RESEARCH REPORT

ANIMAL SCIENCE

Title: Effects of pelleting and extrusion on energy and nutrient digestibility in diets fed to pigs – NPB #13-041 revised

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Industry Summary

The objective of the present work was to determine if extrusion, pelleting or the combination of extrusion and pelleting has the ability to improve the digestibility of energy and nutrients in diets fed to pigs. The second objective was to determine if the effects of extrusion and pelleting depend on the type of diets that is being fed and if high fiber diets respond differently to feed technologies than low fiber diets. Thus, diets based on corn and soybean meal, corn, soybean meal, and DDGS, or corn, soybean meal, DDGS, and soybean hulls were formulated and each diet was fed either in a meal form, in a pelleted form, in a meal form after extrusion, or in a pelleted form after extrusion. Results indicated that the digestibility of energy in the diets based on corn and soybean meal or corn, soybean meal, and DDGS is improved if diets are pelleted. However, if diets are based on corn, soybean meal, DDGS, and soybean hulls, the improvement in energy digestibility is achieved only if diets are extruded or extruded and pelleted. These results indicate that it is possible to increase the utilization of energy in all types of diets by use of pelleting or extrusion, but the improvement is greatest in high fiber diets that are both extruded and pelleted. The economic feasibility of these technologies depends on the cost of feed and the cost of installing and operating a pellet press and an extruder.

Key Findings

- The digestibility of energy and AA in diets based on corn and soybean meal or corn, soybean meal and DDGS is increased if diets are pelleted.
- The digestibility of energy and AA in high fiber diets based on corn, soybean meal, DDGS, and soybean hulls is increased if diets are extruded or extruded and pelleted.
- The increased digestibility of AA that is obtained if diets are pelleted or extruded will result in less soybean meal being needed.
- The increase in energy digestibility and ME of the diets that is a result of pelleting and/or extrusion will result in improved feed conversion rates for pigs fed these diets
- Pelleting and extrusion will reduce the total costs of feed needed to produce a market pig.

This projected was co-founded by the National Pork Board and Bühler AG, Switzerland.

Key words: Digestibility, energy, extrusion, pelleting, pigs

Scientific abstract

An experiment was conducted to determine effects of pelleting, extrusion, and extrusion and pelleting on energy and nutrient digestibility in diets containing low, medium, or high levels of fiber. Three diets were formulated. The low fiber diet contained mainly corn and soybean meal, the medium fiber diet contained corn, soybean meal, and 25% distillers dried grains with solubles (DDGS), and the high fiber diet contained corn, soybean meal, 25% DDGS, and 20% soybean hulls. All diets were formulated to meet the nutrient requirements of growing pigs. Concentrations of NDF were approximately 7, 11, and 20% in the low, medium, and high fiber diets, respectively. Each diet was divided into 4 sub-batches after mixing. One batch was not further processed and fed in a meal form. One batch was pelleted at 95^{o}C , one batch was extruded at 115^{o}C using a single screw extruder, and the last batch was first extruded at 115^{o}C and then pelleted at 95^{o}C. Thus, 12 different diets were produced. A total of 24 growing pigs with a T-cannula installed in the distal ileum were allotted to the diets with 8 pigs allotted to low fiber, medium fiber, and high fiber diets, respectively. Within each type of diets, the

8 pigs were allotted to a replicated 4 × 4 Latin square design with four 14-d periods and the 4 different diet technologies in each square. Thus, there were 8 replicate pigs per diet. Pigs were adjusted to their diets for 14 d before the experiment started. After a 5 d adaptation period, fecal samples were collected for 5 d according to the marker to marker approach and ileal digesta were collected on d 13 and 14 of eah period. Results indicated that pelleting, extrusion, or pelleting and extrusion improved (P < 0.05) the apparent ileal digestibility (AID) of starch and most indispensable AA. In most cases, there were no differences between the pelleted, the extruded, and the extruded plus pelleted diets, but AID values for starch and AA were in most cases greater (P < 0.05) than for the meal diet. The apparent total tract digestibility of energy was also improved (P < 0.05) by pelleting in the low fiber and the medium fiber diets, but in the high fiber diets, only extrusion or extrusion and pelleting improved ATTD of GE. Because of the increased ATTD of GE, ME values for pelleted or extruded and pelleted low fiber diets, pelleted or extruded medium fiber diets, and extruded or extruded and pelleted high fiber diets were greater (P < 0.05) than in the meal diets. These data indicate that energy utilization may be improved by pelleting or extrusion or by the combination of the 2 technologies, but the response seems to be greater for extrusion in diets that are relatively high in fiber.

Introduction

Pelleting is a well-known technology that results in an increase in feed conversion (Richert and DeRouchey, 2010) and it has been reported that feed efficiency is improved by 6 to 7% if diets are pelleted (Hancock and Behnke, 2001; Richert and DeRouchey, 2010). The main reason for this observation is that feed wastage is reduced and digestibility of energy is improved because of gelatinization of starch (Richert and DeRouchey, 2010; NRC, 2012). A corn-soybean meal diet fed to pigs in a pellet form increased the digestibility of DM, N, and GE by 5 to 8% (Wondra et al., 1995). Likewise, Lahaye et al. (2008) reported that pelleting a wheat-canola meal diet improved the ileal digestibility of CP and AA. Recently it was reported that pigs fed pelleted diets had a greater feed efficiency compared with pigs fed meal diets, and reduced performance of pigs fed diets containing high-fiber by-products was ameliorated if the diet was pelleted (Fry et al., 2012). It is, therefore, possible that the effects of pelleting on energy and nutrient digestibility are greater in high fiber diets than in low fiber diets, but this hypothesis has not been tested.

Extrusion in the United States is mainly used in the pet and aquaculture industries and consists of heating, pressuring, and steam conditioning (Hancock and Behnke, 2001; Richert and DeRouchey, 2010). This technology may be used on the whole diet or on individual ingredients. Sauer et al. (1990) reported that extrusion of a whole diet compared with pelleting improved feed conversion by 8% and DM and CP digestibility improved by 3 and 6%, respectively. Ileal digestibility of DM is improved by extrusion of corn, but AA digestibility is not different between extruded and non-extruded corn (Muley et al., 2007), but the ileal digestibility of CP is greater in extruded soybean meal compared with non-extruded soybean meal (Chae et al., 1997). Extrusion of field peas has a positive effect on the apparent total tract digestibility (ATTD) of GE and on the apparent ileal digestibility of most indispensable AA (Stein and Bohlke, 2007; Htoo et al., 2008) and the DE of field peas is improved by 4.8% by extrusion (Stein and Bohlke, 2007). Extrusion may also increase the solubility of dietary fiber, which in turn may result in an increased energy digestibility because soluble fibers are much more fermentable by pigs than insoluble fibers (Urriola et al., 2010). It is, therefore, possible that the benefits of extrusion and pelleting are greater in high fiber diets than in low fiber diets, but this hypothesis has not been investigated.

Objectives.

The hypothesis of this experiment was that pelleting and extrusion of diets, either alone or in combination, will improve nutrient and energy digestibility, and that the response is greater in high fiber diets than in low fiber diets. The objective was to determine energy and nutrient digestibility in diets with low, medium, or high concentrations of fiber that have been pelleted, extruded, or pelleted and extruded.

Materials and methods

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

Animals, Housing, Diets, and Experimental Design

Twenty-four growing barrows were equipped with a T-cannula in the distal ileum. Pigs were allotted to a split plot design with a 3 × 4 factorial with 3 types of diets (low-fiber, medium-fiber, and high-fiber) and 4 post-mixing technological treatments (no treatment, pelleting, extrusion, and pelleting and extrusion). Pigs were housed individually in metabolism crates in an environmentally controlled room. A feeder and a nipple drinker were installed in each of the crates, and a screen and a funnel placed below the slatted floor of the crates allowed for the total, but separate, collection of feces and urine from each pig.

The low-fiber diet was based on corn and soybean meal, the medium-fiber diet was based on corn, soybean meal, and 25% DDGS, and the high-fiber diet was based on corn, soybean meal, 25% DDGS, and 20% soybean hulls. Vitamins and minerals were included in all diets to meet or exceed current requirement estimates for growing pigs (NRC, 2012). All diets also contained 0.5% titanium dioxide as an indigestible marker. All raw materials were sourced by and paid for by Bühler AG, Switzerland, and all diets were mixed at the Bühler Pilot Plant in Uzwil, Switzerland. Employees from Bühler processed ingredients and diets and a representative from the University of Illinois was present during this process.

Corn, soybean meal, DDGS, and soybean hulls were ground using a Bühler Hammer mill model DFZC 655 with 56 beaters. The tip speed was 92 m/s. One batch of each diet was mixed, and this batch then was divided into 4 sub-batches. One sub-batch of each diet was fed in meal form without any further processing. One sub-batch of each diet was pelleted after conditioning for 12 seconds using a Bühler DNSA short term conditioner with a length of 800 mm and a diameter of 250 mm. Pelleting took place at a temperature of 95°C using a 55 kW pellet press model Bühler DPDB 304.75. Pelleted diets were cooled in a Bühler Model DFKG counter flow cooler with a capacity of 1.9 m3 and a height of 1.1 m. One sub-batch was extruded at a temperature of 115°C using a Bühler Model AHSF 133 single screw extruder conveyer extruder with a diameter of 133 mm. The extrudate was then ground using the hammer mill described above. The last sub-batch was first extruded at 115°C and then pelleted at 95°C. Following diet processing, diets were packaged in 1,000 kg plastic coated tote bags and shipped from Uzwil to the University of Illinois using ocean freight. Bühler Ag paid all expenses related to the shipment.

Feeding and Sample Collection

Eight pigs were allotted to each level of fiber and these 8 pigs were arranged in a replicated 4 x 4 Latin square design for a total of 8 observations per diet. Feed was provided in a daily amount of 3.3 times the maintenance energy requirement (i.e., 197 kcal of ME/kg of $BW^{0.60}$; NRC, 2012) of the smallest pig in each replicate. The total amount of feed was divided into 2 equal meals that were fed at 0800 and 1700 h. Water was available throughout the experiment.

All pigs were adapted to the level of fiber for 14 d prior to starting the experiment. Pig weights were recorded at the beginning and at the end of each period. The initial 5 days of each period was considered an adaptation period to the diet. Fecal and urine samples were quantitatively collected for 5 days from day 6 to day 11 using the marker to marker approach (Adeola, 2001) and ileal digesta were collected for 8 h on d 13 and 14 using standard operating procedures. In short, a plastic bag was attached to the cannula barrel and digesta flowing into the bag was collected. Bags were removed whenever they were filled with digesta, or at least once every 30min, and immediately frozen at – 20ºC to prevent bacterial degradation of the AA. On the completion of one experimental period, animals were deprived of feed overnight and the following morning, a new experimental diet was offered.

At the conclusion of the experiment, ileal samples was thawed, mixed within animal and diet, and a sub-sample was lyophilized and finely ground. A sample of each diet was collected as well. Feces were collected twice daily and stored at -20ºC immediately after collection. Urine collections started on d 6 at 0800 h and ceased on d 11 at 0800 h. Urine buckets were placed under the metabolism cages to permit total collection. Buckets were emptied in the morning and afternoon and a preservative of 50 mL of 6*N* HCL was added to each bucket when they were emptied. The collected urine was weighed and a 20% subsample was stored at -20ºC.

Sample Analysis

Diet and ileal samples were analyzed for DM, ash, GE, CP, (Method 990.03; AOAC Int., 2007), amino acids [Method 982.30 E (a, b, c); AOAC Int., 2007], titanium dioxide (Myers, et al., 2004), and starch (Xiong et al. 1990). Diets and fecal samples were also analyzed for NDF (Holst, 1973) and GE using bomb calorimetry (Model 6300, Parr Instruments, Moline, IL) and urine samples were analyzed for GE (Kim et al., 2009).

Calculations and Statistical Analysis

Energy values that were determined from the excretion of GE in the feces and urine were subtracted from the intake of GE to calculate DE and ME for each diet (Adeola, 2001). Values for the apparent ileal digestibility (**AID**) of DM, GE, CP, ash, OM, AA, and starch, and the apparent total tract digestibility (**ATTD**) of GE and NDF were calculated using standard procedures (Stein et al., 2007) for each diet

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

Results

For the low fiber diets, pelleting, extrusion, or the combination of pelleting and extrusion increased ($P < 0.05$) the AID of GE, DM, and OM, but no differences among the 3 technologies were observed (Table 4). However, for the medium and high fiber diets, only extrusion and the combination of extrusion and pelleting increased ($P < 0.05$) the AID of GE, DM, and OM compared with the meal diet, whereas pelleting alone did not increase AID in these diets. The AID of starch was improved ($P < 0.05$) in the low fiber diets and in the high fiber diets if both pelleting and extrusion was used, but either technology alone did not increase the AID of starch compared with the meal diet. However, in the medium fiber diets, the AID of starch was increased ($P < 0.05$) by either pelleting or extrusion or the combination of pelleting and extrusion.

The AID of CP and all indispensable AA except Arg and His and the mean of all indispensable AA was increased ($P < 0.05$) in the low fiber diet if pelleting, extrusion, or the combination of pelleting and extrusion was used. The AID of CP, Arg and Phe was also greater ($P < 0.05$) if extrusion or the combination of extrusion and pelleting was used compared with pelleting alone, but for all other indispensable AA and the mean of the indispensable AA, no difference among the 3 technologies were observed.

For the medium fiber diets, extrusion increased ($P < 0.05$) the AID of CP and all indispensable AA and the mean of the indispensable AA compared with the meal diet and if the combination of pelleting and extrusion was used, the AID of CP and all indispensable AA except Arg, Lys, and Thr and the mean of all indispensable AA also increased ($P < 0.05$) compared with the meal diet. If pelleting was used, the AID of His, Leu, Lys, Met and Phe also increased ($P < 0.05$) compared with the meal diet, but this was not the case for the AID of CP and the remaining indispensable AA or for the mean of the indispensable AA. The AID of CP and all indispensable AA was greater ($P < 0.05$) for the extruded diet compared with the pelleted diet.

For the high fiber diets, the AID of CP and all indispensable AA and the mean of the dispensable AA was greater ($P < 0.05$) if diets were extruded or extruded and then pelleted than if they were fed in a meal form. Pelleting alone increased ($P < 0.05$) the AID of all indispensable AA except Arg, His, Lys, and Thr compared with the meal diet, but the AID of CP and most indispensable AA in the pelleted diet was less ($P < 0.05$) than in the extruded diet or in the diet that was extruded and then pelleted.

In general, the AID of dispensable AA followed the same patterns as the AID for the indispensable AA. For most AA except Lys, no differences in AID between the low fiber and the medium fiber diets were observed regardless of technological treatment, but the AID of most AA was less ($P < 0.05$) in the high fiber diets than in the other diets.

The ATTD of GE was reduced ($P < 0.05$) as the level of fiber in the diets increased (Table 5). For diets with low or medium levels of fiber, pelleting increased ($P < 0.05$) the ATTD of GE, but that was not the case for the diets with the greatest levels of fiber. Extrusion did not influence the ATTD of GE in diets with the low or medium levels of fiber, but in the high-fiber diets, the ATTD of GE increased ($P < 0.05$) by extrusion. Pigs fed diets that were both pelleted and extruded had greater ($P < 0.05$) ATTD of GE than pigs fed the meal diets regardless of the level of fiber in the diet, but there were no significant improvements of pelleting and extrusion compared with only pelleting.

Energy intake and energy excretion in the feces increased ($P < 0.05$) as the level of fiber in the diets increased (Table 6). The DE and ME (DM basis) were less ($P < 0.05$) in the high fiber diets compared with the low or medium fiber diets, but no differences were observed between low and medium fiber diets. In the low fiber diets, the DE and ME calculated on a DM basis increased ($P < 0.05$) if diets were pelleted or pelleted and extruded, whereas no differences between the meal diet and extrusion alone were observed. For the medium fiber diets, either pelleting or extrusion, but not the combination, also increased ($P < 0.05$) DE and ME compared with the meal diet. However, in the high fiber diets, no effects of pelleting were observed, but extrusion or the combination of extrusion and pelleting increased ($P < 0.05$) the DE and ME compared with the meal diets.

Discussion

The increased AID of starch that was observed as diets were extruded or pelleted is consistent with data for field peas (Stein and Bohlke, 2007) and indicates that starch in corn will become more digestible if extruded or pelleted. This increase in starch digestibility likely had a positive impact on energy utilization from the pigs. The increases in AID of AA that were observed also are consistent with previous research (Muley et al., 2007; Stein and Bohlke, 2007; Lundblad et al., 2012) although it has also been reported that extrusion of corn does not influence the AID of AA (Herkelman et al., 1990). The reason for the increased AID of AA in diets that are pelleted or extruded may be that the processing may partly denature the proteins in the diets (Svihus and Zimonja, 2011). The improvements obtained in the present experiment for the AID of most AA was 3-4 percentage units, which will add value to the diets because the inclusion of SBM potentially can be reduced if diets are pelleted or extruded or both pelleted and extruded. Thus, the added costs of pelleting or extrusion may be offset by reducing the inclusion of soybean meal in the diets.

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

The ME values that were obtained for the low fiber and medium fiber meal diets were within 25 kcal per kg from the values calculated for these diets from NRC (2012). The observation that there was no difference in the ME between the low fiber diets and the medium fiber diets is also in line with expectations because the ME for conventional DDGS is not different from the ME for corn and soybean meal (Pedersen et al., 2007; NRC, 2012). In contrast, the ME of the high fiber diet was approximately 155 kcal greater than the value calculated from NRC, which indicates that the soybean hulls used in this experiment contained slightly more ME than predicted from NRC (2012). Nevertheless, the reduction in ME in the high fiber diets that was expected because of the inclusion of soybean hulls in the diets was observed in the experiment. This reduction is a result of a linear reduction in the ATTD of GE as NDF in the diets increase (Jaworski, 2012). The increase in NDF from the low fiber to the high fiber diet was 10-12 percentage units, and the reduction in ATTD of GE was approximately 10 percentage units. This observation is in agreement with Le Gall et al. (2009) who suggested that the ATTD of GE will be reduced by 1percentage unit for each 1 percentage unit NDF increases in the diet.

The increase in ME that was observed as a result pelleting was not influenced by the concentration of fiber in the diet and was calculated as 2.1, 2.5, and 1.9 percent increase for the low fiber, the medium fiber and the high fiber diets when compared with control diets. These values are greater than the improvement of approximately 1.5% that was reported by Le Gall et al. (2009) who also conducted a digestibility experiment using diets with different fiber levels. In agreement with the results by Le Gall et al. (2009) the response to pelleting was not influenced by the level of fiber in the diets. However, the improvement in ME obtained in this experiment is less than the percentage improvement in feed conversion rate that has been reported when pigs are offered ad libitum access to feed (Wondra et al., 1995; Xing et al., 2004), but it is possible that some of the improvement in feed conversion rate observed for ad libitum fed pigs is a result of reduced feed wastage. With the restricted feeding regime used in this experiment, feed wastage was less of a problem, and any wastage was carefully collected and weighted and subtracted from feed allowance to calculate feed consumption.

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

In conclusion, pelleting and extrusion of low fiber, medium fiber, and high fiber diets independently and in combination improved the AID of starch and most AA and the ATTD of energy. The increase in ATTD of energy was not a result of increased fermentation of fiber, but likely a result of the increased digestibility of starch and AA. The increase in ME that was observed for pelleting or extrusion was between 0.6 and 2.9% for the 3 types of diets. However, if diets were both extruded and pelleted, ME increased by up to 3.7% with the greatest improvement observed for the diets with the greatest concentrations of fiber.

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Table 1. Analyzed nutrient composition of corn, distiller dried grains with solubles (DDGS), soybean hulls, and soybean meal (SBM), as-fed basis

	Ingredient			
Item	Corn	DDGS	Soybean hulls	SBM
GE, kcal/kg	3,938	4,984	3,907	4,198
DM, %	86.57	87.13	88.30	87.50
CP, %	7.70	26.78	13.56	49.51
Ash, %	1.36	3.89	4.62	6.26
OM[1], %	85.21	83.24	83.69	81.24
NDF, %	7.21	25.79	51.79	9.29
P, %	0.27	0.66	0.19	0.61
Ca, %	-	0.05	0.49	0.26
Indispensable, AA %				
Arg	0.34	1.33	0.62	3.56
His	0.24	0.91	0.34	1.38
Ile	0.26	1.02	0.47	2.26
Leu	0.90	3.04	0.83	3.87
Lys	0.26	1.00	0.85	3.11
Met	0.15	0.52	0.15	0.67
Phe	0.37	1.30	0.51	2.60
Thr	0.28	1.04	0.46	1.93

Trp	0.06	0.19	0.06	0.73
Val	0.36	1.35	0.54	2.29
Dispensable, AA %				
Ala	0.55	1.89	0.53	2.15
Asp	0.50	1.67	1.15	5.66
Cys	0.16	0.52	0.20	0.67
Glu	1.35	3.55	1.54	8.90
Gly	0.30	1.08	0.87	2.09
Pro	0.65	2.05	0.63	2.52
Ser	0.36	1.24	0.59	2.30
Tyr	0.23	1.04	0.45	1.87
Total AA	7.32	24.74	10.79	48.56

[1]OM was calculated as the difference between DM and ash.

Table 2. Ingredient composition of experimental diets with three different levels of fiber containing corn, distillers dried grains with solubles (DDGS), soybean hulls, and soybean meal (SBM), as-fed basis

Ingredient, %	Low fiber	Medium fiber	High fiber
Ground corn	69.70	47.95	29.9
SBM	27.50	24.50	22.80
DDGS	-	25.00	25.00
Soybean hulls	-	-	20.00
Dicalcium phosphate	0.75	0.15	0.25
Ground limestone	0.85	1.20	0.85
Sodium chloride	0.40	0.40	0.40
Titanium dioxide	0.50	0.50	0.50
Vitamin mineral premix[1]	0.30	0.30	0.30
Total	100.00	100.00	100.00

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

Table 3. Analyzed nutrient composition of experimental diets containing corn, distillers dried grains with solubles (DDGS), soybean hulls, and soybean meal (SBM) and processed with 4 different feed technologies, as-fed basis

	Low fiber				Medium fiber				High fiber			
Item	Meal	Pelleted	Extruded	Pex[2]	Meal	Pelleted	Extruded	Pex	Meal	Pelleted	Extruded	Pex
GE, kcal/kg	3,916	3,920	4,112	4,083	4,168	4,154	4,415	4,400	4,180	4,144	4,363	4,184
DM, %	85.32	85.11	89.64	88.96	84.24	83.99	87.54	91.83	88.83	87.80	92.62	88.18
CP, %	19.42	19.48	20.68	20.42	22.75	22.37	23.79	23.45	23.20	22.53	24.44	23.21
Starch, %	43.91	43.80	45.30	44.05	32.53	33.45	31.09	32.91	20.94	22.43	20.82	22.52
Ash, %	4.87	4.69	5.13	4.95	5.32	5.21	5.19	5.11	5.27	5.30	5.55	5.24
OM[1], %	80.45	80.42	84.51	84.02	78.91	78.78	82.35	86.72	83.56	82.50	87.07	82.94
NDF, %	7.75	5.90	7.03	8.42	11.79	11.06	12.58	10.40	20.49	19.80	19.93	20.09
P, %	0.48	0.48	0.51	0.51	0.49	0.48	0.52	0.49	0.48	0.48	0.49	0.47
Ca, %	0.59	0.46	0.78	0.64	0.55	0.55	0.50	0.69	0.49	0.51	0.50	0.45
Indispensable, AA %												

Arg	1.18	1.22	1.31	1.29	1.33	1.30	1.42	1.37	1.30	1.27	1.40	1.35
His	0.54	0.56	0.59	0.58	0.61	0.65	0.69	0.67	0.65	0.63	0.70	0.67
Ile	0.81	0.83	0.89	0.87	0.91	0.90	0.96	0.94	0.90	0.87	1.00	0.96
Leu	1.73	1.77	1.88	1.83	2.10	2.09	2.23	2.21	2.03	1.98	2.21	2.11
Lys	1.03	1.06	1.14	1.10	1.10	1.09	1.13	1.13	1.17	1.10	1.24	1.20
Met	0.28	0.28	0.29	0.28	0.34	0.33	0.37	0.35	0.34	0.33	0.35	0.34
Phe	0.98	1.00	1.07	1.05	1.12	1.10	1.18	1.17	1.09	1.06	1.19	1.14
Thr	0.72	0.74	0.80	0.78	0.85	0.84	0.90	0.89	0.85	0.83	0.91	0.88
Trp	0.23	0.23	0.25	0.25	0.23	0.24	0.25	0.26	0.22	0.24	0.25	0.24
Val	0.88	0.91	0.97	0.95	1.05	1.04	1.11	1.08	1.03	0.99	1.13	1.09
Dispensable, AA %												
Ala	0.98	1.01	1.08	1.04	1.24	1.24	1.32	1.30	1.22	1.18	1.29	1.24
Asp	1.92	1.97	2.12	2.07	2.02	1.98	2.15	2.10	2.01	1.96	2.18	2.10
Cys	0.30	0.30	0.32	0.31	0.35	0.35	0.39	0.37	0.38	0.35	0.40	0.37

Glu	3.42	3.49	3.73	3.64	3.70	3.67	3.95	3.91	3.55	3.47	3.84	3.68
Gly	0.76	0.79	0.85	0.82	0.90	0.90	0.97	0.93	0.97	0.94	1.01	0.99
Pro	1.13	1.16	1.21	1.19	1.41	1.43	1.50	1.46	1.37	1.33	1.41	1.42
Ser	0.85	0.87	0.93	0.91	1.00	1.00	1.08	1.06	1.03	0.99	1.07	1.04
Tyr	0.66	0.69	0.73	0.73	0.79	0.79	0.84	0.83	0.80	0.79	0.86	0.81
Total AA	18.40	18.88	20.16	19.69	21.05	20.94	22.44	22.03	20.91	20.31	22.44	21.63

[1]OM was calculated as the difference between DM and ash.

[2]Pex = pelleted + extruded.

Table 4. Apparent ileal digestibility (AID) of GE, starch, CP, DM, ash, OM, and AA (%) in experimental diets with three different levels of fiber containing corn, distillers dried grains with solubles (DDGS), soybean hulls, and soybean meal (SBM) and processed with four different feed technologies, as-fed basis[1]

	Low fiber				Medium fiber				High fiber				SEM	P-value
Item	Meal	Pellet	Extrud	Pex[2]	Meal	Pellet	Extrud	Pex	Meal	Pellet	Extrud	Pex		
GE, %	72.83^{bc}	76.87^{a}	78.56^{a}	78.23^{a}	68.92^{d}	70.34^{cd}	77.58^{a}	73.33^{b}	56.73^{f}	58.09^{f}	61.85^{e}	61.33^{e}	1.0	< 0.01
Starch, %	97.80^{bcd}	98.68^{ab}	98.94^{ab}	99.19^{a}	95.31^{f}	97.95^{bcd}	98.31^{ab}	98.03^{abc}	96.06^{ef}	96.77^{cde}	96.58^{def}	97.84^{abc}	0.8	< 0.01
CP, %	73.75^{e}	76.68^{cd}	79.99^{ab}	79.77^{ab}	74.65^{de}	75.80^{cde}	80.74^{a}	77.42^{bc}	68.94^{f}	68.17^{f}	73.00^{e}	72.72^{e}	1.3	< 0.01
DM, %	71.68^{bc}	74.59^{a}	76.38^{a}	76.04^{a}	65.65^{d}	66.94^{d}	73.86^{ab}	70.52^{c}	53.13^{f}	54.30^{f}	58.57^{e}	57.22^{e}	1.1	< 0.01
Ash, %	23.11^{de}	26.42^{cd}	33.31^{b}	31.78^{b}	31.16^{bc}	31.12^{bc}	42.63^{a}	32.36^{b}	10.70^{g}	15.99^{f}	21.31^{de}	17.97^{ef}	2.2	< 0.01
OM[1], %	74.67^{cd}	77.40^{ab}	78.99^{a}	78.65^{a}	67.98^{e}	69.31^{e}	75.83^{bc}	72.77^{d}	55.92^{g}	56.94^{g}	60.95^{f}	59.70^{f}	1.0	< 0.01
Arg	88.8^{bc}	89.64^{b}	92.53^{a}	92.57^{a}	89.36^{b}	89.41^{b}	92.40^{a}	90.96^{ab}	86.63^{d}	86.81^{cd}	89.78^{b}	90.05^{b}	0.9	< 0.01
His	85.83^{ab}	87.08^{a}	87.41^{a}	87.63^{a}	83.56^{bc}	86.65^{a}	87.60^{a}	86.24^{a}	79.93^{e}	81.1^{de}	82.32^{cd}	83.05^{cd}	0.9	< 0.01
Ile	80.20^{e}	83.89^{bc}	85.69^{ab}	85.48^{ab}	81.06^{de}	82.55^{cd}	86.27^{a}	83.99^{bc}	75.00^{g}	77.57^{f}	81.01^{de}	81.82^{cde}	0.8	< 0.01

Leu	83.06^{ef}	86.38^{bc}	87.61^{ab}	87.43^{ab}	84.10^{de}	86.11^{bc}	88.95^{a}	86.87^{b}	79.51^{g}	82.07^{f}	84.86^{de}	85.04^{cd}	0.6	< 0.01
Lys	80.99^{cd}	83.91^{a}	84.77^{a}	83.40^{ab}	79.43^{de}	80.82^{bd}	83.31^{ac}	81.10^{bd}	73.58^{f}	74.05^{f}	77.24^{e}	78.19^{e}	0.9	< 0.01
Met	84.28^{d}	88.11^{ab}	88.29^{ab}	87.76^{ab}	83.82^{d}	87.17^{bc}	89.28^{a}	87.24^{bc}	81.74^{e}	84.06^{d}	85.53^{d}	85.49^{cd}	0.7	< 0.01
Phe	81.98^{fg}	85.53^{cd}	87.72^{ab}	87.44^{ab}	83.40^{ef}	85.06^{d}	88.84^{a}	86.98^{bc}	78.33^{h}	81.11^{g}	85.22^{de}	85.17^{cde}	0.7	< 0.01
Thr	71.48^{de}	75.71^{abc}	76.63^{ab}	75.62^{bc}	72.85^{cd}	74.49^{bcd}	78.66^{a}	75.68^{bc}	68.27^{f}	69.82^{ef}	71.92^{de}	73.19^{cd}	1.1	< 0.01
Trp	80.12^{d}	82.61^{bc}	84.89^{ab}	84.54^{ab}	80.94^{cd}	82.86^{bc}	85.76^{a}	85.09^{ab}	73.11^{f}	75.96^{e}	78.94^{d}	80.62^{cd}	0.9	< 0.01
Val	77.22^{d}	81.30^{ab}	82.19^{ab}	81.81^{ab}	78.13^{cd}	80.02^{bc}	83.46^{a}	80.61^{b}	71.57^{f}	73.78^{e}	75.74^{d}	77.75^{cd}	0.9	< 0.01
Mean	81.74^{f}	84.75^{bc}	86.19^{ab}	85.86^{ab}	82.16^{ef}	83.81^{cde}	86.84^{a}	84.86^{bcd}	77.30^{g}	78.71^{g}	81.63^{f}	82.40^{def}	0.7	< 0.01
Ala	76.32^{cd}	79.94^{b}	81.81^{ab}	81.49^{ab}	76.93^{cd}	79.11^{bc}	83.58^{a}	80.68^{b}	71.14^{e}	73.25^{e}	75.53^{d}	76.46^{cd}	1.2	< 0.01
Asp	79.47^{bc}	81.91^{a}	82.92^{a}	81.97^{a}	77.89^{cde}	78.26^{cde}	81.72^{ab}	79.38^{cd}	72.57^{g}	74.30^{fg}	76.22^{ef}	76.83^{de}	1.0	< 0.01
Cys	69.93^{bc}	74.08^{a}	70.30^{abc}	70.14^{abc}	67.70^{cde}	70.31^{abc}	72.06^{ab}	68.88^{abcd}	62.52^{ef}	61.38^{f}	61.41^{f}	63.88^{def}	1.9	< 0.01
Glu	82.81^{cd}	86.59^{ab}	87.80^{a}	88.06^{a}	81.34^{de}	84.56^{bc}	87.29^{a}	85.83^{abc}	76.43^{f}	78.23^{ef}	81.18^{d}	83.24^{cd}	1.2	< 0.01
Gly	58.12^{cde}	61.17^{bc}	66.12^{ab}	66.12^{ab}	59.91^{bcd}	59.72^{bcd}	69.98^{a}	63.08^{bc}	49.35^{ef}	43.55^{f}	52.11^{de}	52.96^{de}	3.2	< 0.01
Pro	55.86^{cde}	47.48^{de}	74.32^{ab}	74.77^{ab}	72.84^{ab}	67.05^{abc}	76.76^{a}	78.46^{ab}	66.90^{abc}	46.36^{e}	63.85^{abcd}	59.01^{bcd}	7.11	< 0.01

Ser	80.06^{e}	82.58^{bc}	84.13^{ab}	83.47^{ab}	80.66^{cde}	82.22^{bcd}	85.52^{a}	83.57^{b}	76.47^{g}	77.75^{fg}	79.15^{ef}	80.14^{de}	1.0	< 0.01
Tyr	83.55^{ef}	87.07^{bcd}	88.53^{ab}	88.79^{ab}	85.45^{de}	87.63^{bc}	90.10^{a}	88.55^{ab}	81.88^{f}	83.91^{e}	85.16^{de}	85.90^{cd}	0.7	< 0.01
Mean	76.44^{bc}	77.79^{bc}	82.38^{a}	82.31^{a}	77.36^{bc}	77.13^{bc}	82.69^{a}	79.94^{ab}	71.69^{de}	70.47^{e}	74.56^{cd}	74.97^{c}	1.6	< 0.01
Total AA	79.08^{de}	81.07^{cd}	84.09^{ab}	83.86^{ab}	79.54^{de}	80.31^{cde}	84.66^{a}	82.24^{bc}	74.23^{f}	74.82^{f}	77.89^{e}	78.55^{de}	1.0	< 0.01

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

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

[22]Pellet = pelleted; Extrud = extruded; Pex = pelleted + extruded.

Table 5. Apparent total tract digestibility (%) of GE and NDF in experimental diets, as-fed basis[1]

Item	Low fiber				Medium fiber				High fiber				SEM	P-value
	Meal	Pelleted	Extruded	Pex[2]	Meal	Pelleted	Extruded	Pex	Meal	Pelleted	Extruded	Pex		
GE	89.4^{b}	90.8^{a}	89.8^{ab}	90.8^{a}	84.7^{d}	86.4^{c}	85.1^{d}	86.5^{c}	80.0^{f}	80.7^{ef}	81.8^{e}	81.9^{e}	0.77	< 0.01
NDF	56.1	51.5	54.0	54.0	48.9	48.3	45.1	46.0	59.1	55.5	56.1	59.9	3.38	0.16

$^{a\text{-}f}$Means within a row lacking a common superscript letter differ ($P < 0.05$).

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

[2]Pex = pelleted + extruded.

Table 6. Concentration of digestible and metabolizable energy in diets with different level of fiber containing corn, distillers dried grains with solubles (DDGS), soybean hulls, and soybean meal (SBM), as-fed basis[1]

	Low fiber				Medium fiber				High fiber				SEM	P-value
Item	Meal	Pellet	Extrud	Pex[2]	Meal	Pellet	Extrud	Pex	Meal	Pellet	Extrud	Pex		
GE intake[1] kcal/kg	7,206^{d}	7,196^{d}	7,571^{c}	7,542^{c}	7,838^{c}	7,835^{c}	8,398^{b}	8,282^{b}	8,525^{b}	8,421^{b}	8,971^{a}	8,535^{b}	590.	< 0.01
GE in feces, kcal/kg	765.5^{f}	652.4^{g}	754.8^{fg}	683.0^{fg}	1,189^{cd}	1,057^{e}	1,252^{c}	1,107^{de}	1,670^{a}	1,605^{ab}	1,617^{a}	1,500^{b}	81.3	< 0.01
GE in urine, kcal/kg	361.3	359.3	379.0	349.9	393.2	367.3	389.4	377.3	352.5	281.6	320.8	309.4	47.0	0.80
DE, kcal/kg	3502^{ef}	3561^{f}	3691^{b}	3708^{b}	3532de	3588^{c}	3755^{ab}	3805^{a}	3343^{g}	3345^{g}	3568^{cdf}	3428^{f}	32.3	< 0.01
DE, kcal/kg DM	4105^{e}	4184^{bc}	4117de	4168^{cd}	4192^{cde}	4272^{ab}	4289^{a}	4144^{cde}	3777^{h}	3810^{gh}	3853^{fg}	3888^{f}	36.6	< 0.01
ME, kcal/kg	3300^{f}	3361de	3490^{bc}	3520^{b}	3325^{ef}	3396^{d}	3549^{ab}	3605^{a}	3172^{g}	3206^{g}	3415^{f}	3278^{ef}	34.0	< 0.01
ME, kcal/kg DM	3868^{d}	3949^{bc}	3893^{cd}	3957^{bc}	3947^{cd}	4044^{ab}	4055^{a}	3926^{cd}	3583^{f}	3651^{ef}	3687^{g}	3717^{e}	38.8	< 0.01

$^{a-g}$Means within a row lacking a common superscript letter differ ($P < 0.05$).

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

[2]Pellet = pelleted; Extrud = extruded; Pex = pelleted + extruded.