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Energy concentration and amino acid digestibility in corn and corn coproducts from the wet-milling industry fed to growing pigs[1]

Y. Liu,* M. Song,*[2] F. N. Almeida,* S. L. Tilton,† M. J. Cecava,† and H. H. Stein*[3]

*Department of Animal Sciences, University of Illinois, Urbana 61801; and †Archer Daniels Midland Company, Decatur, IL 62521

ABSTRACT: Two experiments were conducted to determine DE and ME and the apparent ileal digestibility (AID) and the standardized ileal digestibility (SID) of CP and AA in corn and corn coproducts (high-fat corn germ [HFCG], corn bran, liquid corn extractives [LCE], and a mixture of corn germ meal and LCE [CGM-LCE]) fed to growing pigs. In Exp. 1, 40 growing barrows (initial BW: 33.4 ± 5.77 kg) were housed individually in metabolism cages and randomly allotted to 1 of 5 diets. A corn-based diet (97.4% corn) and 4 diets that contained both corn and each of the corn coproducts were formulated. Each diet was fed to 8 pigs. Feces and urine samples were collected using the marker to marker method with 5-d adaptation and 5-d collection periods. The DE and ME were calculated using the difference procedure. The concentrations of DE and ME in HFCG, corn bran, LCE, and CGM-LCE were less ($P < 0.05$) than in corn. Among corn coproducts, the concentration of DE in HFCG was greater ($P < 0.05$) than in corn bran, but the DE in corn bran was not different from DE values in LCE and CGM-LCE. No differences were observed in the ME concentrations among corn coproducts. In Exp. 2, 6 growing barrows (initial BW: 96.6 ± 1.16 kg) with a T-cannula in the distal ileum were randomly allotted to a 6 × 6 Latin square design with 6 diets and 6 periods. A N-free diet and 5 diets that contained corn, HFCG, corn bran, LCE, or CGM-LCE as the sole source of CP and AA were formulated. Each period lasted 7 d and ileal digesta were collected on d 6 and 7 of each period. The SID of CP and all indispensable AA was greater ($P < 0.05$) in corn than in all corn coproducts with the exception that the SID of Lys in corn was not different from the SID of Lys in HFCG, and the SID of Trp in corn was also not different from the SID of Trp in CGM-LCE. Among corn coproducts, the SID of CP, Arg, and Lys were greater ($P < 0.05$) in HFCG and CGM-LCE than in corn bran, the SID of Lys and Val was greater ($P < 0.05$) in LCE than in corn bran, and the SID of Arg was greater ($P < 0.05$) in HFCG and CGM-LCE than in LCE, but for the remaining indispensable AA, no differences among corn coproducts were observed. In conclusion, the corn coproducts used in these experiments contain less ME and have reduced SID of most AA compared with corn, but there are no differences in ME among corn coproducts and only few differences in the SID of indispensable AA among HFCG, corn bran, LCE, and CGM-LCE.

Key words: amino acid digestibility, corn bran, corn germ, energy, liquid corn extractives, pigs

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INTRODUCTION

Many coproducts from the corn processing industry may be used in diets fed to pigs. Corn germ produced from the dry grind industry contains 16 to 18% ether extract (Widmer et al., 2007; NRC, 2012), but corn germ produced from the wet milling industry contains 30 to 40% ether extract, and is referred to as high-fat corn germ (**HFCG**). The DE and ME of corn germ from the dry grind industry have been reported to be similar to values in corn, but the apparent ileal digestibility (**AID**) and standardized ileal digestibility (**SID**) of CP and AA in this ingredient are less than in corn (Widmer et al., 2007; Anderson et al., 2012; NRC, 2012). However, the DE and ME and the AID and SID of AA in HFCG have not been reported.

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[2]Current address: Department of Animal Science and Biotechnology, College of Agriculture and Life Sciences, Chungnam National University, 99 Daehangro, Yuseong-gu, Daejeon 305–764, South Korea.

[3]Corresponding author: hstein@illinois.edu

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Corn bran is the most fibrous component of the corn kernel, and is often included in other corn coproducts, but it can also be marketed as a separate feed ingredient. Values for DE and ME in corn bran were recently reported (Anderson et al., 2012), but values for the AID and SID of AA are not available.

Liquid corn extractives (**LCE**) is produced when the soluble portion of the corn kernel is removed during the steeping process (Archer Daniels Midland, 2008). Corn germ meal is produced when corn germ is de-oiled, and corn germ meal, therefore, has a relatively high concentration of fiber and a relatively low concentration of fat. The DE and ME and the digestibility of AA in corn germ meal have been reported (Almeida et al., 2011; Anderson et al., 2012; Rojas et al., 2013). However, a new coproduct may be produced if corn germ meal is mixed with LCE, because corn germ meal can absorb large quantities of LCE, which will allow LCE to be utilized by pigs. There are, however, limited data on the nutritional value of LCE and the mixture of corn germ meal and LCE (**CGM-LCE**). Therefore, the objectives of this work were to determine the DE and ME and the AID and SID of CP and AA in HFCG, corn bran, LCE, and CGM-LCE, and to compare these values to those determined in corn.

Table 1. Analyzed composition of ingredients (as fed-basis)

	Ingredient[1,2]				
Item	Corn	HFCG	Corn bran	LCE	CGM-LCE
DM, %	87.21	93.59	89.94	60.84	90.87
GE, kcal/kg	4,001	5,929	4,368	2,018	4,211
CP, %	6.84	17.00	9.85	24.43	25.13
AEE,[3] %	3.20	30.60	3.10	2.02	2.50
NDF, %	7.50	40.90	61.00	–	24.70
ADF, %	3.40	18.20	16.70	–	9.15
Starch, %	62.91	11.90	16.20	24.00	16.00
Ca, %	0.02	0.03	0.07	0.07	0.02
P, %	0.25	0.70	0.14	2.76	1.57
Indispensable AA, %					
Arg	0.37	1.26	0.40	1.02	1.51
His	0.21	0.49	0.34	0.85	0.75
Ile	0.27	0.63	0.34	0.61	0.83
Leu	0.90	1.30	1.13	1.25	1.68
Lys	0.26	0.73	0.30	0.71	0.89
Met	0.16	0.31	0.16	0.22	0.36
Phe	0.36	0.77	0.46	0.56	0.91
Thr	0.27	0.63	0.37	0.70	0.86
Trp	0.06	0.12	0.07	0.13	0.23
Val	0.36	1.04	0.48	1.07	1.33
Total	3.22	7.28	4.05	7.12	9.35
Dispensable AA, %					
Ala	0.55	1.04	0.64	1.64	1.53
Asp	0.51	1.25	0.55	1.20	1.61
Cys	0.17	0.21	0.23	0.66	0.45
Glu	1.36	2.10	1.64	2.81	3.09
Gly	0.30	0.96	0.40	1.31	1.36
Pro	0.66	0.76	0.97	2.27	1.47
Ser	0.33	0.67	0.37	0.67	0.89
Tyr	0.24	0.49	0.33	0.58	0.68
Total	4.12	7.48	5.13	11.14	11.08

[1]HFCG = high-fat corn germ; LCE = liquid corn extractives; CGM-LCE = a mixture of corn germ meal and liquid corn extractives.

[2]High-fat corn germ, corn bran, LCE, and CGM-LCE were provided by Archer Daniels Midland Company, Decatur, IL.

[3]AEE = acid hydrolyzed ether extract.

MATERIALS AND METHODS

General

Two experiments were conducted, and the protocol for each experiment was reviewed and approved by the Institutional Animal Care and Use Committee at the University of Illinois. Both experiments were conducted at the Swine Research Center at the University of Illinois at Urbana-Champaign. Pigs used in both experiments were the offspring of G-Performer boars and F-25 sows (Genetiporc Inc., Alexandria, MN).

Yellow dent corn and 4 corn coproducts were used. The 4 corn coproducts included: HFCG, corn bran, LCE (60.84% DM), and CGM-LCE. Yellow dent corn was sourced from the University of Illinois Feed Mill (Champaign, IL) and the 4 corn coproducts were provided by Archer Daniels Midland Company (Decatur, IL). The CGE-LCE was produced by mixing corn germ meal and LCE in a 2:1 ratio on a DM basis and the mixture was then dried. All 4 corn coproducts and corn were analyzed in duplicate (Table 1) for DM (Method 927.05; AOAC International, 2007) and CP (Method 990.03; AOAC International, 2007). The concentration of GE was determined using an adiabatic bomb calorimeter (Model 6300; Parr Instruments, Moline, IL). Acid hydrolyzed ether extraction (**AEE**) was determined after acid hydrolysis using 3*N* HCl (Sanderson, 1986) followed by crude fat extraction using petroleum ether (Method 2003.06, AOAC Int., 2007) on a Soxtec 2050 automated analyzer (FOSS North America, Eden Prairie, MN). Ingredients were also analyzed for ADF (Method 973.18; AOAC International, 2007), NDF (Holst, 1973), starch (Method 948.02; AOAC International, 2007), Ca and P (Method 985.01; AOAC International, 2007), and AA (Method 982.30 E [a, b, c]; AOAC International, 2007).

Experiment 1: Energy Measurements

Experiment 1 was conducted to determine DE and ME in corn and in the 4 corn coproducts. A total of 40 barrows (Initial BW: 33.4 ± 5.77 kg) were used in a randomized complete block design with 2 groups of 20 pigs and 5 diets. There were 4 replicate pigs per diet in each group and a total of 8 replicate pigs per diet. Pigs were

Table 2. Ingredient composition of experimental diets (as-fed basis), Exp. 1

	Diet[1,2]				
Item	Corn	HFCG	Corn bran	LCE	CGM-LCE
Ingredient, %					
Ground corn	97.40	57.60	57.60	48.19	57.60
HFCG	–	40.00	–	–	–
Corn bran	–	–	40.00	–	–
LCE	–	–	–	50.00	–
CGM-LCE	–	–	–	–	40.00
Ground limestone	1.10	1.00	1.00	0.75	1.00
Mono-calcium phosphate	0.80	0.70	0.70	0.53	0.70
Salt	0.40	0.40	0.40	0.30	0.40
Vitamin-mineral premix[3]	0.30	0.30	0.30	0.23	0.30
Analyzed composition					
DM, %	84.70	88.01	86.57	67.07	87.09
GE, kcal/kg	3,876	4,626	3,984	2,947	3,960

[1]HFCG = high-fat corn germ; LCE = liquid corn extractives; CGM-LCE = a mixture of corn germ meal and liquid corn extractives.

[2]High-fat corn germ, corn bran, LCE, and CGM-LCE were provided by Archer Daniels Midland Company, Decatur, IL.

[3]The vitamin-mineral premix 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, 2204 IU; vitamin E as DL–α-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, 1.0 mg, and nicotinic acid, 43.0 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; Zn, 100 mg as zinc oxide.

placed in metabolism cages equipped with a feeder and a nipple drinker, fully slatted floors, a screen floor, and urine trays that allowed for the total, but separate, collection of urine and fecal materials from each pig.

A corn diet consisting of 97.40% corn and 2.6% vitamins and minerals was formulated (Table 2). Four additional diets were formulated by mixing corn with each source of corn coproduct. The quantity of feed provided per pig daily was calculated as 3 times the estimated requirement for maintenance energy (i.e., 106 kcal ME per $kg^{0.75}$; NRC, 1998) for the smallest pig in each replicate and divided into 2 equal meals. Water was available at all times. The experimental diets were provided for 12 d. The initial 5 d was considered an adaptation period to the diet. Fecal markers were fed on d 6 (chromic oxide) and on d 11 (ferric oxide) and fecal collections were initiated when chromic oxide appeared in the feces and ceased when ferric acid appeared (Adeola, 2001). Feces were collected twice daily and stored at -20°C immediately after collection. Urine was also collected at the same time as fecal samples were collected and urine collections started on d 6 at 1700 h and ceased on d 11 at 1700 h. Urine buckets with a preservative of 50 mL of 6*N* HCl were placed under the metabolism cages to permit total collection. They were emptied in the morning and afternoon and a preservative of 50 mL of 6*N* HCl was added to each bucket again when they had been emptied. Fecal samples and 20% of the collected urine were stored at -20°C immediately after collection. At the conclusion of the experiment, urine samples were thawed and mixed within animal, and a subsample was collected for chemical analysis. Fecal samples were dried in a forced-air drying oven and finely ground before analysis. Urine samples were lyophilized before analysis as described by Kim et al. (2009). Fecal, urine, and diet samples were analyzed in duplicate for GE as explained for the ingredients and fecal and diet samples were also analyzed for DM.

Following chemical analysis, the apparent total tract digestibility (**ATTD**) of GE was calculated for each diet. The amount of energy lost in the feces and in the urine, respectively, was determined, and the quantities of DE and ME in each of the 5 diets were calculated (Baker and Stein, 2009; Kim et al., 2009). The DE and ME in corn were then calculated by dividing the DE and ME values for the corn diet by the inclusion rate of corn in this diet and these values were then used to calculate the contribution from corn to the DE and ME in the diets containing each corn coproduct. The DE and ME in each corn coproduct were then calculated by difference as previously explained (Baker and Stein, 2009; Kim et al., 2009).

Normality of data was verified and outliers were tested using the UNIVARIATE procedure (SAS Inst. Inc., Cary, NC), but no outliers were identified. Data were analyzed by ANOVA using the Proc MIXED procedure of SAS (SAS Inst. Inc.) in a randomized complete block design with pig as the experimental unit. The statistical model included diet or ingredient as the fixed effect and block as the random effect. Treatment means were calculated using the LSMEANS statement and means were separated using the PDIFF option of PROC MIXED. Statistical significance and tendency were considered at $P < 0.05$ and $0.05 \le P < 0.10$, respectively.

Experiment 2: Amino Acid Digestibility

Experiment 2 was conducted to determine the AID and SID of CP and AA in corn and in teh 4 corn coproducts. Six growing barrows (96.6 ± 1.16 kg of initial BW) were randomly allotted to a 6 × 6 Latin square design with 6 diets and six 7-d periods in each square. Pigs were surgically equipped with a T-cannula in the distal ileum when they were approximately 25 kg using procedures adapted from Stein et al. (1998), and all pigs had been used in a previous experiment before being fed a conventional grower diet for 2 wk and then being allotted to diets in the present experiment. Pigs were housed in individual pens (1.2 × 1.5 m) with tri-bar floors in an environmentally controlled room. A feeder and a nipple drinker were installed in each pen.

Table 3. Ingredient composition of experimental diets (as-fed basis), Exp. 2

	Diet[1,2]					
Item	Corn	HFCG	Corn bran	LCE	CGM-LCE	N-free
Ground corn	97.00	–	–	47.89	–	–
HFCG	–	40.00	–	–	–	–
Corn bran	–	–	40.00	–	–	
LCE	–	–	–	50.00	–	–
CGM-LCE	–	–	–	–	40.00	–
Cornstarch	–	43.20	43.20	–	43.20	67.85
Soybean oil	–	3.60	3.60	–	3.60	4.00
Sucrose	–	10.00	10.00	–	10.00	20.00
Solka floc[3]	–	–	–	–	–	4.00
Ground limestone	1.10	1.00	1.00	0.75	1.00	0.85
Monocalcium phosphate	0.80	1.10	1.10	0.53	1.10	1.70
Magnesium oxide	–	–	–	–	–	0.10
Potassium carbonate	–	–	–	–	–	0.40
Chromic oxide	0.40	0.40	0.40	0.30	0.40	0.40
Salt	0.40	0.40	0.40	0.30	0.40	0.40
Vitamin-mineral premix[4]	0.30	0.30	0.30	0.23	0.30	0.30

[1]HFCG = high-fat corn germ; LCE = liquid corn extractives; CGM-LCE = a mixture of corn germ meal and liquid corn extractives.

[2]High-fat corn germ, corn bran, LCE, and CGM-LCE were provided by Archer Daniels Midland Company, Decatur, IL.

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

[4]The vitamin-mineral premix 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, 2204 IU; vitamin E as DL–α-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, 1.0 mg, and nicotinic acid, 43.0 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; Zn, 100 mg as zinc oxide.

Six diets were prepared (Tables 3 and 4). One diet was based on corn (97%), and 3 diets contained 40% HFCG, corn bran, or CGM-LCE and starch, sugar, and soybean oil. Corn, HFCG, corn bran, or CGM-LCE was the sole source of AA in these 4 diets. One diet was formulated with corn and 50% LCE on an as-fed basis. The last diet was a N-free diet that was used to calculate basal endogenous losses of AA and CP. Solka floc was included in the N-free diet (4%) to increase the concentration of crude fiber, and potassium carbonate and magnesium oxide were added to the N-free diet to meet the requirements for K and Mg. Vitamins and minerals were included in all diets to meet or exceed requirement estimates (NRC, 1998). All diets also contained 0.4% chromic oxide as an indigestible marker. Pigs were fed at a daily level of 3 times the maintenance requirement for energy (i.e., 106 kcal ME per $kg^{0.75}$; NRC, 1998). Water was available at all times during the experiment. Pig weights were recorded at the beginning of each period and the amount of feed supplied each day was also recorded.

The initial 5 d of each period was considered an adaptation period to the diet. Ileal digesta were collected for 8 h on d 6 and 7 as described by Stein et al. (1999). In short, cannulas were opened, a plastic bag was attached to the cannula barrel, and digesta flowing into the bag were collected. Bags were removed whenever they were filled with digesta, or at least once every 30 min, and immediately frozen at -20°C to prevent bacterial degradation of the AA in the digesta. At the conclusion of the experiment, ileal samples were thawed, mixed within animal and diet, and a subsample was collected for chemical analysis. A sample of each diet and of corn and of each of the corn coproducts was collected as well. Digesta samples were lyophilized and finely ground before chemical analysis. Digesta and diet samples were analyzed in duplicate for Cr (Method 990.08; AOAC International, 2007), and these samples were also analyzed for DM, CP, and AA as explained for the ingredients.

The AID values for CP and AA in samples obtained from feeding corn or the 3 diets containing corn coproducts were calculated (Stein et al., 2007). Because corn, corn bran, HFCG, or CGM-LCE were the only feed ingredients contributing CP and AA to each of these diets, the AID values calculated for the diets also represent the digestibility values for each of these ingredients. Values for the AID of CP and AA in the diet containing corn and LCE were also calculated. The daily intake of AA was calculated as well, and the contribution of digestible AA from corn was then subtracted from the total amount of digestible AA in the diet to calculate the digestibility of AA in LCE using the difference procedure (Mosenthin et al., 2007). The basal endogenous losses of CP and each AA were determined based on the flow to the distal ileum obtained after feeding the N-free diet, and SID values for each diet were calculated by correcting the AID of CP and each AA for the basal endogenous losses (Stein et al., 2007). Values for the SID of CP and AA in LCE were calculated using the difference procedure as described for AID values. For all calculations, analyzed values for Cr and AA in each diet and in ileal digesta were used. Data were analyzed as explained for Exp. 1, except that the statistical model included diet or ingredient as the fixed effect and pig and period as the random effect.

RESULTS

Experiment 1: Energy Measurements

Total feed intake was not different among diets, except that pigs fed the diet containing LCE consumed more feed than pigs fed the other diets ($P < 0.05$; Table 5), primarily due to the lower DM concentration in this diet. However, DM intake was not different among diets. Compared with the corn, LCE, or CGM-LCE diets, pigs fed the corn bran or HFCG diet had less ($P < 0.05$) ATTD of GE. Pigs fed the corn diet had the greatest ($P < 0.05$) ATTD of GE and pigs fed the HFCG diet had the least ($P < 0.05$) ATTD of GE, compared with pigs fed the other diets. Diets containing corn, HFCG, or CGM-LCE contained more ($P < 0.05$) DE than diets containing corn bran or LCE, and the corn bran diet contained more ($P < 0.05$) DE than the LCE diet. Values for ME were greater ($P < 0.05$) in the corn diet than in corn bran, LCE, or CGM-LCE diets. The diet containing HFCG also had greater ($P < 0.05$) ME than the diet containing LCE.

On an as-fed basis, the DE in corn, HFCG, and CGM-LCE were greater ($P < 0.05$) than in corn bran and LCE, and the DE in corn bran was greater ($P < 0.05$) than in

Table 4. Analyzed composition of experimental diets (as fed-basis), Exp. 2

	Diet[1,2]					
Item	Corn	HFCG	Corn bran	LCE	CGM-LCE	N-free
DM, %	86.48	92.59	90.99	67.92	91.90	92.43
CP, %	6.35	7.63	4.85	10.47	10.32	0.19
Indispensable AA, %						
Arg	0.40	0.52	0.18	0.50	0.63	0.01
His	0.21	0.20	0.15	0.36	0.29	0.00
Ile	0.27	0.27	0.17	0.32	0.33	0.03
Leu	0.83	0.55	0.53	0.80	0.71	0.04
Lys	0.29	0.32	0.15	0.35	0.35	0.03
Met	0.16	0.11	0.08	0.15	0.14	0.00
Phe	0.35	0.32	0.21	0.34	0.37	0.01
Thr	0.26	0.27	0.17	0.35	0.38	0.02
Trp	0.06	0.10	0.05	0.09	0.14	0.05
Val	0.36	0.42	0.22	0.50	0.52	0.01
Total	3.19	3.08	1.91	3.76	3.86	0.20
Dispensable AA, %						
Ala	0.52	0.44	0.29	0.76	0.65	0.02
Asp	0.52	0.53	0.26	0.62	0.69	0.02
Cys	0.16	0.09	0.11	0.28	0.18	0.01
Glu	1.28	0.94	0.76	1.49	1.40	0.03
Gly	0.31	0.40	0.18	0.55	0.57	0.02
Pro	0.68	0.42	0.49	1.03	0.70	0.10
Ser	0.30	0.30	0.17	0.38	0.41	0.01
Tyr	0.28	0.22	0.17	0.41	0.29	–
Total	4.05	3.34	2.43	5.52	4.89	0.21

[1]HFCG = high-fat corn germ; LCE = liquid corn extractives; CGM-LCE = a mixture of corn germ meal and liquid corn extractives.

[2]High-fat corn germ, corn bran, LCE, and CGM-LCE were provided by Archer Daniels Midland Company, Decatur, IL.

Table 5. Energy digestibility and concentrations of DE and ME in diets containing corn, high-fat corn germ, corn bran, liquid corn extractives, and a mixture of corn germ meal and corn extractives, (as-fed basis),[1,2] Exp. 1

	Diet[3,4]						
Item	Corn	HFCG	Corn bran	LCE	CGM-LCE	SEM	*P*-value
Total feed intake, kg/5 d	5.51[a]	5.39[a]	5.49[a]	7.28[b]	5.89[a]	0.23	< 0.05
GE intake, kcal/5 d	21,367[a]	24,919[b]	21,876[a]	21,447[a]	23,311[ab]	908	< 0.05
Dry feces output, kg/5 d	0.561[a]	1.111[d]	0.957[cd]	0.736[ab]	0.877[bc]	0.061	< 0.05
GE in dry feces, kcal/kg	4,789[a]	6,147[c]	4,776[a]	4,096[b]	4,471[b]	36	< 0.05
Fecal GE output, kcal/5 d	2,685[a]	6,838[d]	4,564[c]	3,025[ab]	3,920[bc]	334	< 0.05
ATTD,[5] GE %	87.36[a]	72.67[d]	79.20[c]	85.60[ab]	83.29[b]	1.01	< 0.05
DE in diet, kcal/kg	3,386[a]	3,362[a]	3,155[b]	2,523[c]	3,299[a]	42	< 0.05
Urine output, kg/5 d	19.90	24.58	18.33	16.23	24.76	7.21	0.915
GE in urine, kcal/kg	39.75	100.79	71.53	84.72	109.19	29.22	0.490
Urinary GE output, kcal/5 d	541[a]	942[ab]	578[a]	1,010[b]	978[ab]	187	0.256
ME in diet, kcal/kg	3,288[a]	3,194[ab]	3,052[b]	2,381[c]	3,134[b]	61	< 0.05

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

[1]Each least squares mean represents 8 observations.

[2]Total feed intake, GE intake, dry feces output, fecal GE output, urine output, and urine GE output were based on 5 d of collection.

[3]HFCG = high-fat corn germ; LCE = liquid corn extractives; CGM-LCE = a mixture of corn germ meal and liquid corn extractives.

[4]High-fat corn germ, corn bran, LCE, and CGM-LCE were provided by Archer Daniels Midland Company, Decatur, IL.

[5]ATTD = apparent total tract digestibility.

Table 6. Concentrations of DE and ME in corn, high-fat corn germ, corn bran, liquid corn extractives, and a mixture of corn germ meal and corn extractives fed to pigs,[1] Exp. 1

	Ingredient[2,3]						
Item	Corn	HFCG	Corn bran	LCE	CGM-LCE	SEM	*P*-value
As-fed basis							
DE, kcal/kg	3,476[a]	3,397[a]	2,881[b]	1,695[c]	3,241[a]	98	< 0.05
ME, kcal/kg	3,376[a]	3,123[ab]	2,768[b]	1,508[c]	2,973[b]	145	< 0.05
DM basis							
DE, kcal/kg	3,986[a]	3,631[b]	3,204[c]	3,485[bc]	3,567[bc]	115	< 0.05
ME, kcal/kg	3,871[a]	3,336[b]	3,077[b]	3,102[b]	3,272[b]	168	< 0.05

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

[1]Each least squares mean represents 8 observations.

[2]HFCG = high-fat corn germ; LCE = liquid corn extractives; CGM-LCE = a mixture of corn germ meal and liquid corn extractives.

[3]High-fat corn germ, corn bran, LCE, and CGM-LCE were provided by Archer Daniels Midland Company, Decatur, IL.

LCE (Table 6). The ME in corn was also greater ($P < 0.05$) than in corn bran, LCE, and CGM-LCE, and the ME in corn bran, HFCG, and CGM-LCE were greater ($P < 0.05$) than in LCE. On a DM-basis, the DE and ME in corn were greater ($P < 0.05$) than in all corn coproducts. The DE in HFCG was also greater ($P < 0.05$) than in corn bran, but no differences were observed for the ME among the corn coproducts if calculated on a DM basis.

Experiment 2: Amino Acid Digestibility

The AID of CP in HFCG, LCE, and CGM-LCE was greater ($P < 0.05$) than in corn bran (Table 7). The AID of all AA was not different among HFCG, LCE, and CGM-LCE, except for Arg, Ala, Glu, and Pro. The AID of all AA in corn bran was least ($P < 0.05$) among all corn coproducts, except for the AID of His, Leu, Met, Cys, and Glu. The mean AID of both indispensable and dispensable AA in corn bran was less ($P < 0.05$) than in corn and the other corn coproducts. The AID of CP was greater ($P < 0.05$) in corn than in corn bran, HFCG, and CGM-LCE, and the AID for all AA was greater in corn ($P < 0.05$) than in all corn coproducts, except for Arg, Lys, Thr, Trp, Val, Ala, Gly, Pro, and Tyr.

The SID of CP in HFCG and CGM-LCE was greater ($P < 0.05$) than in corn bran, but not different from the SID of CP in LCE (Table 8). No differences were observed in the SID of most indispensable AA among corn coproducts, except that corn bran had less ($P < 0.05$) SID for Arg and Lys than HFCG, less ($P < 0.05$) SID for Lys and Val than LCE, and less ($P < 0.05$) SID for Arg, Lys, Thr, and Val than CGM-LCE. For dispensable AA, corn bran had the least ($P < 0.05$) SID for Ala, Gly, and Pro, whereas LCE had the least ($P < 0.05$) SID for Asp, Cys, and Glu among corn coproducts. No difference was observed in the SID of all AA between HFCG and CGM-LCE. The mean SID for both indispensable and dispensable AA in corn bran was less ($P < 0.05$) than for corn and the other corn coproducts. However, the SID for CP was greater ($P < 0.05$) in corn than in corn coproducts, and the SID for all AA except Lys, Trp, Gly, Pro, and Tyr was greater ($P < 0.05$) in corn than in all corn coproducts.

DISCUSSION

Composition of Ingredients

Ground corn can be fed directly to animals but may also be used to produce industrial or food products, such as ethanol, corn oil, and corn gluten, etc. However, only a part of the corn kernel is used in the production of the industrial and food products, and the remaining part may be used for feed. As a consequence, a number of coproducts are available to the feed industry and many of these products are included in diets fed to pigs. The composition of corn coproducts depends on the processing that was used to generate the primary products (NRC, 2012). The nutritional value of many corn coproducts have been recently reported (Almeida et al., 2011; Anderson et al., 2012; Rojas et al., 2013). However, concentrations of DE and ME have not been reported for LCE and CGM-LCE and the AID and SID of AA have not been reported for HFCG, corn bran, LCE, and CGM-LCE.

Concentrations of GE, CP, AEE, starch, Ca, P, and all AA that were observed in the corn used in this experiment are in agreement with the values reported by NRC (2012). The HFCG used in this experiment was produced from the wet milling industry, and contained more ether extract and GE, but less starch, than corn germ produced from the dry grind industry (Widmer et al., 2007; NRC, 2012). Concentrations of ADF, NDF, and all AA except Lys were greater than in the corn germ used by Anderson et al. (2012).

The corn bran used in this experiment had concentrations of CP and most AA that are in agreement with values reported by NRC (2012), but less than the values reported by Anderson et al. (2012). The concentrations of NDF and ADF of corn bran were greater, but the concentration of ether extract was less than recently reported values (Anderson et al., 2012; NRC, 2012).

Table 7. Apparent ileal digestibility (%) of CP and AA in corn, high-fat corn germ, corn bran, liquid corn extractives, and a mixture of corn germ meal and corn extractives fed to pigs,[1] Exp. 2

	Ingredient[2,3]						
Item	Corn	HFCG	Corn bran	LCE	CGM-LCE	SEM	*P*-value
CP	63.6[a]	38.8[b]	8.1[c]	43.8[b]	45.5[b]	6.73	< 0.05
Indispensable AA							
Arg	83.0[a]	74.2[a]	38.0[b]	69.8[b]	78.2[a]	6.03	< 0.05
His	85.2[a]	66.3[b]	65.4[b]	67.7[b]	69.3[b]	2.96	< 0.05
Ile	79.4[a]	57.4[bc]	46.1[c]	61.6[b]	64.1[b]	5.13	< 0.05
Leu	87.9[a]	63.8[b]	70.3[b]	67.1[b]	71.9[b]	3.87	< 0.05
Lys	56.7[a]	42.8[ab]	-32.4[c]	35.4[b]	39.1[ab]	6.66	< 0.05
Met	88.0[a]	61.9[b]	65.6[b]	61.5[b]	71.4[b]	4.00	< 0.05
Phe	84.2[a]	68.5[bc]	57.9[c]	66.6[bc]	72.1[b]	4.24	< 0.05
Thr	71.5[a]	48.3[b]	23.0[c]	45.1[b]	54.7[ab]	6.31	< 0.05
Trp	74.8[a]	69.1[a]	54.6[b]	72.1[a]	73.4[a]	4.26	< 0.05
Val	77.2[a]	57.0[b]	37.3[c]	64.2[ab]	63.0[b]	4.81	< 0.05
Mean	79.0[a]	60.7[b]	42.8[c]	61.1[b]	65.7[b]	3.96	< 0.05
Dispensable AA							
Ala	79.8[a]	52.2[c]	30.9[d]	66.9[ab]	63.9[bc]	4.88	< 0.05
Asp	76.8[a]	48.3[b]	23.0[c]	36.7[bc]	46.8[b]	6.17	< 0.05
Cys	80.1[a]	43.4[b]	52.4[b]	39.5[b]	48.7[b]	6.71	< 0.05
Glu	85.9[a]	64.8[b]	64.0[b]	50.9[c]	68.9[b]	4.07	< 0.05
Gly	42.6[a]	31.2[a]	–97.2[b]	28.8[a]	27.2[a]	12.45	< 0.05
Pro	23.2[a]	–94.4[b]	-113.8[b]	31.6[a]	-21.6[ab]	39.43	< 0.05
Ser	78.0[a]	57.4[b]	37.8[c]	50.9[bc]	60.0[b]	4.86	< 0.05
Tyr	83.4[a]	60.0[bc]	55.2[c]	72.5[ab]	70.7[ab]	4.88	< 0.05
Mean	68.1[a]	32.9[b]	5.9[c]	47.2[b]	45.6[b]	6.85	< 0.05
Total AA	74.1[a]	48.3[b]	26.4[c]	54.9[b]	56.8[b]	4.37	< 0.05

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

[1]Each least squares mean represents 6 observations.

[2]HFCG = high-fat corn germ; LCE = liquid corn extractives; CGM-LCE = a mixture of corn germ meal and liquid corn extractives.

[3]High-fat corn germ, corn bran, LCE, and CGM-LCE were provided by Archer Daniels Midland Company, Decatur, IL.

Table 8. Standardized ileal digestibility (%) of CP and AA in corn, high-fat corn germ, corn bran, liquid corn extractives, and a mixture of corn germ meal and corn extractives fed to pigs,[1] Exp. 2

	Ingredient[2,3]						
Item	Corn	HFCG	Corn bran	LCE	CGM-LCE	SEM	*P*-value
CP	83.4[a]	56.5[b]	35.4[c]	51.3[bc]	58.5[b]	6.73	< 0.05
Indispensable AA							
Arg	91.6[a]	81.3[b]	70.4[c]	74.6[c]	84.0[b]	2.93	< 0.05
His	90.7[a]	74.6[b]	73.4[b]	69.7[b]	73.3[b]	3.07	< 0.05
Ile	88.0[a]	66.7[b]	60.6[b]	66.7[b]	71.6[b]	5.13	< 0.05
Leu	92.3[a]	70.9[b]	77.5[b]	70.4[b]	77.3[b]	3.87	< 0.05
Lys	72.7[a]	58.4[ab]	0.1[c]	44.6[b]	53.2[b]	6.66	< 0.05
Met	91.7[a]	67.7[b]	73.5[b]	64.5[b]	76.0[b]	4.00	< 0.05
Phe	90.2[a]	70.6[b]	68.5[b]	71.1[b]	78.1[b]	4.24	< 0.05
Thr	87.0[a]	64.3[bc]	48.0[c]	52.6[bc]	66.0[b]	6.31	< 0.05
Trp	88.0[a]	77.5[b]	71.2[b]	77.3[b]	79.4[ab]	4.26	0.043
Val	87.6[a]	66.5[bc]	55.2[c]	69.3[b]	70.7[b]	4.81	< 0.05
Mean	88.2[a]	69.8[b]	58.9[c]	66.1[bc]	73.0[b]	3.96	< 0.05
Dispensable AA							
Ala	88.6[a]	63.3[b]	47.5[c]	70.8[b]	71.4[b]	4.88	< 0.05
Asp	87.4[a]	59.4[b]	45.2[bc]	42.8[c]	55.3[bc]	6.17	< 0.05
Cys	87.6[a]	57.5[bc]	63.8[b]	42.2[c]	55.7[bc]	6.71	< 0.05
Glu	91.3[a]	72.7[b]	73.6[b]	54.1[c]	74.1[b]	3.05	< 0.05
Gly	83.2[a]	64.9[ab]	-23.6[c]	43.5[b]	50.6[ab]	12.45	< 0.05
Pro	87.8[a]	17.6[ab]	-19.5[b]	59.6[ab]	45.1[ab]	39.43	0.074
Ser	89.5[a]	69.6[b]	59.0[b]	56.8[b]	68.9[b]	4.86	< 0.05
Tyr	90.2[a]	69.3[b]	66.9[b]	76.2[b]	77.7[ab]	4.88	< 0.05
Mean	87.6[a]	59.3[b]	38.5[c]	55.7[b]	62.4[b]	6.85	< 0.05
Total AA	87.9[a]	65.1[b]	49.8[c]	61.5[b]	68.2[b]	4.37	< 0.05

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

[1]Each least squares mean represents 6 observations. Values for standardized ileal digestibility were calculated by correcting apparent ileal digestibility values for basal endogenous losses (g/kg of DMI), which were determined by feeding pigs a N-free diet: CP, 14.54; Arg, 0.40; His, 0.12; Ile, 0.27; Leu, 0.42; Lys, 0.54; Met, 0.07; Phe, 0.24; Thr, 0.47; Trp, 0.09; Val, 0.43; Ala, 0.53; Asp, 0.64; Cys, 0.14; Glu, 0.80; Gly, 1.46; Pro, 5.08; and Ser, 0.40.

[2]HFCG = high-fat corn germ; LCE = liquid corn extractives; CGM-LCE = a mixture of corn germ meal and liquid corn extractives.

[3]High-fat corn germ, corn bran, LCE, and CGM-LCE were provided by Archer Daniels Midland Company, Decatur, IL.

Liquid corn extractives are obtained by the partial removal of water from the liquid that results from steeping corn in a water- and sulphur dioxide solution in the wet milling process. Liquid corn extractives are thick, viscous liquid materials that contain approximately 60% DM and 25% CP (Archer Daniels Midland, 2008). Corn germ meal is produced when corn germ is de-oiled, and the product has a relatively high concentration of fiber, which results in corn germ meal being able to absorb relatively large quantities of liquid material. Therefore, LCE may be added to corn germ meal, which results in a product containing much less fiber than corn germ meal. We are not aware of any other published values for the nutrient composition of LCE or the CGM-LCE mixture.

Experiment 1: Energy Measurements

The ATTD of GE and the concentrations of DE and ME in corn obtained in this experiment concur with values published by Widmer et al. (2007), Anderson et al. (2012), and NRC (2012). Despite the greater concentration of fat in the HFCG used in this experiment, the concentration of DE and ME in this ingredient was less than values in the corn germ reported by Widmer et al. (2007) and Anderson et al. (2012) who used corn germ from the dry grind industry. The increased concentration of ADF and NDF in the HFCG compared with the corn germ produced from the dry grind industry was likely the reason for the reduced concentration of DE and ME determined in this experiment. Also, the true ileal digestibility of lipids in corn germ is only 50% (Kim et al., 2013), which contributes to a relatively low ATTD of GE in HFCG.

The DE and ME values for corn bran obtained in this experiment were less than reported values (Anderson et al., 2012; NRC, 2012), which likely is a result of a relatively high concentration of fiber and a relatively low concentration of ether extract in corn bran used in this experiment. A slightly greater concentration of GE and the reduced ATTD of GE, DE, and ME in corn bran compared with corn was also reported by Anderson et al. (2012). This observation is likely due to the high concentration of ADF and NDF in corn bran, which reduces the digestibility of GE and, therefore, decreases the DE and ME compared with the values in corn (Wilfart et al., 2007).

Surprisingly, the DE and ME values in LCE were less than in corn when calculated on a DM basis. Liquid corn extractives consist primarily of starch, CP, and organic acids. Reasons for the decreased digestibility of GE in LCE compared with corn were not evident because these nutrients are usually well digested by pigs. However, the starch in LCE is primarily resistant starch, which has a reduced digestibility compared with nonresistant starch (Bird et al., 2007), but resistant starch was not quantified in the LCE used in this experiment. We are not aware of other data for DE and ME in LCE. A second possibility is that the evaporative heating used to increase the DM in LCE caused formation of a resistant protein and starch complex, which reduced ATTD of GE and subsequently reduced DE and ME.

The concentration of DE and ME in CGM-LCE are in close agreement with values for corn germ meal reported by Anderson et al. (2012), but greater than the values in corn germ meal reported by NRC (2012) and by Rojas et al. (2013). We are not aware of other experiments in which DE and ME have been determined for CGM-LCE.

Experiment 2: Amino Acid Digestibility

The AID and SID for CP and most AA in corn agree with values from NRC (2012), but are greater than values reported by Almeida et al. (2011). The difference is likely due to differences among different hybrids of corn grain or seasonal variations.

The AID and SID for CP and all AA in the HFCG used in this experiment are in agreement with the values reported by Muley et al. (2007) and Widmer et al. (2007). However, the low AID and SID for CP and AA in HFCG compared with corn indicates that the protein in the germ fraction may be of poor quality. The high concentration of ADF and NDF in HFCG may also contribute to the low AID and SID for CP and AA in HFCG because fiber in feed ingredients increases the specific endogenous losses of AA by increasing intestinal cell sloughing and mucin synthesis (Nyachoti et al., 1997; Stein et al., 2007). The specific endogenous losses are not included in the fraction quantified by the N-free diet because the N-free diet determines only the basal endogenous losses and only basal endogenous losses are included in the calculations for SID values (Stein et al., 2007; NRC, 2012). Increased specific endogenous losses, therefore, will be accounted against values for AID and SID, which most likely is the main reason for the relatively low values for AID and SID that were determined in this experiment for HFGC.

The AID and SID for CP and AA in corn bran were less than the values reported by NRC (2012). The most likely reason for this observation is that the corn bran used in this experiment contains almost twice as much ADF and NDF compared with corn bran reported by NRC (2012). Greater concentrations of ADF and NDF have a depressive effect on values for AID of AA (Mosenthin et al., 1994; Schultze et al., 1994; Lenis et al., 1996; Nyachoti et al., 1997). As explained for HFGC, high concentrations of fiber in feed ingredients also reduce calculated values for SID because the specific endogenous losses induced by dietary fiber are not included in the calculations of SID values. The very low AID and SID for Lys in corn bran may also have been a result of excess heating and subsequent Maillard reactions, which negatively affects Lys digestibility (Pahm et al., 2008; González-Vega et al., 2011). The relatively high concentration of fiber and the low digestibility of AA in corn bran indicate that corn bran may not be suitable for high-level inclusion in diets for growing pigs, whereas inclusion in diets for sows may be possible.

To our knowledge, this is the first time AID and SID values for CP and AA have been reported in LCE, but the relatively low SID of most AA in LCE indicates that the source of protein in LCE has a reduced digestibility compared with intact corn protein. The AID and SID values for AA in CGM-LCE are relatively close to values in corn germ meal (Almeida et al., 2011; NRC, 2012), and not different from values in LCE.

Conclusions

All corn coproducts used in the present experiments have a reduced digestibility of energy and AA compared with corn. However, HFCG, LCE, and CGM-LCE can likely be used in swine diets because these ingredients contain more CP than corn. Combining corn coproducts to form feed mixtures may improve handling characteristics and result in complementary nutrient profiles, thereby enhancing the potential nutritional value of the mixture. Corn bran has the least digestibility of energy and AA compared with HFCG, LCE, and CGM-LCE, and corn bran is a poor source of digestible energy and AA when compared with corn and other corn coproducts.

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