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Effects of pelleting, extrusion, or extrusion and pelleting on energy and nutrient digestibility in diets containing different levels of fiber and fed to growing pigs[1]

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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 concentrations of fiber. Three diets were formulated: 1) the low-fiber diet contained corn and soybean meal; 2) the medium-fiber diet contained corn, soybean meal, and 25% distillers dried grains with solubles (DDGS); and 3) the high-fiber diet contained corn, soybean meal, 25% DDGS, and 20% soybean hulls. Each diet was divided into 4 batches after mixing. One batch was not further processed and was fed in a meal form, one batch was pelleted at 85°C, one batch was extruded at 115°C using a single-screw extruder, and one batch was extruded at 115°C and then pelleted at 85°C. Thus, 12 different diets were produced. Twenty-four growing pigs (26.5 ± 1.5 kg initial BW) had a T-cannula installed in the distal ileum and were allotted to the 12 diets in a split-plot design with 8 pigs allotted to the low-fiber diets, the medium-fiber diets, and the high-fiber diets, respectively. Diets were fed to the pigs during four 14-d periods. Within each type of diet, the 8 pigs were fed the diets produced using the 4 processing technologies. Therefore, there were 8 replicate pigs per diet. Pigs were adjusted to their diets for 14 d before the experiment was initiated. Each of the four 14-d periods consisted of 5 d for adaptation, 5 d of fecal collection according to the marker to marker approach, and ileal digesta were collected on d 13 and 14. Results indicated that pelleting, extrusion, or extrusion and pelleting improved ($P < 0.05$) the apparent ileal digestibility of starch and most indispensable AA. In most cases, there were no differences between the pelleted, the extruded, and the extruded and pelleted diets. The apparent total tract digestibility of GE was also improved ($P < 0.05$) by pelleting and by the combination of extrusion and pelleting. The ME of pelleted diets was greater ($P < 0.05$) than that of meal diets for the low- and medium-fiber diets, but this was not the case for high-fiber diets (interaction, $P < 0.05$). Medium- and high-fiber diets that were extruded had greater ME ($P < 0.05$) than meal diets, but that was not the case for low-fiber diets. These data indicate that energy utilization may be improved by pelleting or extrusion or by a combination of the 2 technologies, but the response seems to be greater for extrusion in diets that are relatively high in fiber.

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

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INTRODUCTION

Pelleting of pig diets may increase the feed conversion rate by 6 to 7% (Hancock and Behnke, 2001; Richert and DeRouchey, 2010) due to reduced feed wastage and improved digestibility of energy and nutrients, which possibly is a consequence of increased gelatinization of starch (Wondra et al., 1995; Richert and DeRouchey, 2010; NRC, 2012). Recently, it was reported that reduced growth performance of pigs fed diets containing high-fiber coproducts was ameliorated if the diet was pelleted (Fry et al., 2012), in-

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

	Ingredient			
Item	Corn	DDGS	Soybean hulls	Soybean meal
GE, kcal/kg	3,938	4,984	3,907	4,198
DM, %	86.57	87.13	88.30	87.50
CP, %	7.70	26.78	13.56	49.51
Ash, %	1.36	3.89	4.62	6.26
OM, %	85.21	83.24	83.69	81.24
AEE,[1] %	3.79	13.17	2.43	1.72
NDF, %	7.21	25.79	51.79	9.29
ADF, %	2.12	10.38	37.60	7.64
Hemicellulose,[2] %	5.09	15.41	14.19	1.65
P, %	0.27	0.66	0.19	0.61
Ca, %	–	0.05	0.49	0.26
WBC,[3] g/g	1.13	1.93	3.74	2.54
Indispensable AA, %				
Arg	0.34	1.33	0.62	3.56
His	0.24	0.91	0.34	1.38
Ile	0.26	1.02	0.47	2.26
Leu	0.90	3.04	0.83	3.87
Lys	0.26	1.00	0.85	3.11
Met	0.15	0.52	0.15	0.67
Phe	0.37	1.30	0.51	2.60
Thr	0.28	1.04	0.46	1.93
Trp	0.06	0.19	0.06	0.73
Val	0.36	1.35	0.54	2.29
Dispensable AA, %				
Ala	0.55	1.89	0.53	2.15
Asp	0.50	1.67	1.15	5.66
Cys	0.16	0.52	0.20	0.67
Glu	1.35	3.55	1.54	8.90
Gly	0.30	1.08	0.87	2.09
Pro	0.65	2.05	0.63	2.52
Ser	0.36	1.24	0.59	2.30
Tyr	0.23	1.04	0.45	1.87
Total AA	7.32	24.74	10.79	48.56

[1]AEE = acid-hydrolyzed ether extract.

[2]Hemicellulose was calculated as the difference between NDF and ADF.

[3]WBC = water-binding capacity.

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

Ingredient, %	Low fiber	Medium fiber	High fiber
Corn	69.70	47.95	29.90
Soybean meal	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 microminerals per kilogram of complete diet: 11,128 IU vitamin A as retinyl acetate, 2,204 IU vitamin D_3 as cholecalciferol, 66 IU vitamin E as DL-alpha tocopheryl acetate, 1.42 mg vitamin K as menadione nicotinamide bisulfite, 0.24 mg thiamin as thiamine mononitrate, 6.58 mg riboflavin, 0.24 mg pyridoxine as pyridoxine hydrochloride, 0.03 mg vitamin B_{12}, 23.5 mg d-pantothenic acid as d-calcium pantothenate, 44 mg niacin as nicotinamide and nicotinic acid, 1.58 mg folic acid, 0.44 mg biotin, 10 mg Cu as copper sulfate, 125 mg Fe as iron sulfate, 1.26 mg I as potassium iodate, 60 mg Mn as manganese sulfate, 0.3 mg Se as sodium selenite, and 100 mg Zn as zinc oxide.

dicating that responses to pelleting may be different among different types of diets.

Extrusion in the United States is mainly used in the pet food and aqua feed industries and consists of heating, pressuring, and steam conditioning (Hancock and Behnke, 2001). This technology may be used on the mixed diet or on individual ingredients. Extrusion of field peas has a positive effect on the apparent total tract digestibility (**ATTD**) of GE and on the apparent ileal digestibility (**AID**) of starch and most indispensable AA (Stein and Bohlke, 2007; Htoo et al., 2008). Extrusion may also increase the solubility of dietary fiber, which, in turn, may result in increased energy digestibility because soluble fibers are 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. Therefore, the objective of this experiment was to test the hypothesis that pelleting, extrusion, or the combination of extrusion and pelleting is more effective in improving nutrient and energy digestibility in high-fiber diets than in diets containing less fiber.

MATERIALS AND METHODS

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

Sourcing of Ingredients, Processing, and Feed Mixing

Diets containing 3 different levels of fiber (low, medium, or high) were processed at the Bühler Pilot Plant located in Uzwil, Switzerland. The low-fiber diet was based on corn and soybean meal; the medium-fiber diet was based on corn, soybean meal, and 25% distillers dried grains with solubles (**DDGS**); and the high-fiber diet was based on corn, soybean meal, 25% DDGS, and 20% soybean hulls (Tables 1, 2, and 3). Vitamins and minerals were included in all diets to meet or exceed current requirement estimates for growing pigs (NRC, 2012). All diets also contained 0.5% titanium dioxide as an indigestible marker. All raw materials were sourced by Bühler AG (Uzwil,

Table 3. Analyzed nutrient composition of experimental diets, as-fed basis

	Low fiber				Medium fiber				High fiber			
Item	Meal	Pelleted	Ext[1]	EP[1]	Meal	Pelleted	Ext	EP	Meal	Pelleted	Ext	EP
GE, kcal/kg	3,919	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	87.70	87.22	92.07	92.00	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, %	80.45	80.42	84.51	84.02	78.91	78.78	82.35	86.72	83.56	82.50	87.07	82.94
AEE,[2] %	2.33	3.26	2.84	2.76	5.63	6.02	6.19	5.77	5.59	5.84	5.49	5.52
NDF, %	7.75	6.98	7.45	7.67	11.79	11.32	12.58	10.40	20.78	19.80	19.23	20.35
ADF, %	3.65	3.00	2.82	2.68	5.69	5.16	5.17	4.37	12.60	13.24	12.12	12.89
Hemicellulose,[3] %	4.10	3.98	4.63	4.99	6.10	6.16	7.41	6.03	8.18	6.56	7.11	7.46
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
WBC,[4] g/g	1.45	2.04	3.90	5.59	1.55	2.21	3.15	4.30	1.98	2.65	3.77	4.18
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]Ext = extruded; EP = extruded and pelleted.

[2]AEE = acid-hydrolyzed ether extract.

[3]Hemicellulose was calculated as the difference between NDF and ADF.

[4]WBC = water-binding capacity.

Switzerland). Before mixing the diets, all ingredients were ground using a Bühler horizontal hammer mill, model DFZC 655, with the objective of achieving a mean particle size between 550 and 650 µm. Diets were mixed using a Bühler Speedmix DFML paddle mixer. One batch of each diet was mixed, and this batch was then divided into 4 subbatches.

One subbatch of each diet was used in the meal form without further processing. One subbatch of each diet was pelleted after steam conditioning for 120 s using a Bühler DNSA short-term conditioner with a length of 800 mm and a diameter of 250 mm. Pelleting took place at a temperature of 85°C in the conditioned mash using a Bühler 55 kW pellet press, model DPDB 304.75, with a die of 4 × 70 mm. Pelleted diets were cooled in a Bühler model DFKG counter flow cooler. One subbatch of the mixed diet was extruded using a Bühler model AHSF 133 single-screw extruder with a diameter of 133 mm. The temperature of the mash as it passed the cone in the extruder was 115°C. The last subbatch was first extruded at 115°C and then pelleted at 85°C using the same 4 × 70 mm die that was used in the diets that were only pelleted. Following diet processing, diets were packaged in 600-kg plastic-coated tote bags and shipped from Uzwil, Switzerland, to the University of Illinois, Urbana – Champaign, using ocean freight.

Animals, Housing, and Experimental Design

Pigs used in this experiment were the offspring of G-performer boars mated to F-25 gilts (Genetiporc, Alexandria, MN). Twenty-four growing barrows (26.5 ± 1.5 kg initial BW) were equipped with a T-cannula in the distal ileum (Stein et al., 1998). Pigs were allotted to the diets in a split-plot design with 8 pigs allotted to the low-fiber diets, 8 pigs were allotted to the medium-fiber diets, and 8 pigs were allotted to the high-fiber diets. Diets were fed to the pigs during four 14-d periods. Within each type of diet, the 8 pigs were allotted to a repeated 4 × 4 Latin square and fed the diets produced using the 4 processing technologies in such a way that 2 pigs were fed each diet in each period and no pig received the same diet twice. Therefore, there were 8 replicate pigs per diet. Pigs were individually housed in metabolism crates in an environmentally controlled room. A feeder and a nipple drinker were installed in each crate, and a screen and a funnel placed below the slatted floor of the crates allowed for the total, but separate, collection of feces and urine from each pig.

Feeding and Sample Collection

Feed was provided in a daily amount of 3.3 times the maintenance energy requirement (i.e., 197 kcal ME/kg $BW^{0.60}$; 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 on an ad libitum basis throughout the experiment.

To adapt the pigs to the level of fiber in the diets, pigs within each type of diet were fed a mixture of the 4 batches for 14 d before starting the experiment. Pig weights were recorded at the beginning and at the end of each period. The initial 5 d of each period was considered an adaptation period to the diet. Fecal and urine samples were quantitatively collected from d 6 to 11 using the marker-to-marker approach (Adeola, 2001). Feces were collected twice daily and stored at −20°C immediately after collection. Urine collections started on d 6 at 0800 h and ceased on d 11 at 0800 h. Urine buckets were placed under the metabolism crates to permit total collection. Buckets were emptied in the morning and afternoon and a preservative of 50 mL of 6 *N* HCl was added to each bucket when they were emptied. The collected urine was weighed and a 20% subsample was stored at −20°C. Ileal digesta were collected for 8 h on d 13 and 14 using standard operating procedures (Stein et al., 1998).

At the conclusion of the experiment, fecal samples were dried at 65°C in a forced-air oven and ground through a 1-mm screen in a Wiley mill (model 4; Thomas Scientific, Swedesboro, NJ) before analyses. Urine samples were thawed and mixed within animal and diet, and a subsample was lyophilized before energy analysis (Kim et al., 2009). Ileal samples were thawed and mixed within animal and diet, and a subsample was lyophilized and finely ground.

Sample Analysis

Diets, ingredients, ileal digesta, and fecal samples were analyzed for DM (method 930.15; AOAC Int., 2007) and ash (method 942.05; AOAC Int., 2007), and diets, ileal digesta, and fecal samples were also analyzed for starch (method 76-13; AACC International, 2000) using a modified starch assay kit (product code STA-20; Sigma-Aldrich, St. Louis, MO). Diets, ingredients, and fecal samples were analyzed for NDF (Holst, 1973) and ADF (method 973.18; AOAC Int., 2007), and acid-hydrolyzed ether extract (**AEE**) was determined in diets and ingredients by acid hydrolysis using 3 *N HCl* (Sanderson, 1986) followed by crude fat extraction with petroleum ether (method 2003.06, AOAC Int., 2007) on a Soxtec 2050 automated analyzer (FOSS North America, Eden Prairie, MN). Diets and ingredients were also analyzed for water-binding capacity (Robertson et al., 2000) and for P and Ca by inductively coupled plasma spectroscopy (method 975.03; AOAC Int., 2007) after wet ash sample preparation (method 975.03; AOAC Int., 2007). Diets and ileal digesta samples were analyzed for AA (method 982.30 E [a, b, c]; AOAC Int., 2007) and for titanium dioxide (Myers et al., 2004). Diets, ingredients, and ileal samples were also analyzed for CP by combustion (method 999.03; AOAC Int., 2007) using a Rapid N cube (Elementar Americas Inc., Mt. Laurel, NJ). Diets, ingredients, ileal digesta, fecal samples, and urine samples were analyzed for GE using bomb calorimetry (model 6300; Parr Instrument Company, Moline, IL).

Calculations and Statistical Analysis

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

Table 4. Apparent ileal digestibility (%) of GE, starch, CP, DM, ash, OM, acid-hydrolyzed ether extract, and AA in experimental diets[1]

	Type of processing						Level of fiber				
Item	Meal	Pelleted	Ext[2]	EP[2]	SEM	P-value	Low	Medium	High	SEM	P-value
GE	66.16^{d}	68.43^{c}	72.66^{a}	70.96^{b}	0.60	<0.01	76.62^{x}	72.54^{y}	59.50^{z}	0.52	<0.01
Starch	96.39^{b}	97.74^{a}	97.95^{a}	98.35^{a}	0.68	<0.01	98.65^{x}	97.36^{y}	96.81^{y}	0.66	<0.01
CP	72.50^{b}	73.55^{b}	77.91^{a}	76.63^{a}	0.90	<0.01	77.59^{x}	77.15^{x}	70.71^{y}	0.84	<0.01
DM	63.49^{d}	65.28^{c}	69.60^{a}	67.93^{b}	0.67	<0.01	74.67^{x}	69.24^{y}	55.81^{z}	0.60	<0.01
Ash	21.67^{c}	24.42^{bc}	32.42^{a}	27.37^{b}	1.48	<0.01	28.66^{y}	34.32^{x}	16.44^{z}	1.34	<0.01
OM	66.19^{c}	67.88^{b}	71.92^{a}	70.37^{a}	0.64	<0.01	77.43^{x}	71.47^{y}	58.38^{z}	0.57	<0.01
Indispensable AA, %											
Arg	88.27^{b}	88.62^{b}	91.57^{a}	91.13^{a}	0.57	<0.01	90.89^{x}	90.49^{x}	88.32^{y}	0.53	<0.01
His	83.11^{b}	84.94^{a}	85.78^{a}	85.59^{a}	0.61	<0.01	86.99^{x}	85.97^{x}	81.60^{y}	0.57	<0.01
Ile	78.75^{c}	81.34^{b}	84.32^{a}	83.66^{a}	0.44	<0.01	83.81^{x}	83.39^{x}	78.85^{y}	0.38	<0.01
Leu	82.22^{c}	84.85^{b}	87.14^{a}	86.44^{a}	0.35	<0.01	86.12^{x}	86.51^{x}	82.87^{y}	0.30	<0.01
Lys	78.00^{c}	79.59^{b}	81.77^{a}	80.90^{ab}	0.53	<0.01	83.27^{x}	81.16^{y}	75.77^{z}	0.46	<0.01
Met	83.28^{c}	86.45^{b}	87.70^{a}	86.74^{ab}	0.40	<0.01	87.11^{x}	86.81^{x}	84.20^{y}	0.35	<0.01
Phe	81.24^{c}	83.90^{b}	87.25^{a}	86.45^{a}	0.44	<0.01	85.67^{x}	86.01^{x}	82.45^{y}	0.40	<0.01
Thr	70.86^{c}	73.34^{b}	75.74^{a}	74.71^{ab}	0.62	<0.01	74.86^{x}	75.33^{x}	70.80^{y}	0.53	<0.01
Trp	78.05^{c}	80.48^{b}	83.20^{a}	83.39^{a}	0.55	<0.01	83.04^{x}	83.64^{x}	77.16^{y}	0.47	<0.01
Val	75.64^{c}	78.36^{b}	80.46^{a}	79.94^{a}	0.49	<0.01	80.63^{x}	80.47^{x}	74.71^{y}	0.42	<0.01
Mean	80.40^{c}	82.42^{b}	84.89^{a}	84.29^{a}	0.42	<0.01	84.63^{x}	84.36^{x}	80.01^{y}	0.36	<0.01
Dispensable AA, %											
Ala	74.78^{c}	77.42^{b}	80.31^{a}	79.42^{a}	0.87	<0.01	79.88^{x}	79.98^{x}	74.09^{y}	0.82	<0.01
Asp	76.64^{c}	78.16^{b}	80.29^{a}	79.29^{ab}	0.62	<0.01	81.57^{x}	79.24^{y}	74.98^{z}	0.56	<0.01
Cys	66.71	68.59	67.92	67.63	1.09	0.67	71.11^{x}	69.74^{x}	62.30^{y}	0.94	<0.01
Glu	80.19^{c}	83.13^{b}	85.42^{a}	85.65^{a}	0.70	<0.01	86.31^{x}	84.71^{y}	79.77^{z}	0.63	<0.01
Gly	55.65^{b}	54.81^{b}	62.74^{a}	60.43^{a}	2.26	<0.01	62.77^{x}	62.95^{x}	49.49^{y}	2.11	<0.01
Pro	64.99^{a}	53.36^{b}	71.64^{a}	70.61^{a}	4.38	<0.01	62.95^{y}	73.63^{x}	58.87^{y}	4.00	<0.01
Ser	79.06^{c}	80.84^{b}	82.93^{a}	82.31^{a}	0.77	<0.01	82.56^{x}	82.93^{x}	78.38^{y}	0.74	<0.01
Tyr	83.63^{c}	86.20^{b}	87.93^{a}	87.68^{a}	0.44	<0.01	86.98^{x}	87.88^{x}	84.21^{y}	0.38	<0.01
Mean	75.13^{b}	75.10^{b}	79.88^{a}	78.96^{a}	0.95	<0.01	79.71^{x}	79.20^{x}	72.90^{y}	0.86	<0.01
Total AA	77.61^{b}	78.73^{b}	82.21^{a}	81.45^{a}	0.59	<0.01	82.02^{x}	81.61^{x}	76.37^{y}	0.51	<0.01

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

$^{x–z}$Means within a row lacking a common superscript letter differ ($P < 0.05$).

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

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

Data were analyzed as a 3 × 4 factorial with fiber level and postmixing processing as factors using the Mixed procedure of SAS (SAS Inst. Inc., Cary, NC). The model included fiber level, postmixing processing, and the fiber level × postmixing processing interaction as fixed effects and period and pig as the random effects. However, interactions between fiber level and postmixing processing were not significant for the response variables analyzed, except for the concentrations of DE and ME. Therefore, the interaction was removed from the final model and only main effects of fiber level and postmixing processing were included for the variables that had no interaction. Homogeneity of the variances among treatments was confirmed using the HOVTEST = BF procedure of SAS. The UNIVARIATE procedure of SAS was used to test for outliers, but no outliers were identified. The least squares means statement was used to calculate treatment means. The pig was the experimental unit for all analyses and an α level of 0.05 was used to assess significance among means.

RESULTS

The AID of GE and DM was less ($P < 0.05$) for meal diets than for the postmixing processed diets (Table 4). However, the AID of GE and DM was greater ($P < 0.05$) for extruded diets than for pelleted diets or the combination of extruded and pelleted diets than for meal diets. Meal diets had less ($P < 0.05$) AID of starch compared with postmixing processed diets, but no differences were observed for the AID of starch among the postmixing processed diets. The AID of CP and OM was greater ($P < 0.05$) for extruded diets and diets that were extruded and pelleted than for meal diets or pelleted diets, and the AID of OM was greater ($P < 0.05$) for pelleted diets

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

	Type of processing						Level of fiber				
Item	Meal	Pelleted	Ext[2]	EP[2]	SEM	*P*-value	Low	Medium	High	SEM	*P*-value
GE	84.70[b]	85.97[a]	85.54[ab]	86.40[a]	0.68	0.02	90.19[x]	85.66[y]	81.11[z]	0.65	<0.01
Starch	99.59	99.70	99.64	99.69	0.14	0.54	99.91[x]	99.71[y]	99.35[z]	0.14	<0.01
DM	84.87	85.64	85.42	86.24	0.67	0.14	89.99[x]	85.54[y]	81.09[z]	0.64	<0.01
OM	86.21	87.08	86.71	87.79	0.70	0.06	91.75[x]	86.63[y]	82.48[z]	0.67	<0.01
ADF	48.55	53.41	46.38	50.96	2.22	0.10	41.82[z]	46.88[y]	60.78[x]	1.96	<0.01
NDF	54.70	51.77	51.73	53.91	2.62	0.60	53.90[x]	47.09[y]	57.64[x]	2.46	<0.01

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

[x–z]Means within a row lacking a common superscript letter differ ($P < 0.05$).

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

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

than for meal diets. The AID of ash was greater ($P < 0.05$) for extruded diets than for all other diets.

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

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

The ATTD of GE was less ($P < 0.05$) for meal diets than for pelleted diets or diets that were extruded and pelleted, but there were no differences among the postmixing processed diets for the ATTD of GE (Table 5). For starch, DM, OM, ADF, and NDF, no differences among meal, pelleted, extruded, and extruded and pelleted diets were observed. The ATTD of GE, starch, DM, and OM was greater ($P < 0.05$) for medium-fiber diets than for high-fiber diets but less ($P < 0.05$) than for low-fiber diets. High-fiber diets had greater ($P < 0.05$) ATTD of ADF than low- or medium-fiber diets, and the AID of ADF was less ($P < 0.05$) for low-fiber diets than for medium-fiber diets. The ATTD of NDF was greater ($P < 0.05$) for low- and high-fiber diets than for medium-fiber diets.

The hindgut fermentation of GE, DM, and OM was greater ($P < 0.05$) for meal diets or pelleted diets than for the extruded diets or diets that were extruded and pelleted (Table 6), but the hindgut fermentation of GE, DM, and OM was less ($P < 0.05$) for extruded diets than for the combination of extruded and pelleted diets. Meal diets had greater ($P < 0.05$) hindgut fermentation of starch compared with the other diets, but there were no differences in the hindgut fermentation of starch among the postmixing processed diets. The hindgut fermentation of GE, DM, and OM was greater ($P < 0.05$) for high-fiber diets than for low- or medium-fiber diets, but the hindgut fermentation of GE, DM, and OM was not different between low- and medium-fiber diets. Medium- and high-fiber diets had greater ($P < 0.05$) hindgut fermentation of starch than low-fiber diets.

The DE and ME (DM basis) were less ($P < 0.05$) in the high-fiber diets compared with the low- or medium-fiber diets (Table 7). For low-fiber and medium-fiber diets, the DE (DM basis) was less ($P < 0.05$) in the meal diets compared with the pelleted diets, but this was not the case for high-fiber diets (interaction, $P < 0.01$). Medium-fiber and high-fiber diets also had greater ($P < 0.05$) concentrations of DE (DM basis) if diets were extruded compared with the meal diets, but for low-fiber diets, no difference between meal and extruded diets were observed (interaction, $P < 0.01$). The DE (DM basis) was increased ($P < 0.05$) in low-fiber and high-fiber diets but not in medium-fiber diets if diets were extruded and pelleted (interaction, $P < 0.01$).

Low-fiber diets and medium-fiber diets that were pelleted had greater ($P < 0.05$) ME (DM basis) than meal diets, but in high-fiber diets, no difference between meal and pelleted diets was observed (interaction, $P < 0.01$). If diets were extruded, ME (DM basis) increased for medium-fiber and high-fiber diets but not for low-fiber diets (interaction, $P < 0.01$). Extrusion and pelleting also resulted in increased ($P < 0.05$) ME (DM basis) in low-fiber and high-fiber diets but not in medium-fiber diets (interaction, $P < 0.01$).

Table 6. Hindgut fermentation (%) of GE, starch, DM, and OM by growing pigs, as-fed basis[1]

Item	Type of processing				SEM	*P*-value	Level of fiber			SEM	*P*-value
	Meal	Pelleted	Ext[2]	EP[2]			Low	Medium	High		
GE	18.53[a]	17.54[a]	12.87[c]	15.44[b]	1.05	<0.01	13.57[y]	13.12[y]	21.61[x]	1.00	<0.01
Starch	3.20[a]	1.96[b]	1.69[b]	1.34[b]	0.70	<0.01	1.25[y]	2.35[x]	2.54[x]	0.68	<0.01
DM	21.38[a]	20.36[a]	15.81[c]	18.31[b]	1.13	<0.01	15.31[y]	16.30[y]	25.29[x]	0.64	<0.01
OM	20.03[a]	19.19[a]	14.79[c]	17.42[b]	1.12	<0.01	14.32[y]	15.16[y]	24.10[x]	1.08	<0.01

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

[x,y]Means within a row lacking a common superscript letter differ ($P < 0.05$).

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

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

DISCUSSION

The increase in the concentration of energy and nutrients in extruded or extruded and pelleted diets compared with the other diets is a result of the increase in DM in these diets. The heat generated during the extrusion process appears to have removed moisture in the diets, which resulted in the increase in DM. However, if energy and nutrients are expressed on a DM basis, there was no increase in concentrations of energy and nutrients in diets that were extruded or extruded and pelleted.

The increased AID of starch that was observed as diets were pelleted, extruded, or extruded and pelleted is consistent with data for field peas (Stein and Bohlke, 2007) and indicates that starch in corn will become more digestible if extruded or pelleted. This increase in starch digestibility likely had a positive impact on energy utilization by the pigs and may be one of the reasons for the increase in ME that was observed in some of the diets that were extruded. Recently, increased ME of diets containing extruded corn compared with diets containing nonextruded corn was also reported (Liu et al., 2015). However, the ATTD of starch was not different among diets because hindgut fermentation of starch was greater for the meal diets compared with the pelleted, extruded, or extruded and pelleted diets. This observation is a reflection of the fact that starch that escapes digestion in the small intestine is easily fermented in the hindgut, as has previously been reported (Stein and Bohlke, 2007; Cervantes-Pahm et al., 2014). It is, however, assumed that starch that is digested in the small intestine results in absorption of glucose whereas starch that is fermented in the large intestine results in absorption of VFA. The increased DE and ME that is obtained from increasing the AID of starch is, therefore, caused by the more efficient utilization of energy in the form of starch than in the form of microbial fermentation followed by absorption of VFA.

The increase in AID of AA that were observed as diets were pelleted or extruded also is 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 always influence the AID of AA (Herkelman et al., 1990). The reason for the increased AID of AA in diets that are pelleted or extruded may be that processing may partly denature proteins in the diets (Svihus and Zimonja, 2011), which increases digestion by small intestinal proteases. The improvements obtained in the present experiment for the AID of most AA was 3 to 4 percentage units, which will add value to the diets because the inclusion of soybean meal or other protein sources potentially can be reduced if diets are pelleted, extruded, or extruded and pelleted. Therefore, the costs of pelleting or extrusion may be fully or partly offset by reducing the inclusion of protein meals in the diets.

The increased hindgut fermentation of OM observed as the level of fiber increased in the diet was expected, because more substrate in the hindgut will increase fermentation (Anguita et al., 2006). However, the observation that ME in the diets was reduced if high-fiber ingredients are included is a result of the reduced efficiency of hindgut fermentation compared with small intestinal digestion (Noblet and le Goff, 2001; Anguita et al., 2006; le Gall et al., 2009).

The increased DE and ME in some of the diets that were pelleted, extruded, or extruded and pelleted was not a result of increased fermentation of fiber as indicated by the lack of differences in ATTD of ADF and NDF. Instead, the increased ATTD of GE that was observed for pelleted diets and diets that were extruded and pelleted appeared to be a result of increased AID of AA and starch. This observation is in agreement with data indicating that extrusion of field peas also results in an increase in ATTD of GE (Stein and Bohlke, 2007). Pigs fed diets that were pelleted or extruded also have an improved 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; Hongtrakul et al., 1998; Xing et al., 2004; Lundblad et al., 2011). Although G:F was not determined in the current experiment, it is, therefore, likely that the improvement in DE and ME that was determined as diets were pelleted or extruded will result in improved G:F for growing pigs.

Table 7. Concentration of DE and ME (kcal/kg, DM basis) in experimental diets[1]

	Low fiber				Medium fiber				High fiber					*P*-value		
Item	Meal	Pelleted	Ext[2]	EP[2]	Meal	Pelleted	Ext	EP	Meal	Pelleted	Ext	EP	SEM	Fiber	Process	Fiber × process
DE	4,105[e]	4,184[bc]	4,117[de]	4,168[cd]	4,192[cde]	4,272[ab]	4,289[a]	4,144[cde]	3,777[h]	3,810[gh]	3,853[fg]	3,888[f]	42	<0.01	<0.01	<0.01
ME	3,868[d]	3,949[bc]	3,893[cd]	3,957[bc]	3,947[cd]	4,044[ab]	4,055[a]	3,926[cd]	3,583[f]	3,651[ef]	3,687[e]	3,717[e]	44	<0.01	<0.01	<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.

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

The ME values that were obtained for the low-fiber and medium-fiber meal diets were very close to values calculated for these diets from NRC (2012), but the ME of the high-fiber diet was approximately 160 kcal/kg greater than the value calculated from NRC, which indicates that the soybean hulls may have contained more ME than predicted from NRC (2012). The lack of a difference in ME between the low-fiber and medium-fiber diets is also in agreement with expectations because ME in conventional DDGS is not different from ME in corn (Pedersen et al., 2007; NRC, 2012). The reduction in ME in the high-fiber diets compared with the low- or medium-fiber diet was expected because there is a linear reduction in the ATTD of GE as NDF in diets increases (Jaworski et al., 2015). The increase in NDF from the low-fiber to the high-fiber diet was 10 to 12 percentage units, and the reduction in ATTD of GE was approximately 10 percentage units. This observation is in agreement with le Gall et al. (2009), who suggested that the ATTD of GE will be reduced by 1 percentage unit for each 1 percentage unit NDF increases in the diet.

The increase in ME that was observed as a result of pelleting was calculated as 2.1, 2.5, and 1.9% increase for the low-fiber, the medium-fiber, and the high-fiber diets, respectively, if compared with the meal diets. These values are greater than the improvement of approximately 1.5% that was reported by le Gall et al. (2009) for pelleted diets. However, the improvement in ME obtained in this experiment is less than the improvement in the feed conversion rate that has been reported when pigs are offered ad libitum access to pelleted diets (Wondra et al., 1995; Xing et al., 2004; Ulens et al., 2015). It is possible that some of the improvement in the feed conversion rate observed for pelleted diets offered to pigs on an ad libitum basis is a result of reduced feed wastage, because if diets are pelleted and then ground into a meal, feed efficiency is not different from that observed for an unpelleted meal diet (Lewis et al., 2015). With the restricted feeding regime used in this experiment, feed wastage was less of a problem, and any wastage was carefully collected and weighed and subtracted from feed allowance to calculate feed consumption.

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

In conclusion, pelleting, extrusion, or a combination of extrusion and pelleting improved the AID of starch and most AA regardless of the level of fiber in the diet. The increase in ATTD of GE that was observed in diets that were pelleted, extruded, or extruded and pelleted was not a result of increased fermentation of fiber but likely a result of the increased digestibility of starch and AA. The increase in ME that was observed for pelleting or extrusion was between 0.6 and 2.9% for the 3 types of diets. However, if diets were extruded and pelleted, ME increased by up to 3.7%, with the greatest improvement observed for the diet with the greatest concentration of fiber. This indicates that if high-fiber ingredients are used in diets fed to pigs, extrusion or the combination of extrusion and pelleting may ameliorate some of the reduction of energy that is observed when those ingredients are added to the diet.

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