soybean hulls	-	30.00	30.00	-
Sucrose	15.00	15.00	15.00	20.00
Soybean oil	4.00	4.00	4.00	4.00
Solka Floc[1]	-	-	-	4.00
Magnesium oxide	-	-	-	0.10
Potassium carbonate	-	-	-	0.40
Dicalcium phosphate	1.45	1.60	1.60	2.00
Ground limestone	0.60	0.10	0.10	0.45
Sodium chloride	0.40	0.40	0.40	0.40
Chromic oxide	0.40	0.40	0.40	0.40
Vitamin-mineral premix[2]	0.15	0.15	0.15	0.15

[1]Fiber Sales and Development Corp., Urbana, OH.

[2]The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kg of complete diet: vitamin A as retinyl acetate, 11,150 IU; vitamin D_3 as cholecalciferol, 2,210 IU; vitamin E as selenium yeast, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.42 mg; thiamin as thiamine mononitrate, 1.10 mg; riboflavin,6.59 mg; pyridoxine as pyridoxine hydrochloride, 1.00 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-

Table 6.2. (Cont.)

calcium pantothenate, 23.6 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 125 mg as iron sulfate; I, 1.26mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese hydroxychloride; Se, 0.30mg as sodium selenite and selenium yeast; and Zn, 125.1mg as zinc hydroxychloride.

Table 6.3. Nutrient composition of experimental diets (Exp. 1)

	Diet			
Item, %	Soybean meal	Non-extruded soybean hulls	Extruded soybean hulls	N-free
DM	90.7	92.1	92.1	91.2
Ash	4.19	4.73	4.60	3.25
CP	11.43	11.02	11.59	0.39
Indispensable AA				
Arg	0.80	0.65	0.75	0.01
His	0.29	0.27	0.30	0.01
Ile	0.55	0.50	0.55	0.01
Leu	0.89	0.80	0.89	0.03
Lys	0.72	0.73	0.79	0.02
Met	0.15	0.13	0.14	0.01
Phe	0.60	0.52	0.59	0.02
Thr	0.44	0.41	0.46	0.01
Trp	0.15	0.13	0.16	0.02
Val	0.57	0.52	0.58	0.01
Dispensable AA				
Ala	0.50	0.46	0.51	0.01
Asp	1.25	1.12	1.26	0.02
Cys	0.15	0.17	0.18	0.01
Glu	2.07	1.69	1.92	0.03

Table 6.3. (Cont.)

Gly	0.49	0.59	0.64	0.01
Ser	0.64	0.59	0.67	0.01
Tyr	0.51	0.50	0.56	0.01

Table 6.4. Ingredient composition and analyzed nutrient composition of experimental diets (Exp. 2)

Item, %	Diet		
	Basal	Non-extruded soybean hulls	Extruded soybean hulls
Ingredient composition, as-fed basis			
Corn	73.30	49.55	49.55
Soybean meal, 48% CP	24.40	16.50	16.50
Soybean hulls	-	32.00	32.00
Dicalcium phosphate	0.80	1.00	1.00
Ground limestone	0.85	0.30	0.30
Sodium chloride	0.50	0.50	0.50
Vitamin-mineral premix[1]	0.15	0.15	0.15
Analyzed nutrient composition			
DM	87.2	87.7	88.4
Ash	4.19	4.43	4.77
GE, kcal/kg	3,845	3,854	3,851
Neutral detergent fiber	7.60	23.64	21.95
Acid detergent fiber	2.44	15.71	14.89

[1]The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kg of complete diet: vitamin A as retinyl acetate, 11,150 IU; vitamin D_3 as cholecalciferol, 2,210 IU; vitamin E as selenium yeast, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.42 mg; thiamin as thiamine mononitrate, 1.10 mg; riboflavin,6.59 mg;

Table 6.4. (Cont.)

pyridoxine as pyridoxine hydrochloride, 1.00 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.6 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 125 mg as iron sulfate; I, 1.26mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese hydroxychloride; Se, 0.30mg as sodium selenite and selenium yeast; and Zn, 125.1mg as zinc hydroxychloride.

Table 6.5. Apparent ileal digestibility (AID) and standardized ileal digestibility (SID) of CP and AA in diets fed to growing pigs[1,2] (Exp. 1)

	AID					SID				
Item, %	Soybean meal	Non-extruded soybean hulls	Extruded soybean hulls	SEM	*P*-value	Soybean meal	Non-extruded soybean hulls	Extruded soybean hulls	SEM	*P*-value
CP	68.1[a]	55.5[b]	53.5[b]	3.5	< 0.001	86.6[a]	75.0[b]	72.9[b]	3.5	< 0.001
Indispensable AA										
Arg	80.7[a]	72.6[b]	75.6[ab]	3.1	0.016	92.5	87.3	88.3	3.0	0.097
His	84.3[a]	70.3[b]	73.2[b]	1.3	< 0.001	91.3[a]	78.0[b]	80.0[b]	1.3	< 0.001
Ile	83.6[a]	72.3[b]	76.1[b]	1.3	< 0.001	90.4[a]	79.9[b]	82.9[b]	1.3	< 0.001
Leu	83.4[a]	72.9[c]	76.9[b]	1.2	< 0.001	90.3[a]	80.7[b]	83.9[b]	1.2	< 0.001
Lys	84.0[a]	70.7[b]	72.7[b]	1.6	< 0.001	90.8[a]	77.6[b]	79.1[b]	1.6	< 0.001
Met	84.4[a]	76.1[b]	77.9[b]	2.0	0.001	91.3[a]	84.1[b]	85.4[b]	2.0	0.003
Phe	84.2[a]	74.0[c]	77.7[b]	1.1	< 0.001	90.9[a]	81.9[b]	84.6[b]	1.1	< 0.001
Thr	74.1[a]	63.6[b]	67.3[b]	1.4	0.002	88.2[a]	78.9[b]	81.0[b]	1.4	< 0.001
Trp	84.1[a]	76.3[b]	78.9[b]	1.2	< 0.001	92.3[a]	86.0[b]	86.8[b]	1.2	0.005

Table 6.5. (Cont.)

Val	80.5[a]	67.5[b]	71.3[b]	1.3	< 0.001	89.7[a]	77.8[b]	80.5[b]	1.3	< 0.001
Total	82.2[a]	71.2[b]	74.5[b]	1.3	< 0.001	91.1[a]	80.8[b]	83.1[b]	1.3	< 0.001
Dispensable AA										
Ala	70.4[a]	55.4[b]	58.4[b]	3.0	< 0.001	86.2[a]	72.9[b]	74.1[b]	3.1	0.001
Asp	80.6[a]	69.9[c]	74.0[b]	1.2	< 0.001	87.8[a]	78.1[b]	81.3[b]	1.2	< 0.001
Cys	68.6[a]	58.6[b]	59.4[b]	1.9	0.001	83.6[a]	72.0[b]	72.0[b]	1.9	< 0.001
Glu	85.3[a]	75.8[b]	77.9[b]	1.4	< 0.001	90.6[a]	82.3[b]	83.6[b]	1.4	< 0.001
Gly	37.2[a]	19.7[b]	20.3[b]	8.7	0.004	80.9[a]	56.7[b]	54.4[b]	8.7	< 0.001
Ser	77.9[a]	63.4[c]	67.2[b]	1.4	< 0.001	89.9[a]	75.8[b]	78.3[b]	1.4	< 0.001
Tyr	80.6[a]	66.7[c]	70.8[b]	1.3	< 0.001	89.6[a]	75.8[b]	78.8[b]	1.3	< 0.001
Total	60.7[a]	46.8[b]	50.5[b]	5.6	0.001	84.4[a]	73.1[b]	73.9[b]	5.7	0.002
Total AA	70.7[a]	58.0[b]	61.5[b]	3.4	< 0.001	87.3[a]	76.6[b]	78.1[b]	3.4	< 0.001

[a-c]Within a row, means without a common superscript differ ($P < 0.05$).

[1]Each least squares mean for experimental diets from growing pigs represents 8 observations, respectively, with the exception for the diet containing non-extruded soyhulls (n = 7).

Table 6.5. (Cont.)

[2]Values for standardized ileal digestibility were calculated by correcting the values for apparent ileal digestibility for basal ileal endogenous losses. Basal ileal endogenous losses were determined (g/kg of dry matter intake) as CP, 23.30; Arg, 1.04; His, 0.22; Ile, 0.41; Leu, 0.68; Lys, 0.54; Met, 0.11; Phe, 0.44; Thr, 0.68; Trp, 0.14; Val, 0.58; Ala, 0.87; Asp, 1.00; Cys, 0.25; Glu, 1.20; Gly, 2.36; Ser, 0.67; and Tyr, 0.36.

Table 6.6. Apparent ileal digestibility (AID) and standardized ileal digestibility (SID) of AA in non-extruded and extruded soybean hulls[1,2,3] (Exp. 1)

	AID				SID			
Item, %	Non-extruded soybean hulls	Extruded soybean hulls	SEM	*P*-value	Non-extruded soybean hulls	Extruded soybean hulls	SEM	*P*-value
CP	47.7	44.5	5.5	0.408	67.8	64.4	5.5	0.388
Indispensable AA								
Arg	66.7	71.8	5.6	0.385	83.5	85.3	5.6	0.762
His	61.4	66.0	2.3	0.137	69.5	72.8	2.3	0.255
Ile	64.7	71.1	2.4	0.055	72.7	78.0	2.4	0.100
Leu	65.8	72.5	2.2	0.036	74.2	79.7	2.2	0.075
Lys	63.1	66.1	2.8	0.380	70.0	72.1	2.8	0.518
Met	69.7	73.4	3.7	0.207	78.6	81.3	3.7	0.338
Phe	66.9	73.2	2.1	0.043	75.6	80.3	2.1	0.107
Thr	56.8	63.0	2.4	0.117	72.9	76.4	2.4	0.331
Trp	70.9	75.4	2.4	0.220	81.6	83.0	2.4	0.682

Table 6.6. (Cont.)

Val	58.8	65.2	2.3	0.054	69.7	74.4	2.3	0.134
Total	63.9	69.4	2.2	0.097	74.2	78.0	2.2	0.224
Dispensable AA								
Ala	45.7	50.6	4.7	0.391	64.2	66.3	4.7	0.710
Asp	63.0	69.5	2.1	0.064	71.8	76.9	2.1	0.133
Cys	53.8	54.4	2.9	0.874	66.3	65.9	2.9	0.914
Glu	69.2	72.4	2.7	0.374	76.7	78.5	2.7	0.594
Gly	13.1	11.9	11.0	0.893	46.6	41.1	11.0	0.533
Ser	54.6	60.7	2.2	0.055	67.2	71.2	2.2	0.171
Tyr	58.3	64.9	2.1	0.049	67.5	72.3	2.1	0.127
Total	38.9	43.8	8.4	0.445	66.8	67.0	8.4	0.969
Total AA	50.2	55.5	5.0	0.269	70.0	72.0	5.0	0.664

[1]Each least squares mean for experimental diets from growing pigs represents 8 observations, respectively, with the exception for the diet containing non-extruded soybean hulls (n = 7).

Table 6.6. (Cont.)

[2]Values for SID were calculated by correcting the values for apparent ileal digestibility for basal ileal endogenous losses. Basal ileal endogenous losses were determined (g/kg of dry matter intake) as CP, 23.30; Arg, 1.04; His, 0.22; Ile, 0.41; Leu, 0.68; Lys, 0.54; Met, 0.11; Phe, 0.44; Thr, 0.68; Trp, 0.14; Val, 0.58; Ala, 0.87; Asp, 1.00; Cys, 0.25; Glu, 1.20; Gly, 2.36; Ser, 0.67; and Tyr, 0.36.

[3]Values for SID of AA in non-extruded and extruded soybean hulls were calculated by difference (Adeola, 2001).

Table 6.7. Apparent total tract digestibility (ATTD) of GE and DE and ME in experimental diets fed to pigs[1], as-fed basis (Exp. 2)

Item, %	Basal diet	Soybean hulls[2]		SEM	*P*-value
		Non-extruded	Extruded		
Feed intake, kg/d	2.07	2.19	2.17	0.07	0.452
GE intake, Mcal/d	7.95	8.44	8.37	0.28	0.427
Dry feces output, kg/d	0.19[b]	0.45[a]	0.48[a]	0.03	< 0.001
ATTD of GE, %	88.5[a]	76.2[b]	74.7[b]	0.9	< 0.001
DE in diet, kcal/kg	3,402[a]	2,937[b]	2,877[b]	33	< 0.001
Urine output, kg/d	8.80	7.84	11.07	1.73	0.385
ME in diet, kcal/kg	3,273[a]	2,833[b]	2,759[b]	37	< 0.001

[a,b]Within a row, means without a common superscript differ ($P < 0.05$).

[1]Each least squares mean for experimental diets from growing pigs represents 8 observations, respectively.

[2]Both non-extruded and extruded soybean hulls-containing diets contained 66.83% corn and soybean meal (basal) and 30.0% soybean hulls.

Table 6.8. Apparent total tract digestibility (ATTD) of GE and concentrations of DE and ME in non-extruded and extruded soybean hulls[1,2] (Exp. 2)

Item	Soybean hulls		SEM	*P*-value
	Non-extruded	Extruded		
ATTD of GE, %	49.6	45.1	2.9	0.297
As-fed basis, kcal/kg				
DE	1,941	1,755	114	0.268
ME	1,893	1,662	127	0.219
DM basis, kcal/kg DM				
DE	2,086	1,909	123	0.328
ME	2,034	1,808	137	0.262

[1]Each least squares mean for experimental diets from growing pigs represents 8 observations, respectively.

[2]Values for DE and ME in non-extruded and extruded soybean hulls were calculated by difference (Adeola, 2001).

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CHAPTER 7: CONCLUSION

Swine diets in the U.S. are formulated primarily based on corn and soybean meal. However, the increase in ethanol production makes it possible for the feed industry to use corn distiller dried grains with solubles (DDGS) as an alternative ingredient. Use of feed technologies including pelleting or extrusion improve nutrient digestibility and energy utilization in cereal grains and DDGS. Results from this work indicated that pelleting diets that contained 30% DDGS improved average daily feed intake and G:F of nursery pigs as well as growing finishing pigs. Likewise, pigs fed pelleted diets obtained an increase in back fat compared with pigs fed diets in a meal form.

Extrusion increased apparent ileal digestibility (AID) of starch and standardized ileal digestibility of AA in cereal grains. There was a reduction in concentrations of acid detergent fiber and neutral detergent fiber after extrusion, which indicates that by extruding cereal grains, some of the fermentable fiber are solubilized. Apparent total tract digestibility of energy in corn and sorghum increased by extrusion. The increased ME is likely a result of the increase in AID of starch and possibly also a result of the greater solubilization of fiber. However, increase in energy and nutrient digestibility was not observed if soybean hulls were extruded.

Overall, pelleting or extrusion of feed ingredients and diets may change nutrient compositions and improve nutrient digestibility in pigs, but it appears that responses to pelleting and extrusion are different among different ingredients and mixed diets.