Energy content and amino acid digestibility of extruded and dehulled-extruded corn by pigs and its effect on the performance of weaned pigs

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ABSTRACT: Three experiments were conducted to compare raw corn, extruded corn, and dehulled-extruded corn in piglets' feeding. In Experiment (Exp.) 1, 8 barrows (19.9 ± 0.6 kg) were fed experimental diets containing one out of three corn samples and a rice-soybean meal basal diet in a double 4 × 4 Latin square design to determine the digestible energy (DE) and metabolizable energy (ME) in the corn samples using the difference method. The DE content in extruded (14.29 MJ/kg) and dehulled-extruded (14.42 MJ/kg) corn was greater (P < 0.05) than in raw corn (13.57 MJ/kg). In Exp. 2, 5 barrows (26.2 ± 1.3 kg) were fitted with ileal T-cannulas and used in a 5 × 5 Latin square design to determine the apparent (AID) and standardized (SID) ileal digestibility of amino acids (AA). The diets comprised the basal diet, the three corn diets from Exp. 1, as well as a nitrogen-free diet to estimate basal endogenous losses of AA. The AID and SID of isoleucine, leucine, lysine, threonine, and valine in dehulled-extruded corn was lower (P < 0.05) than in raw or extruded corn. In Exp. 3, 108 weaned 35 days old piglets (8.4 ± 1.2 kg) were allotted to one of the three diets based on corn type. Weaned pigs fed diets containing extruded or dehulled-extruded corn exhibited reduced (P < 0.05) weight gain and feed intake than pigs fed diets containing raw corn. The diet containing dehulled-extruded corn resulted in a higher incidence of diarrhoea. In summary, extrusion of corn did not result in improvements in digestibility and dehulling corn prior to extrusion appeared to result in heat damage which reduced ileal digestibility of AA. Substitution of raw corn with extruded or dehulled-extruded corn in starter diets formulated to equal quantities of ME and SID AA content did not improve the performance of weaned pigs.

Keywords: digestible energy; extrusion processing; growth; metabolizable energy

Extrusion is a short time processing technology involving heat (Van Der Poel et al., 1990). Extrusion of raw corn increases starch gelatinization and the surface area of the starch granules (Bjorck et al., 1985; Muley et al., 2007), which enhances the digestion of starch (Van Kempen et al., 2007; Wierenga et al., 2008). Therefore, the utilization of energy may be greater in pigs fed extruded corn versus raw corn. However, the ileal digestibility of lysine or nitrogen in extruded corn is not different from that in raw corn (Herkelman et al., 1990; Chae et al., 2000). Dietary fibre reduces energy and nutrient digestibility by pigs and as a consequence, increases fecal mass and nutri-

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ent excretion (Shi and Noblet, 1994; Canh et al., 1998; Davidson and McDonald, 1998). Although the fibre content (e.g. 5–10% neutral detergent fibre (NDF)) of corn is low, approximately 50% of the total dietary fibre in corn-based diets may be attributed to corn. This fibre plays a key role in affecting nutrient digestibility (Moeser et al., 2002). Therefore, dehulling of corn to reduce its fibre content is one way to improve its nutritional value (Muley et al., 2007).

Extrusion could increase starch gelatinization and the proportion of rapidly digestible starch (Sun et al., 2006), while dehulling decreases the fibre content (Moeser et al., 2002) and, therefore, dehulled-extruded corn possesses both advantages. The hypothesis of our study, therefore, was that pigs fed diets containing extruded and dehulled-extruded corn would have better nutrient and energy digestibility and thereby performance will be increased. Limited data are available evaluating the nutrient utilization and feeding value of extruded and dehulled-extruded corn for pigs. Therefore, the objective of this study was to determine the digestibility of the energy and amino acids (AA) in corn subjected to extrusion and dehulled-extrusion processing and to subsequently use these values in diet formulation to determine the effects of its use on the performance of weaned pigs.

MATERIAL AND METHODS

General. Experimental materials of raw, extruded, and dehulled-extruded corn came from a single batch and were obtained from Shandong Province in P.R. China. Dehulled corn was not available from the manufactory. Dehulled-extruded corn was dehulled by an emery-roller dehuller (model MNS180) (Zhengzhou Chengli Grain & Oil Machinery Company, Zhengzhou, P.R. China) prior to extrusion. Both the extruded and the dehulled-extruded corn were processed after being ground in a hammer mill with a 2.5-mm screen. The extruded as well as the dehulled-extruded corn were extruded by a single-screw extruder (model TPH200C) (Jiangsu Muyang Group, Jiangsu, P.R. China). The unit was equipped with a volumetric feeding system and a die-nozzle having an 8-mm diameter opening. The length and diameter of the screw were 900 and 30 mm, respectively (production rate: 1 t/h, motor: 132 kW). The raw and the dehulled corn were both steam-cooked at 80°C for 20 s and then expanded at 110°C for 5 s. The temperature was measured with an infrared non-contact MT4 thermometer (Raytek GmbH, Berlin, Germany). The corn was mixed with tap water to provide a total moisture content of 14%. After extrusion, the corn was cooled by a counterflow coolling procedure and ground through a 2.5-mm screen to provide the corn samples in mash form. All corn samples were analyzed to determine nutrient and energy content, starch gelatinization, and particle size before starting the experiment (Table 1).

The animal protocols used in these experiments were approved by the China Agricultural University Institutional Animal Care and Use Committee (Beijing, P.R. China). All pigs used were Duroc × (Landrace × Large White) crossbred barrows. In Exp. 1 and 2, pigs were individually housed in 1.2 × 0.7 × 0.96 m stainless steel metabolism cages located in an environmentally controlled room (22 ± 2°C). In Exp. 3, the weaned pigs were housed in groups of 6 in 1.8 × 1.2 m pens with half the floor solid cement and half the floor plastic slats. Piglets had *ad libitum* access to feed and water.

Experiment 1: Energy digestibility. Eight barrows (19.9 ± 0.6 kg body weight (BW)) were used to measure the digestible energy (DE) and metabolizable energy (ME) content, as well as the apparent total tract digestibility (ATTD) of various chemical constituents in raw, extruded, and dehulled-extruded corn. Pigs were individually housed in 1.2 × 0.7 × 0.96 m stainless steel metabolism cages designed to allow separate collection of urine and faeces and were allotted to double 4 × 4 Latin square design with four periods and four diets and each diet was fed to eight pigs.

The diets comprised a rice-soybean meal basal diet and three experimental diets that were formulated to contain 38.64% of raw, extruded or dehulled-extruded corn added at the expense of the rice-soybean meal basal diet (Table 2). Diets were formulated by using the analyzed chemical composition of the three corn samples (Table 1).

The daily feed allowance was equivalent to 4% of body weight at the beginning of each experimental period (Adeola, 2001) and was divided into two equal portions at 8:00 and 17:00 h and fed in mash form. Water was provided *ad libitum* through a nipple drinker. The amount of feed supplied each day was recorded as well as any feed refusals.

Each experimental period consisted of a 7-day adaptation period followed by a 5-day total collection of faeces and urine. The collection of faeces

Table 1. Particle size, degree of gelatinization, and chemical composition of raw, extruded, and dehulled-extruded corn (% as-fed basis)[1]

Item	Raw corn	Extruded corn	Dehulled-extruded corn
Dry matter	86.65	89.99	89.07
Crude protein	8.00	7.96	7.94
Ether extract	4.10	4.13	3.99
Total starch	58.42	61.08	64.42
Gelatinized starch	5.37	57.84	62.17
Gelatinized starch (% of total starch)	9.20	94.69	96.52
Neutral detergent fibre	9.88	9.83	7.64
Acid detergent fibre	1.58	1.59	1.50
Ash	1.22	1.20	1.11
Calcium	0.03	0.02	0.03
Phosphorus	0.14	0.19	0.17
Gross energy (MJ/kg)	15.77	16.39	16.18
Indispensable amino acids			
Arginine	0.34	0.37	0.34
Histidine	0.25	0.25	0.24
Isoleucine	0.31	0.32	0.29
Leucine	0.95	0.97	0.96
Lysine	0.22	0.20	0.17
Methionine	0.16	0.17	0.17
Phenylalanine	0.38	0.37	0.36
Threonine	0.28	0.27	0.24
Tryptophan	0.05	0.06	0.06
Valine	0.36	0.35	0.33
Dispensable amino acids			
Alanine	0.56	0.51	0.50
Aspartate	0.51	0.51	0.49
Cystine	0.22	0.21	0.21
Glutamate	1.33	1.33	1.32
Glycine	0.28	0.30	0.26
Proline	0.75	0.74	0.72
Serine	0.34	0.33	0.30
Tyrosine	0.27	0.25	0.22
Lysine/crude protein	2.75	2.51	2.14
Particle size (μm)	461	453	466

[1]all data are the results of a chemical analysis conducted in duplicate

and urine samples was conducted according to the methods described by Song et al. (2003). Faeces were collected, sealed in plastic bags, and stored at −20°C. Urine was collected into plastic buckets containing 50 ml of 6N HCl and emptied each afternoon. The collected urine was weighed and 10% of the daily urinary excretion was stored at −20°C. At the end of the experiment, faeces and urine samples were thawed and separately mixed within animal and diet and a sub-sample was saved for chemical analysis. Faecal samples were oven-dried at 65°C for 72 h, ground through a 1-mm screen, and thoroughly mixed before a sub-sample was collected for chemical analysis. Faecal, urine, diet, and ingredient samples were analyzed using a bomb calorimeter (model 6400; Parr Instrument Company, Moline, USA) to determine gross energy (GE). The ATTD of GE in each diet was then calculated. The amount of energy lost in the faeces and urine, respectively, was calculated as well, and the quantities of DE and ME in each of the 4 diets were calculated. The DE and ME in the basal diet was then multiplied by 61.36% to calculate the contribution from the basal diet to the DE and ME in diets containing raw, extruded, or dehulled-extruded corn. The DE and ME in raw, extruded, and dehulled-extruded corn were then calculated by difference (Adeola, 2001).

Experiment 2: Amino acid digestibility. Five barrows (26.2 ± 1.3 kg BW) were surgically fitted with a T-cannula in the distal ileum using procedures adapted from Stein et al. (1998). Before surgery, the barrows were fasted for 24 h. The post-operative period was 14 days during which the pigs were fed a commercial corn-soybean meal diet *ad libitum*. Housing for pigs was similar to that described for Exp. 1.

Pigs were allotted randomly to 5 dietary treatments in a 5 × 5 Latin square design, with five pigs and five periods, to measure the apparent ileal digestibility (AID) of crude protein (CP) and AA in raw, extruded, and dehulled-extruded corn. Each diet was fed to five pigs. The basal diet and the three experimental diets were similar to those in Exp. 1 (Table 3). A nitrogen-free diet was used to estimate basal endogenous losses of dry matter (DM), crude protein, and AA. All diets contained 0.3% chromic oxide as an indigestible marker to calculate the nutrient digestibility.

The daily feed allowance was equivalent to 4% of BW at the beginning of each experimental period (Adeola, 2001) and was divided into two equal

Table 2. Composition of experimental diets used in Experiment 1 (% as-fed basis)

Ingredient	Basal diet	Experimental diets		
		raw corn	extruded corn	dehulled-extruded corn
Raw corn	–	38.64	–	–
Extruded corn	–	–	38.64	–
Dehulled-extruded corn	–	–	–	38.64
Rice	64.00	38.40	38.40	38.40
Soybean meal	32.30	19.38	19.38	19.38
Monocalcium phosphate	1.60	1.60	1.60	1.60
Limestone	1.00	1.00	1.00	1.00
Salt	0.30	0.30	0.30	0.30
L-Lysine·HCl (78%)[1]	0.30	0.18	0.18	0.18
Vitamin-mineral premix[2]	0.50	0.50	0.50	0.50
Chemical content (analyzed values)				
Dry matter	87.66	87.71	88.41	88.07
Crude protein	21.92	16.18	15.97	15.74
Ether extract	1.89	2.81	2.82	2.81
Total starch	49.46	56.10	57.97	59.23
Neutral detergent fibre	4.33	5.42	5.47	4.42
Acid detergent fibre	1.21	1.44	1.43	1.00
Ash	4.87	4.54	4.55	4.49
Calcium	0.91	0.97	0.96	0.97
Phosphorus	0.51	0.49	0.49	0.48
Gross energy (MJ/kg)	15.52	15.56	15.82	15.74

[1]provided by Dacheng Group (Changchun, P.R. China)

[2]nutrients provided per kg of diet: vitamin A 5512 IU, vitamin D_3 2200 IU, vitamin E 30 IU, vitamin K_3 2.2 mg, vitamin B_{12} 27.6 µg, riboflavin 4 mg, pantothenic acid 14 mg, niacin 30 mg, choline chloride 400 mg, folacin 0.7 mg, thiamine 1.5 mg, pyridoxine 3 mg, biotin 44 µg, Mn (MnO) 40 mg, Fe ($FeSO_4 \cdot H_2O$) 75 mg, Zn (ZnO) 75 mg, Cu ($CuSO_4 \cdot 5H_2O$) 100 mg, I (KI) 0.3 mg, Se (Na_2SeO_3) 0.3 mg

portions at 8:00 and 17:00 h and fed in mash form. Water was provided *ad libitum* through a nipple drinker. Each experimental period consisted of a 5-day acclimation period followed by a 2-day (10 h/day) ileal digesta collection as described by Stein et al. (2006). A plastic bag was attached to the cannula barrel using a cable tie and the digesta flowing into the bag was collected. Bags were removed whenever they were filled with digesta and immediately stored at –20°C to prevent bacterial degradation of AA. At the end of the experiment, the ileal samples were thawed and mixed within animal and diet, and a sub-sample was taken and lyophilized in a vacuum-freeze dryer (Tofflon Freezing Drying Systems, Shanghai, P.R. China), ground through a 1-mm screen, and thoroughly mixed before chemical analysis. Values for AID and standardized ileal digestibility (SID) of CP and AA were then calculated for each diet (Stein et al., 2007). The AID and SID values for the basal diet were used to calculate the contribution of rice, soybean meal, and L-Lys (lysine) HCl to the diets containing raw, extruded, and dehulled-extruded corn. The AID and SID in raw, extruded, and dehulled-extruded corn was calculated by difference (Fan and Sauer, 1995). Basal endogenous losses were assumed to be proportional to DM intake (Hess and Sève, 1999).

Experiment 3: Performance trial. A total of 108 weaned pigs (35 ± 2 days of age and 8.4 ± 1.2 kg BW) were used in a 28-day experiment to determine the influence of the different corn processing techniques on pig performance. Weaned pigs were weighed and allotted by sex, ancestry, and weight. Each treatment was fed to six pens (three pens of barrows and three pens of gilts) of pigs with six pigs

Table 3. Composition of experimental diets used in Experiment 2 (% as-fed basis)

Ingredient	Basal diet	N-free diet	Experimental diets		
			raw corn	extruded corn	dehulled-extruded corn
Raw corn	–	–	38.52	–	–
Extruded corn	–	–	–	38.52	–
Dehulled-extruded corn	–	–	–	–	38.52
Rice	64.00	–	38.40	38.40	38.40
Soybean meal	32.00	–	19.20	19.20	19.20
Cornstarch	–	73.35	–	–	–
Soybean oil	–	3.00	–	–	–
Sucrose	–	15.00	–	–	–
Cellulose acetate	–	4.00	–	–	–
Monocalcium phosphate	1.60	3.00	1.60	1.60	1.60
Limestone	1.00	–	1.00	1.00	1.00
Salt	0.30	0.45	0.30	0.30	0.30
L-Lysine·HCl (78%)[1]	0.30	–	0.18	0.18	0.18
Chromic oxide	0.30	0.30	0.30	0.30	0.30
Potassium carbonate	–	0.30	–	–	–
Magnesium oxide	–	0.10	–	–	–
Vitamin-mineral premix[2]	0.50	0.50	0.50	0.50	0.50
Chemical content (analyzed values)					
Dry matter	87.66	88.25	87.58	88.44	88.19
Crude protein	20.76	2.13	16.12	16.05	15.72
Ether extract	1.88	3.16	2.88	2.89	2.84
Neutral detergent fibre	4.33	–	5.61	5.50	4.93
Acid detergent fibre	1.21	–	1.14	1.13	1.09
Ash	4.87	3.40	4.66	4.59	4.50
Calcium	0.81	0.77	0.87	0.91	0.86
Phosphorus	0.45	0.43	0.49	0.46	0.46
Gross energy (MJ/kg)	15.43	15.70	15.53	15.73	15.55
Indispensable amino acids					
Arginine	1.41	–	0.99	0.96	0.97
Histidine	0.53	–	0.43	0.42	0.41
Isoleucine	0.90	–	0.65	0.64	0.63
Leucine	1.47	–	1.23	1.25	1.24
Lysine	1.32	–	0.90	0.87	0.86
Methionine	0.28	–	0.26	0.25	0.23
Phenylalanine	0.98	–	0.74	0.73	0.75
Threonine	0.70	–	0.52	0.54	0.51
Tryptophan	0.22	–	0.15	0.16	0.15
Valine	1.01	–	0.77	0.75	0.74
Dispensable amino acids					
Alanine	0.90	–	0.76	0.74	0.74
Aspartate	2.12	–	1.48	1.46	1.45
Cystine	0.36	–	0.34	0.33	0.34
Glutamate	3.57	–	2.74	2.71	2.70
Glycine	0.84	–	0.62	0.72	0.70
Proline	0.96	–	0.91	0.86	0.81
Serine	0.76	–	0.56	0.54	0.52
Tyrosine	0.60	–	0.40	0.42	0.39

[1]provided by Dacheng Group (Changchun, P.R. China)

[2]nutrients provided per kg of diet: vitamin A 5512 IU, vitamin D_3 2200 IU, vitamin E 30 IU, vitamin K_3 2.2 mg, vitamin B_{12} 27.6 µg, riboflavin 4 mg, pantothenic acid 14 mg, niacin 30 mg, choline chloride 400 mg, folacin 0.7 mg, thiamine 1.5 mg, pyridoxine 3 mg, biotin 44 µg, Mn (MnO) 40 mg, Fe ($FeSO_4 \cdot H_2O$) 75 mg, Zn (ZnO) 75 mg, Cu ($CuSO_4 \cdot 5H_2O$) 100 mg, I (KI) 0.3 mg, Se (Na_2SeO_3) 0.3 mg

Table 4. Composition of experimental diets used in Experiment 3 (% as-fed basis)

Ingredient	Experimental diets		
	raw corn	extruded corn	dehulled-extruded corn
Raw corn	55.78	–	–
Extruded corn	–	58.39	–
Dehulled-extruded corn	–	–	58.55
Wheat bran	1.50	1.50	1.50
Dehulled soybean meal	17.67	17.27	17.22
Extruded soybean	9.50	9.50	9.50
Fish meal	3.00	3.00	3.00
Whey power	5.00	5.00	5.00
Soybean oil	2.50	0.28	0.10
Limestone	0.38	0.50	0.45
Monocalcium phosphate	1.37	1.25	1.30
Chromic oxide	0.25	0.25	0.25
Salt	0.34	0.34	0.34
L-Lysine·HCl (78%)[1]	0.38	0.40	0.43
L-Threonine (98.5%)	0.17	0.18	0.18
L-Tryptophan (98%)	0.01	0.01	0.01
DL-Methionine (99%)[2]	0.15	0.13	0.16
Vitamin-mineral premix[3]	2.00	2.00	2.00
Chemical content (analyzed values)			
Dry matter	90.86	91.81	91.81
Crude protein	19.06	18.96	18.91
Ether extract	6.99	4.89	4.64
Neutral detergent fibre	13.63	13.46	10.47
Acid detergent fibre	3.92	3.92	3.61
Ash	5.59	5.54	5.51
Calcium	0.78	0.76	0.75
Phosphorus	0.66	0.67	0.67
Gross energy (MJ/kg)	16.88	16.66	16.62
Calculated values[4]			
Metabolizable energy (MJ/kg)	13.80	13.80	13.80
SID lysine	1.25	1.25	1.24
SID methionine + cystine	0.73	0.73	0.73
SID threonine	0.78	0.78	0.78
SID tryptophan	0.20	0.21	0.20

[1]provided by Dacheng Group (Changchun, P.R. China)

[2]provided by Novus (Littleton, USA)

[3]nutrients provided per kg of diet: vitamin A 9000 IU, vitamin D_3 3000 IU, vitamin E 64 IU, vitamin K_3 3 mg, vitamin B_{12} 12 μg, riboflavin 5.5 mg, pantothenic acid 15 mg, niacin 40 mg, choline chloride 551 mg, folacin 0.8 mg, thiamine 1.5 mg, pyridoxine 3 mg, biotin 100 μg, Mn (MnO) 40 mg, Fe ($FeSO_4 \cdot H_2O$) 100 mg, Zn (ZnO) 100 mg, Cu($CuSO_4 \cdot 5H_2O$) 150 mg, I (KI) 0.3 mg, Se(Na_2SeO_3) 0.3 mg

[4]metabolizable energy was calculated on the basis of Experiment 1, SID (standardized ileal digestibility of amino acids) was calculated on the basis of Experiment 2

per pen. Each pen contained one nipple drinker and four-hole self-feeders to provide pigs *ad libitum* access to water and feed. The temperature of the nursery was 35°C for the first week and for the remainder of the experiment it was reduced to 22–29°C. A commercial pre-starter diet based on corn-soybean meal was fed to the piglets from weaning to the start of the experiment, and the adaptation and transition period lasted for 3 days. The three diets (Table 4) containing raw, extruded, and dehulled-extruded corn were fed in mash form and were formulated to contain equal quantities of ME and SID lysine, methionine, threonine, and tryptophan concentrations. The ME concentrations and SID AA values used for raw, extruded, and dehulled-extruded corn were obtained from Exp. 1 and 2, diets were formulated to meet or exceed the nutrient requirements recommended by National Research Council (2012).

Weaned pigs and feeders were weighed on days 0, 14, and 28 to evaluate weight gain, feed intake, and feed efficiency. Pigs that showed signs of diarrhoea, as assessed by veterinarian inspection, were treated with Pefloxacin Mesylate (Hebei Huarun Pharmaceutical Company, Shijiazhuang, P.R. China) (intramuscular injection of 0.1 ml per kg BW for three consecutive days). The diarrhoea incidence was estimated by pen as the proportion of days in which pigs showed clinical signs of diarrhoea symptoms with respect to the total number of days on trial as described by Mateos et al. (2007).

Chemical analysis. The raw, extruded, and dehulled-extruded corn, as well as diets, faeces, and digesta samples were analyzed for crude protein (Thiex et al., 2002), ether extract (Thiex et al., 2003), DM (AOAC, 2000; method 930.15), starch (AOAC, 2000; method 948.02), ash (AOAC, 2000; method 942.05), calcium (AOAC, 2000; method 927.02), phosphorus (AOAC, 2000; method 965.17), NDF (Van Soest et al., 1991), acid detergent fibre (ADF) (Van Soest et al., 1991), and GE was determined with an adiabatic oxygen bomb calorimeter (model 6400; Parr Instrument Company). Gelatinized starch in raw, extruded, and dehulled-extruded corn was determined by enzymatic hydrolysis as described by Xiong et al. (1990).

Before analysis of AA, raw, extruded, and dehulled-extruded corn as well as the diets used in Exp. 2 and ileal digesta samples were hydrolyzed with 6N HCl at 110°C for 24 h (AOAC, 2000; method 999.13) and analyzed for AA using an amino acid analyzer Hitachi L-8900 (Hitachi, Tokyo, Japan). Methionine and cystine were determined as methionine sulfone and cysteic acid after cold performic acid oxidation overnight and hydrolyzing with 7.5N HCl at 110°C for 24 h (AOAC, 2000; method 994.12). Tryptophan was determined after LiOH hydrolysis at 110°C for 22 h (AOAC, 2000; method 998.15) using high performance liquid chromatography (Agilent 1200 Series; Agilent Technologies Inc., Santa Clara, USA). The chromium concentration of diets and digesta samples from Exp. 2 were measured (AOAC, 2000; method 993.23) after nitric acid-perchloric acid wet ash sample preparation.

Statistical analysis. Data for Exp. 1 and 2 were analyzed using the MIXED procedure of SAS (Statistical Analysis System, Version 8.2, 2001), diet was the fixed effect, and period and pig were the random factor in the statistical model. Exp. 3 was analyzed on the basis of weight, gender, and

Table 5. Energy content (MJ/kg as-fed basis) and apparent total tract digestibility of various chemical constituents in raw, extruded, and dehulled-extruded corn diets (Experiment 1)[1]

Item	Experimental diets			Basal diet	SEM	*P*-value
	raw corn	extruded corn	dehulled-extruded corn			
Digestible energy	13.80[b]	14.10[a]	14.16[a]	13.99[ab]	0.08	0.04
Metabolizable energy	13.31	13.64	13.67	13.31	0.12	0.07
ME : DE ratio	0.97	0.97	0.97	0.95	0.01	0.18
Digestibility (%)						
Dry matter	88.65	88.33	89.02	89.45	0.56	0.47
Gross energy	88.68	89.15	89.95	90.49	0.59	0.15
Crude protein	82.35	83.51	83.14	85.09	1.15	0.42
Starch	99.68	99.73	99.72	99.68	0.03	0.32
Organic matter	91.06	90.78	91.70	92.49	0.50	0.11
Neutral detergent fibre	51.36[b]	51.81[b]	53.55[b]	65.67[a]	1.35	< 0.01
Acid detergent fibre	32.09	33.10	37.27	41.57	2.88	0.13
Ash	44.38	43.24	39.06	37.94	2.09	0.06

[1]data are means of 8 observations

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

ancestry in a randomized complete block design by GLM procedure of SAS (Statistical Analysis System, Version 8.2, 2001), and pen was considered as statistic unit. The differences among means were determined by Tukey's Multiple Range Test. Results were considered significant at $P \leq 0.05$ and considered a trend at $P \leq 0.1$.

RESULTS

Chemical composition of corn samples. As expected, the amount of gelatinized starch increased due to extrusion and the proportion of gelatinized starch of total starch in extruded and dehulled-extruded corn almost 10 times as compared with raw corn (Table 1). Also as expected, the concentration of NDF in dehulled-extruded corn was much lower than in raw and extruded corn. The CP content was similar among the corn samples, but the concentration of AA, especially lysine (Lys), in dehulled-extruded corn was lower than in raw and extruded corn. Finally, the Lys/CP ratio was 2.75, 2.51, and 2.14% in raw, extruded, and dehulled-extruded corn, respectively.

Experiment 1: Energy digestibility. The DE content (Table 5) in the extruded and dehulled-extruded corn diet was greater ($P < 0.05$) than in the raw corn diet, while the DE content in the basal diet was not different from the three test diets. The DE content (Table 6) was greater by 5.30 and 6.26% ($P < 0.05$) in extruded and dehulled-extruded corn compared with raw corn (14.29 and 14.42 MJ/kg vs. 13.57 MJ/kg), while the concentration of ME in extruded and dehulled-extruded corn tended to increase ($P = 0.09$) compared with raw corn. The ME and DE ratio of the three corn samples was similar. As should be expected, the ATTD of starch in the three corn ingredients was close to 100%. There were no differences among the three corn ingredients for the ATTD of any chemical constituent measured.

Experiment 2: Amino acid digestibility. The AID (Table 7) and SID (Table 9) of CP in the extruded corn diet and the basal diet was greater ($P < 0.05$) than in the dehulled-extruded diet, and the AID and SID of isoleucine, leucine, lysine, phenylalanine, threonine, valine, alanine, and serine in the dehulled-extruded corn diet were lower ($P < 0.05$) than in the other three diets. The AID (Table 8) and SID (Table 10) of CP in extruded corn was greater ($P < 0.05$) than in dehulled-extruded corn, while the AID and SID of CP in raw corn was not different from either extruded or dehulled-extruded corn. The AID and SID of isoleucine, leucine, lysine, threonine, valine, alanine, and serine in dehulled-extruded corn were lower ($P < 0.05$) than those in raw and extruded corn, but there was no difference, except for the AID and SID of methionine, between the AID and SID of AA in extruded and raw corn. The AID and SID of methionine was greater ($P < 0.01$) in extruded corn than in raw and dehulled-extruded corn.

Table 6. Energy content (MJ/kg as-fed basis) and apparent total tract digestibility of various chemical constituents in raw, extruded, and dehulled-extruded corn (Experiment 1)[1]

	Raw corn	Extruded corn	Dehulled-extruded corn	SEM	*P*-value
Digestible energy	13.57[b]	14.29[a]	14.42[a]	0.19	0.04
Metabolizable energy	13.29	14.15	14.19	0.28	0.09
ME : DE ratio	0.98	0.99	0.99	0.01	0.87
Digestibility (%)					
Dry matter	87.44	86.65	88.37	1.31	0.67
Gross energy	85.98	87.15	89.13	1.38	0.34
Crude protein	78.23	81.13	80.19	3.06	0.80
Starch	99.66	99.80	99.78	0.06	0.17
Organic matter	88.93	88.22	90.53	1.18	0.43
Neutral detergent fibre	29.89	31.03	35.38	2.98	0.41
Acid detergent fibre	19.71	20.38	30.81	3.86	0.06
Ash	54.04	51.20	40.74	4.56	0.19

[1]data are means of 8 observations

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

Table 7. Apparent ileal digestibility of chemical constituents in raw, extruded, and dehulled-extruded corn diets (Experiment 2)[1]

Item	Experimental diets			Basal diet	SEM	P-value
	raw corn	extruded corn	dehulled-extruded corn			
Crude protein	78.36^{ab}	82.20^{a}	74.12^{b}	80.68^{a}	1.36	< 0.01
Indispensable amino acids						
Arginine	89.54^{b}	89.27^{b}	87.67^{b}	92.54^{a}	0.67	< 0.01
Histidine	83.02^{b}	84.43^{ab}	81.87^{b}	88.62^{a}	1.02	< 0.01
Isoleucine	83.05^{ab}	82.09^{b}	73.94^{c}	87.52^{a}	1.15	< 0.01
Leucine	82.38^{b}	83.12^{b}	76.87^{c}	86.51^{a}	1.11	< 0.01
Lysine	84.93^{b}	84.59^{b}	78.37^{c}	90.18^{a}	0.98	< 0.01
Methionine	86.36^{b}	90.05^{a}	84.93^{b}	90.49^{a}	0.65	< 0.01
Phenylalanine	82.52^{b}	83.07^{b}	79.36^{c}	87.88^{a}	0.90	< 0.01
Threonine	71.96^{b}	70.37^{b}	64.74^{c}	77.90^{a}	1.17	< 0.01
Tryptophan	76.60^{ab}	77.59^{ab}	73.20^{b}	81.80^{a}	1.21	< 0.01
Valine	79.85^{b}	78.72^{b}	72.50^{c}	84.79^{a}	1.23	< 0.01
Dispensable amino acids						
Alanine	75.43^{b}	75.94^{b}	68.69^{c}	80.28^{a}	1.31	< 0.01
Aspartate	81.50^{b}	78.69^{bc}	76.87^{c}	85.24^{a}	0.91	< 0.01
Cystine	73.08^{ab}	74.36^{a}	66.92^{b}	72.02^{ab}	1.81	0.03
Glutamate	85.32^{ab}	84.25^{bc}	82.01^{c}	86.68^{a}	0.76	< 0.01
Glycine	67.08^{ab}	68.54^{ab}	64.21^{b}	73.49^{a}	1.93	0.04
Proline	75.04	77.45	75.05	75.11	1.63	0.67
Serine	77.43^{ab}	74.13^{b}	68.85^{c}	80.52^{a}	1.17	< 0.01
Tyrosine	80.87^{bc}	82.59^{ab}	76.82^{c}	85.85^{a}	1.11	< 0.01

[1]data are means of 5 observations

$^{a–c}$within a row, means without a common superscript differ (P < 0.05)

Experiment 3: Performance trial. Pigs fed diets containing extruded or dehulled-extruded corn had lower (P < 0.05) weight gain (days 0–14 and 0–28) and feed intake (days 15–28 and 0–28) than those fed diets containing raw corn, but there were no differences between pigs fed diets containing the two types of extruded corn (Table 11). For days 0–14, a better (P < 0.05) feed efficiency for pigs fed the raw corn diet than for those fed the extruded or dehulled-extruded corn diet was observed. The diarrhoea incidence was higher (P < 0.05) for pigs fed the dehulled-extruded corn diet than for those fed the raw or extruded corn diets during the entire experiment (days 0–28).

DISCUSSION

Feed undergoes significant changes during the course of the conditioning and extrusion process as it is heated, kneaded, and sheared (Chae et al., 1997). In the current study, the percentage of starch that was gelatinized increased in extruded and dehulled-extruded corn compared with raw corn and previous research has also reported that extrusion of raw corn changed the structure of starch granules and increased the gelatinized starch content (Bjorck et al., 1985). Also, as expected, the NDF concentration in dehulled-extruded corn decreased by 22.7% as compared with raw and extruded corn. Therefore, the reason to dehull and extrude corn is to decrease the fibre concentration and to potentially enhance the digestibility of nutrients and energy in corn, thus affecting pig growth rate and feed conversion (Gómez and Aguilera, 1984; Cho et al., 2001).

Extrusion changes the physical characteristics of starch and causes a shift of insoluble non-starch polysaccharides (NSP) to soluble NSP, with higher solubility in water and higher absorption due to gelatinization and dextrinization (Gómez and

Table 8. Apparent ileal digestibility of chemical constituents in raw, extruded, and dehulled-extruded corn (Experiment 2)[1]

Item	Raw corn	Extruded corn	Dehulled-extruded corn	SEM	*P*-value
Crude protein	74.87[ab]	84.49[a]	64.29[b]	3.36	0.02
Indispensable amino acids					
Arginine	85.03	84.35	80.36	1.73	0.22
Histidine	74.61	78.14	71.74	2.66	0.32
Isoleucine	76.34[a]	73.93[a]	53.57[b]	3.07	< 0.01
Leucine	76.18[a]	78.04[a]	62.37[b]	3.00	0.03
Lysine	77.06[a]	76.22[a]	60.67[b]	1.82	< 0.01
Methionine	80.16[b]	89.38[a]	76.58[b]	1.71	< 0.01
Phenylalanine	74.48	75.87	66.59	2.49	0.07
Threonine	63.06[a]	59.08[a]	44.50[b]	2.59	< 0.01
Tryptophan	68.80	71.27	60.30	2.92	0.10
Valine	72.44[a]	69.60[a]	54.07[b]	3.14	0.02
Dispensable amino acids					
Alanine	68.14[a]	69.43[a]	51.30[b]	2.97	< 0.01
Aspartate	75.89[a]	68.88[ab]	64.32[b]	2.35	0.04
Cystine	74.68[a]	77.87[ab]	59.28[b]	3.49	0.02
Glutamate	83.28[a]	80.59[ab]	75.01[b]	1.67	0.04
Glycine	57.45	61.11	50.27	4.43	0.30
Proline	74.95	80.96	74.96	4.21	0.55
Serine	72.79[a]	64.55[a]	51.33[b]	2.43	< 0.01
Tyrosine	73.39[a]	77.70[a]	63.28[b]	2.97	0.03

[1]data are means of 5 observations
[a–c]within a row, means without a common superscript differ ($P < 0.05$)

Aguilera, 1983; Fadel et al., 1988; Grossmann et al., 1998; Svihus et al., 2005). In addition, extrusion could increase the susceptibility of starch to enzyme degradation (Amornthewaphat et al., 2005; de Oliveira et al., 2011) and the proportion of rapidly digestible starch (Sun et al., 2006), and, as was expected in this study, the DE and ME concentrations in extruded and dehulled-extruded diets and extruded and dehulled-extruded corn were greater compared with raw corn diet and raw corn. This finding is in agreement with a previous report that DE and ME concentrations in extruded corn increased slightly compared with non-extruded corn (Herkelman et al., 1990; Menoyo et al., 2011). However, from the current study it is not possible to elicit the exact reason for the slight increases of DE and ME concentrations in extruded and dehulled-extruded corn compared with raw corn because the AID of starch and ether extract were not measured. Therefore, the most logical explanation for the slight increase in both DE and ME may be due to the increased DM concentration in extruded and dehulled-extruded corn compared with raw corn. This reason may also explain why there were no differences in the ATTD of nutrients and energy among raw, extruded, and dehulled-extruded corn.

The AID of CP, although not significant, and methionine in corn were improved by extrusion in the present study. This supports previous reports that extrusion may improve protein digestibility in feeds through protein denaturation making the protein molecules more susceptible to proteolytic enzymes (Fadel et al., 1988; Hancock, 1992; Muley et al., 2007). Also, it is known that starch is associated with proteins in cereal grains and therefore, through the gelatinization of starch, through extrusion, the proteins may also become more accessible to enzymatic digestion (Knudsen, 2011).

In previous reports, the digestibility of AA was shown to be reduced by excess heat processing, especially for lysine (Cho et al., 2001). Liener (1972) and Kim et al. (2009) also reported that overheating made lysine unavailable due to its

Table 9. Standardized ileal digestibility of crude protein and amino acids in raw, extruded, and dehulled-extruded corn diets fed to growing pigs (Experiment 2)[1]

Item	Experimental diets			Basal diet	SEM	*P*-value
	raw corn	extruded corn	dehulled-extruded corn			
Crude protein	85.91^{ab}	89.81^{a}	81.92^{b}	86.28^{a}	1.38	< 0.01
Indispensable amino acids						
Arginine	93.47^{ab}	93.35^{ab}	91.71^{b}	95.31^{a}	0.67	0.03
Histidine	87.01^{b}	88.48^{ab}	86.01^{b}	91.80^{a}	1.02	< 0.01
Isoleucine	86.78^{ab}	85.94^{b}	77.84^{c}	90.22^{a}	1.15	< 0.01
Leucine	86.30^{a}	87.02^{a}	80.75^{b}	89.78^{a}	1.11	< 0.01
Lysine	88.13^{b}	87.96^{b}	81.78^{c}	92.38^{a}	0.67	< 0.01
Methionine	90.58^{b}	94.38^{a}	89.63^{b}	94.40^{a}	0.66	< 0.01
Phenylalanine	86.52^{b}	87.14^{b}	83.30^{c}	90.89^{a}	0.90	< 0.01
Threonine	81.28^{ab}	79.43^{b}	74.15^{c}	84.80^{a}	1.17	< 0.01
Tryptophan	82.95^{ab}	83.75^{ab}	79.54^{b}	86.21^{a}	1.21	0.02
Valine	84.85^{b}	83.88^{b}	77.72^{c}	88.62^{a}	1.23	< 0.01
Dispensable amino acids						
Alanine	81.60^{ab}	82.31^{ab}	75.05^{c}	85.47^{a}	1.31	< 0.01
Aspartate	85.36^{ab}	82.65^{bc}	80.83^{c}	87.93^{a}	0.91	< 0.01
Cystine	80.91^{a}	82.54^{a}	74.76^{b}	79.36^{ab}	1.77	< 0.01
Glutamate	88.02^{a}	87.00^{ab}	84.77^{b}	88.76^{a}	0.76	< 0.01
Glycine	85.32	84.43	80.49	86.97	1.93	0.12
Proline	84.52	87.64	85.30	84.10	1.63	0.45
Serine	84.74^{a}	81.90^{ab}	76.78^{c}	85.92^{a}	1.17	< 0.01
Tyrosine	87.24^{ab}	88.80^{a}	83.38^{b}	90.17^{a}	1.12	< 0.01

[1]data are means of 5 observations

$^{a-c}$within a row, means without a common superscript differ ($P < 0.05$)

interaction with the reducing groups of sugars, called Maillard reactions, and thus it was no longer susceptible to tryptic cleavages making it unavailable to the pig. In the current study, the AID and SID of isoleucine, leucine, lysine, threonine, and valine in diets and corn were reduced by dehulled-extrusion processing, but not in extruded corn or extruded corn diet. The most probable explanation is that the removal of the hull prior to extrusion made the endosperm more exposed to heat. This may have caused increased damage to the protein and AA thus causing the reduction of AA digestibility in dehulled-extruded corn and dehulled-extruded corn diet. Finally, dehulled-extruded corn had a much lower Lys : CP ratio compared with raw and extruded corn in this experiment, which is the best method for assessing heat damage and, therefore, a reduction in the AID and SID of AA in dehulled-extruded corn and diet containing dehulled-extruded corn was observed (González-Vega et al., 2011).

Data about the effect of extruded grains on the performance of pigs are inconsistent. Richert et al. (1992) reported that weight gain of pigs fed extruded grains was improved by 12% compared with pigs fed raw grains. However, Chae et al. (1997) reported that weight gain of pigs fed extruded corn was not improved. One possible explanation could be due to the variation of extruded grain quality in response to extrusion conditions (e.g. water and steam flow, temperature, and pressure). In this study, we used slightly heavier pigs to evaluate the digestibilities of energy and amino acids of corn samples due to the need of heavier pigs for inserting cannulae. Our expectation was that weaned pigs fed extruded or dehulled-extruded corn would grow faster than those fed raw corn with the same nutrient levels. However, in the current study, pigs fed diets containing extruded and dehulled-extruded corn had poorer weight gain and feed intake than pigs fed diets containing

Table 10. Standardized ileal digestibility of crude protein and amino acids in raw, extruded, and dehulled-extruded corn (Experiment 2)[1]

Item	Raw corn	Extruded corn	Dehulled-extruded corn	SEM	*P*-value
Crude protein	85.35^{ab}	95.10^{a}	75.38^{b}	3.36	0.02
Indispensable amino acids					
Arginine	90.72	90.42	86.31	1.73	0.23
Histidine	79.83	83.50	77.32	2.66	0.23
Isoleucine	81.62^{a}	79.53^{a}	59.27^{b}	3.07	< 0.01
Leucine	81.09^{a}	82.88^{a}	67.22^{b}	3.00	0.03
Lysine	81.76^{a}	81.32^{a}	65.88^{b}	1.82	< 0.01
Methionine	84.84^{b}	94.36^{a}	82.48^{b}	1.71	< 0.01
Phenylalanine	79.96	81.52	71.92	2.48	0.05
Threonine	76.01^{a}	71.38^{a}	58.17^{b}	2.59	< 0.01
Tryptophan	78.05	80.07	69.54	2.92	0.11
Valine	79.20^{a}	76.79^{a}	61.38^{b}	3.14	0.02
Dispensable amino acids					
Alanine	75.79^{a}	77.57^{a}	59.42^{b}	2.97	< 0.01
Aspartate	81.49^{a}	74.73^{b}	70.19^{b}	2.35	0.05
Cystine	83.25^{a}	87.31^{a}	67.87^{b}	3.49	< 0.01
Glutamate	86.91^{a}	84.37^{a}	78.78^{b}	1.67	< 0.01
Glycine	82.84	80.63	70.78	4.43	0.19
Proline	85.17	92.95	88.36	4.21	0.33
Serine	82.99^{a}	75.89^{a}	63.07^{b}	2.43	< 0.01
Tyrosine	82.85	86.75	73.21	2.97	0.05

[1]data are means of 5 observations
$^{a–b}$within a row, means without a common superscript differ ($P < 0.05$)

raw corn. The lower feed intake of diets containing extruded corn might explain the poorer weight gain observed (Johnston et al., 1999). Weurding et al. (2003) and Van Kempen et al. (2007) also reported that raw corn was preferred for animal feeding due to its slowly digestible starch resulting in a slow and steady release of glucose which did not strongly stimulate insulin, therefore raw corn could improve feed intake and performance. In addition, the reason for the lower feed intake in extruded corn may be due to the poorer palatability caused by higher levels of retrograded starch (Hongtrakul et al., 1998; Lv et al., 2006) compared with raw corn. Another reason for the lower feed intake in extruded corn is that the starch in extruded corn had the fastest rate of digestion and resulted in a higher blood glucose which affects satiety. It follows that pigs in extruded corn had lower feed intake than those in raw corn (Van Kempen et al., 2007).

The higher incidence of diarrhoea in pigs fed the dehulled-extruded corn diet could be due to its lower digestibility of AA at the ileum. AA undigested at the terminal ileum are degraded in the large intestine. Higher levels of indigestible nutrients increase microbial fermentation and encourage proliferation of pathogenic bacteria in the gastrointestinal tract (Ball and Aherne, 1987). Bacterial fermentation of undigested nutrients produces excessive volatile fatty acids and potentially toxic substances such as ammonia and amines that can increase diarrhoea incidence (Gaskins, 2000; Htoo et al., 2007).

CONCLUSION

Our results indicate that extrusion and dehulled-extrusion processing can enhance the utilization of the energy in corn for growing pigs. However, the digestibility of most AA was reduced by dehulled-extrusion processing of corn. A possible explanation is that the removal of the hull prior to extrusion made the endosperm more exposed to

Table 11. Influence of different corn processings on performance of weaned pigs (Experiment 3)[1]

Item	Experimental diets			SEM	*P*-value
	raw corn	extruded corn	dehulled-extruded corn		
Weight gain (g/day)					
Day 0–14	377[a]	311[b]	305[b]	16.32	< 0.01
Day 15–28	477[a]	430[ab]	396[b]	14.59	< 0.01
Day 0–28	423[a]	361[b]	359[b]	14.37	< 0.01
Feed intake (g/day)					
Day 0–14	513	483	478	23.47	0.54
Day 15–28	835[a]	737[b]	721[b]	38.10	0.03
Day 0–28	676[a]	602[b]	608[b]	15.26	0.04
Feed efficiency					
Day 0–14	0.72[a]	0.64[b]	0.62[b]	0.02	< 0.01
Day 15–28	0.57	0.61	0.53	0.03	0.32
Day 0–28	0.63	0.62	0.58	0.03	0.50
Diarrhoea incidence (%)[2]					
Day 0–14	2.18[b]	2.28[b]	4.66[a]	0.73	0.05
Day 15–28	1.39	2.08	2.88	0.50	0.14
Day 0–28	1.79[b]	2.28[b]	3.62[a]	0.44	0.03

[1]data are means of 6 observations
[2]percentage of days having pigs with diarrhoea with respect to the total number of days on trial
[a–b]within a row, means without a common superscript differ ($P < 0.05$)

heat. This may have caused damage to the protein and AA thus causing a reduction of AA digestibility in dehulled-extruded corn. Substitution of raw corn with extruded or dehulled-extruded corn in starter diets formulated to equal ME and SID amino acid content did not improve the performance of weaned pigs in the current study.

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