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In growing pigs, the true ileal and total tract digestibility of acid hydrolyzed ether extract in extracted corn oil is greater than in intact sources of corn oil or soybean oil

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In growing pigs, the true ileal and total tract digestibility of acid hydrolyzed ether extract in extracted corn oil is greater than in intact sources of corn oil or soybean oil[1]

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ABSTRACT: An experiment was conducted to determine the true ileal digestibility (TID) and the true total tract digestibility (TTTD) of acid-hydrolyzed ether extract (AEE) in extracted corn oil, high-oil corn, distillers dried grains with solubles (DDGS), corn germ, and high protein distillers dried grains (HP DDG) and to compare these values to the TID and TTTD of AEE in full-fat soybeans. Nineteen barrows with an initial BW of 52.2 kg (SD = 3.8) were fitted with a T-cannula in the distal ileum and allotted to a 19 × 11 Youden square design with 19 diets and 11 periods. A basal diet based on cornstarch, casein, sucrose, and corn bran was formulated. Eighteen additional diets were formulated by adding 3 levels of extracted corn oil, high-oil corn, DDGS, corn germ, HP DDG, or full-fat soybeans to the basal diet. The apparent ileal and the apparent total tract digestibility of AEE were calculated for each diet. The endogenous flow of AEE associated with each ingredient and values for TID and TTTD were calculated using the regression procedure. Results indicated that digested AEE in ileal digesta and feces linearly increased as AEE intake increased regardless of ingredient ($P < 0.001$) and the regression of ileal and fecal AEE output against AEE intake was significant for all ingredients ($P < 0.001$; $r^2 > 0.77$). However, the ileal and fecal endogenous losses of AEE were different ($P < 0.05$) from 0 only for extracted corn oil, HP DDG, and full-fat soybeans. The TID of AEE was greater ($P < 0.05$) for extracted corn oil (95.4%) than for all other ingredients. The TID of AEE in HP DDG (76.5%) was not different from the TID of AEE in full-fat soybeans (85.2%) but greater ($P < 0.05$) than high-oil corn, DDGS, and corn germ (53.0, 62.1, and 50.1%, respectively). The TTTD of AEE was greater ($P < 0.05$) for extracted corn oil (94.3%) than for all other ingredients, and the TTTD in full-fat soybeans (79.7%) was greater ($P < 0.05$) than the TTTD of AEE in high-oil corn, DDGS, corn germ, and HP DDG (41.4, 51.9, 43.9, and 70.2%, respectively). The TTTD of AEE in HP DDG was also greater ($P < 0.05$) than in high-oil corn, DDGS, and corn germ. In conclusion, the intact sources of oil originating from high-oil corn, DDGS, corn germ, or HP DDG are much less digestible than extracted corn oil, and with the exception of HP DDG, these sources of corn oil are also less digestible than the intact oil in full fat soybeans.

Key words: acid-hydrolyzed ether extract, corn oil, fat, pigs, true ileal digestibility, true total tract digestibility

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INTRODUCTION

Dietary fat is important in diets for swine because of its high energy value (Stahly and Cromwell, 1979) and because dietary fat may influence pork fat quality (Warnants et al., 1999; Averette Gatlin et al., 2002; Weber et al., 2006). As the ethanol industry increases the production of co-products, such as corn distillers dried grains with solubles (**DDGS**), corn germ, and high protein distillers dried grains (**HP DDG**), these co-products are increasingly used in swine diets (Wid-

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mer et al., 2008; Kim et al., 2009; Stein and Shurson, 2009). However, pork fat quality may be compromised as distillers co-products are used because of the unsaturated fatty acids in corn oil (Whitney et al., 2006; Widmer et al., 2008; Benz et al., 2010; Xu et al., 2010). These unsaturated fatty acids may result in softer fat depots in the pigs, which may compromise pork fat quality. To prevent a reduction of pork fat quality as distillers co-products are used, it may become necessary to formulate diets based on concentrations of digestible fat, but there is no information about the digestibility or bioavailability of fat in co-products from the ethanol industry.

Because losses of endogenous fat, including microbial fat, are greater in the hindgut of pigs than in the small intestine, values for the ileal digestibility of fat are sometimes greater than values for the total tract digestibility (Kil et al., 2010) and values for the ileal digestibility of fat may, therefore, give a better estimate of fat bioavailability than values for total tract digestibility. However, to our knowledge, no data that compare ileal and total tract digestibility of fat in corn co-products have been reported. The objective of this research, therefore, was to determine the true ileal digestibility (**TID**) and the true total tract digestibility (**TTTD**) of acid-hydrolyzed ether extract (**AEE**) in corn, corn germ, DDGS, and HP DDG and to compare these values to the TID and TTTD of AEE in corn oil and full-fat soybeans.

MATERIALS AND METHODS

The protocol for the experiment was reviewed and approved by the Institutional Animal Care and Use Committee at the University of Illinois.

The experiment was conducted in an environmentally controlled room (minimum of 22°C and 12 h light and 12 h dark cycle) at the University of Illinois at Urbana-Champaign. The 19 barrows (initial BW of 52.2 ± 3.81 kg) that were used in the experiment were the offspring of line 337 boars that were mated to C22 females (Pig Improvement Company, Hendersonville, TN). Pigs were surgically equipped with a T-cannula in the distal ileum (Stein et al., 1998) and allotted to a 19 × 11 Youden square design with 19 diets and 11 periods (Kim and Stein, 2009). Pigs were individually housed in pens (1.2 by 1.5 m) that were equipped with a feeder, a nipple drinker, and fully slatted T-bar floors.

Diets and Feeding

High-oil corn (Pioneer Hi-Bred, Johnston, IA), DDGS (Archer Daniels Midland, Decatur, IL), and corn germ and HP DDG (Poet Nutrition, Sioux Falls, SD) were obtained from commercial sources (Table 1). Full-fat soybeans and corn oil were obtained locally from the University of Illinois Feed Mill (Champaign, IL).

Table 1. Analyzed composition of the corn co-products and full-fat soybeans, as-fed basis

	Ingredient					
Item	High-oil corn	DDGS[1]	Corn germ	HP DDG[1]	Full-fat soybeans	Corn bran
GE, kcal/kg	4056	4647	4752	5005	5391	4155
CP, %	7.9	25.8	16.3	40.3	35.9	5.8
AEE[2], %	7.1	11.8	18.1	6.8	21.4	2.3
NDF, %	10.6	25.4	23.7	27.1	7.9	66.5

[1]DDGS = distillers dried grains with solubles; HP DDG = high protein distillers dried grains.

[2]AEE = acid-hydrolyzed ether extract.

Nineteen experimental diets were prepared (Tables 2 and 3). A basal diet (1.32% AEE) based on cornstarch, casein, sucrose, and corn bran was formulated. Eighteen additional diets were formulated by adding 3 levels of extracted corn oil (2.00, 4.00, or 6.00%), high-oil corn (24.00, 48.00, or 72.00%), DDGS (17.00, 34.00, or 51.00%), corn germ (11.00, 22.00, or 33.00%), HP DDG (16.00, 32.00, or 48.00%), or full-fat soybeans (9.34, 18.68, or 28.02%) to the basal diet at the expense of corn starch, casein, and corn bran. The concentration of corn bran was adjusted to minimize the potential effects of dietary fiber on the digestibility of AEE (Kil et al., 2010). The concentration of dietary AEE increased with the increasing levels of each feed ingredient. All diets contained 0.5% chromic oxide as an indigestible marker, and vitamins and minerals were included in all diets to meet or exceed nutrient requirement estimates (NRC, 1998).

Feed was provided at daily levels of 2.5 times the estimated maintenance requirement for energy (i.e., 106 kcal of ME/kg $BW^{0.75}$; NRC, 1998) and equal meals were provided at 0800 and 1600 h. The feed allowance was adjusted at the beginning of each period when the BW of each pig was recorded. Animals had free access to water throughout the experiment.

Sample Collection

Each period lasted 7 d. The initial 4 d were an adaptation period to the diet. Fecal samples were collected on d 5 of each period and in the morning of d 6 because the results by Urriola and Stein (2010) indicated that differences in apparent total tract digestibility (**ATTD**) values for energy and fiber are not observed between fecal samples collected on d 5 and 19 of feeding the same diet. Ileal digesta samples were collected for 8 h on d 6 and 7 as previously described (Kil et al., 2010). A plastic bag was attached to the cannula barrel using a zip tie and digesta flowing into the bag were collected. Bags were removed whenever they were filled with digesta, or at

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

Oil source:	Basal	Corn oil			High-oil corn			DDGS			Corn germ			HP DDG			Full-fat soybeans		
Item added oil[2]:	–	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Corn starch	56.00	54.00	52.00	50.00	37.71	18.60	2.00	38.53	31.57	23.80	40.46	34.08	27.43	43.08	37.95	28.62	51.22	45.48	39.73
Casein	11.50	11.50	11.50	11.50	9.80	8.70	4.50	9.00	5.20	2.10	10.60	9.90	9.40	4.90	–	–	8.30	5.80	3.30
Sucrose	10.00	10.00	10.00	10.00	10.00	10.00	10.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	10.00	10.00	10.00
Corn bran	19.60	19.60	19.60	19.60	15.75	11.90	8.10	13.10	6.60	0.13	15.65	11.70	7.80	13.05	6.50	–	18.45	17.35	16.25
Corn oil	–	2.00	4.00	6.00	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
High-oil corn	–	–	–	–	24.00	48.00	72.00	–	–	–	–	–	–	–	–	–	–	–	–
DDGS	–	–	–	–	–	–	–	17.00	34.00	51.00	–	–	–	–	–	–	–	–	–
Corn germ	–	–	–	–	–	–	–	–	–	–	11.00	22.00	33.00	–	–	–	–	–	–
HP DDG	–	–	–	–	–	–	–	–	–	–	–	–	–	16.00	32.00	48.00	–	–	–
Full-fat soybeans	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	9.34	18.68	28.02
L-Lys HCl	–	–	–	–	–	–	0.29	–	0.13	0.32	–	–	–	0.22	0.54	0.40	–	–	–
L-Thr	–	–	–	–	–	–	0.10	–	0.02	0.04	–	–	–	0.05	0.06	–	–	–	–
L-Trp	–	–	–	–	–	–	0.04	–	0.03	0.04	–	–	–	0.04	0.07	0.05	–	–	–
Dicalcium phosphate	0.48	0.48	0.48	0.48	0.52	0.54	0.68	0.15	0.00	–	0.08	–	–	0.69	0.82	0.74	0.56	0.60	0.65
Ground limestone	0.70	0.70	0.70	0.70	0.75	0.79	0.82	1.00	1.23	1.35	0.99	1.10	1.15	0.75	0.84	0.97	0.66	0.62	0.58
Potassium carbonate	0.40	0.40	0.40	0.40	0.20	0.20	0.20	–	–	–	–	–	–	–	–	–	0.20	0.20	0.20
Magnesium oxide	0.10	0.10	0.10	0.10	0.05	0.05	0.05	–	–	–	–	–	–	–	–	–	0.05	0.05	0.05
Chromic oxide	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Sodium chloride	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin–mineral premix[3]	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Santoquin[4]	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

[1]DDGS = distillers dried grains with solubles; HP DDG = high protein distillers dried grains.

[2]Added 3 levels of different oils to the basal diet at the expense of corn starch, casein, and corn bran.

[3]Supplied per kilogram of complete diet: vitamin A, 11,128 IU; vitamin D_3, 2204 IU; vitamin E, 66 IU; vitamin K, 1.42 mg; thiamin, 0.24 mg; riboflavin, 6.58 mg; pyridoxine, 0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid, 23.5 mg; niacin, 44 mg; folic acid, 1.58 mg; biotin, 0.44 mg; Cu, 10 mg as copper sulfate; Fe, 125 mg as iron sulfate; I, 1.26 mg as potassium iodate; Mn, 60 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; and Zn, 100 mg as zinc oxide.

[4]Supplied 130 mg of ethoxyquin per kilogram of complete diet.

least once every 30 min, to prevent bacterial degradation of the nutrients in the digesta. Fecal and ileal samples were stored at –20°C immediately after collection.

Chemical Analysis

At the conclusion of the experiment, fecal samples were dried at 55°C in a forced-air drying oven. Frozen ileal samples were allowed to thaw at room temperature and mixed within animal and diet, and a subsample was collected and lyophilized. Fecal and ileal samples were finely ground through a 1-mm screen before chemical analysis.

Diets, fecal samples, and ileal samples were analyzed for DM and AEE (Method 930.15 and Method 954.02, respectively; AOAC International, 2007). All diets were also analyzed for GE using bomb calorimetry (Model 6300; Parr Instruments Co., Moline, IL) and for NDF (Holst, 1973) and ADF (Method 973.18; AOAC International, 2007). The Cr concentration of diets and ileal and fecal samples was determined using graphite furnace atomic absorption spectrometry (Williams et al., 1962). Corn bran, corn germ, high-oil corn, HP-DDG, DDGS, and full-fat soybeans were analyzed for GE, AEE, and NDF as described for the diets. Crude protein in these samples was analyzed by combustion (Method 999.03; AOAC International, 2007) using a Rapid N cube (Elementar Americas Inc, Mt. Laurel, NJ) with Asp as the internal standard.

Calculations

The ileal and total tract output of AEE and the quantity of AEE digested (g/kg DMI) at the end of the ileum and over the entire intestinal tract were calculated for each diet (Kil et al., 2010). The apparent ileal digestibil-

Table 3. Analyzed nutrient composition of experimental diets, as-fed basis[1]

Oil source:	Basal	Corn oil			High-oil corn			DDGS			Corn germ			HP DDG			Full-fat soybeans		
Item added oil[2]:	–	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
DM, %	91.0	91.0	91.4	91.0	90.0	89.2	89.6	92.0	91.8	91.7	91.7	92.1	92.0	92.5	93.0	93.4	91.4	91.8	92.1
AEE,[3] %	1.32	4.26	6.45	7.39	2.80	3.61	5.58	3.37	4.71	6.48	3.28	5.14	6.19	3.10	4.09	5.27	3.38	5.60	7.88
GE, kcal/kg	3868	3967	4106	4180	3908	4013	3993	3999	4056	4173	3992	4072	4164	3973	4034	4229	3970	4101	4245
NDF, %	15.83	14.55	13.82	12.29	19.11	15.23	14.78	16.27	20.14	21.44	15.24	15.20	15.90	15.39	19.88	21.53	14.64	14.67	14.80
ADF, %	3.76	3.13	3.24	3.25	3.37	3.56	3.56	4.36	5.86	6.32	3.80	3.88	4.51	4.74	5.87	6.56	3.90	4.11	4.34

[1]DDGS = distillers dried grains with solubles; HP DDG = high protein distillers dried grains.

[2]Added 3 levels of extracted corn oil (2.00, 4.00, or 6.00%), high-oil corn (24.00, 48.00, or 72.00%), DDGS (17.00, 34.00, or 51.00%), corn germ (11.00, 22.00, or 33.00%), HP DDG (16.00, 32.00, or 48.00%), or full-fat soybeans (9.34, 18.68, or 28.02%) to the basal diet at the expense of corn starch, casein, and corn bran.

[3]AEE = acid-hydrolyzed ether extract.

ity (**AID**) of AEE was calculated for each diet according to Stein et al. (2007) and the ATTD of AEE in each diet was calculated using the same equation. The TID of AEE, the TTTD of AEE, and the ileal and total tract endogenous losses of AEE were estimated for each diet using regression analyses (Kil et al., 2010) according to the following equation (Jørgensen et al., 1993):

$$AEE_D = -AEE_{EL} + (AEE_{TD} \times AEE_{IN}),$$

in which AEE_D = digested AEE (g/kg of DMI), AEE_{EL} = endogenous AEE loss (g/kg DMI), AEE_{TD} = true digestibility of AEE (%), and AEE_{IN} = AEE intake (g/kg DMI). Because different feed ingredients may elicit different endogenous losses of fat (Kil et al., 2010), regressions lines for each ingredient was established to obtain the intercept for each ingredient.

Statistical Analyses

Data were analyzed using the MIXED procedure (SAS Inst. Inc., Cary, NC). The model included diet as a fixed variable and period and animal as random variables. Orthogonal polynomial contrasts were used to determine effects of increasing dietary AEE concentration from each ingredient on the digestibility of AEE. Appropriate coefficients for unequally spaced AEE intake were obtained using the interactive matrix language procedure of SAS. The REG procedure was used to estimate endogenous AEE losses in ileal digesta and feces. Estimates of true digestibility values (i.e., the slopes of the regression lines) were compared among diets based on confidence intervals of coefficients for regression lines (Dilger and Adeola, 2006) and this procedure was also used to compare TID values with TTTD values within each ingredient. The pig was the experimental unit for all analyses and the α level used for determination of differences among means was 0.05. Probability values between 0.05 and 0.10 were considered tendencies.

RESULTS

The analyzed composition of the feed ingredients was in agreement with previously reported values (NRC, 1998; Widmer et al., 2007). All pigs consumed their assigned diets without any problems and both fecal and ileal samples were successfully collected from all pigs. As pigs consumed increasing amounts of AEE from extracted corn oil, ileal output of AEE calculated as grams per kilogram DMI linearly increased ($P < 0.05$; Table 4). When high-oil corn, DDGS, corn germ, HP DDG, or full-fat soybeans was used as a source of additional oil, both ileal and fecal output linearly increased with increasing dietary concentrations of AEE ($P < 0.001$). Digested AEE at the end of the ileum and over the total tract linearly increased as AEE intake increased regardless of feed ingredient ($P < 0.001$). The AID of AEE also increased (linear and quadratic; $P < 0.01$) with increasing AEE intake from extracted corn oil or full-fat soybeans. A linear increase in the AID of AEE was observed in pigs fed HP DDG ($P < 0.01$) and a tendency ($P = 0.10$) for a linear increase in AID of AEE was observed for DDGS, but there was no effect of dietary AEE level on the AID of AEE in high oil corn or corn germ. The output of AEE in the feces tended (linear; $P = 0.059$) to increase in pigs fed diets containing extracted corn oil and increased (linear; $P < 0.01$) in pigs fed all other ingredients as the concentration of AEE in the diet increased. The ATTD of AEE also increased (linear and quadratic; $P < 0.05$) as the concentration of extracted corn oil, HP DDG, or full-fat soybeans increased in the diet, and there was a tendency ($P = 0.097$) for an increase in the ATTD of AEE in DDGS. However, for high oil corn and corn germ, no differences in the ATTD of AEE were observed due to dietary concentration of AEE.

The regression of ileal AEE output against AEE intake was significant ($P < 0.001$; $r^2 > 0.77$) for all ingredients (Table 5). However, the *y*-intercept, which represents the endogenous loss of AEE, was different from 0 only for extracted corn oil, HP DDG, and full-fat

Table 4. Apparent ileal digestibilty (AID) and apparent total tract digestibility (ATTD) of acid-hydrolyzed ether extract (AEE) in extracted corn oil, high-oil corn, distillers dried grains with solubles (DDGS), high protein distillers dried grains (HP DDG), and full-fat soybeans fed to growing pigs[1]

		Added oil[2]				*P*-value	
Item	Basal	Level 1	Level 2	Level 3	SEM	Linear	Quadratic
Corn oil							
AEE ileal output, g/kg DMI	7.1	7.9	9.3	10.0	1.0	0.021	0.567
AEE ileal digested, g/kg DMI	7.5	38.9	61.3	71.2	1.0	<0.001	0.598
AID of AEE, %	51.5	83.2	86.8	87.7	3.1	<0.001	<0.001
AEE fecal output, g/kg DMI	7.4	9.7	8.6	12.3	1.5	0.059	0.705
AEE total tract digested, g/kg DMI	7.2	37.1	62.0	68.9	1.5	<0.001	0.727
ATTD of AEE, %	49.3	79.3	87.8	84.9	3.5	<0.001	0.001
High-oil corn							
AEE ileal output, g/kg DMI	7.1	16.6	23.8	29.8	1.8	<0.001	0.074
AEE ileal digested, g/kg DMI	7.5	14.5	16.7	32.4	1.8	<0.001	0.088
AID of AEE, %	51.5	46.6	41.2	52.1	4.6	0.939	0.072
AEE fecal output, g/kg DMI	7.4	17.7	26.7	35.4	1.5	<0.001	0.068
AEE total tract digested, g/kg DMI	7.2	13.4	13.8	26.9	1.5	<0.001	0.085
ATTD of AEE, %	49.3	43.1	34.1	43.2	4.0	0.200	0.034
Distillers dried grains with solubles							
AEE ileal output, g/kg DMI	7.1	14.9	20.7	28.2	1.7	<0.001	0.774
AEE ileal digested, g/kg DMI	7.5	21.8	30.6	42.4	1.7	<0.001	0.851
AID of AEE, %	51.5	59.5	59.7	60.1	4.0	0.100	0.309
AEE fecal output, g/kg DMI	7.4	14.4	25.0	33.2	1.4	<0.001	0.248
AEE total tract digested, g/kg DMI	7.2	22.2	26.3	37.4	1.4	<0.001	0.301
ATTD of AEE, %	49.3	60.6	51.3	53.0	3.4	0.721	0.097
Corn germ							
AEE ileal output, g/kg DMI	7.1	18.7	22.5	35.7	2.1	<0.001	0.258
AEE ileal digested, g/kg DMI	7.5	17.1	33.2	31.6	2.1	<0.001	0.265
AID of AEE, %	51.5	47.9	59.6	47.0	5.2	0.918	0.606
AEE fecal output, g/kg DMI	7.4	18.2	29.3	37.0	1.5	<0.001	0.387
AEE total tract digested, g/kg DMI	7.2	17.6	26.4	30.2	1.5	<0.001	0.399
ATTD of AEE, %	49.3	49.1	47.4	44.9	4.2	0.417	0.676
High protein distillers dried grains							
AEE ileal output, g/kg DMI	7.1	11.5	17.1	16.3	1.1	<0.001	0.112
AEE ileal digested, g/kg DMI	7.5	22.0	26.9	40.1	1.1	<0.001	0.135
AID of AEE, %	51.5	65.7	61.1	71.1	3.5	0.001	0.658
AEE fecal output, g/kg DMI	7.4	11.6	16.0	19.5	1.0	<0.001	0.470
AEE total tract digested, g/kg DMI	7.2	21.8	28.0	36.9	1.1	<0.001	0.409
ATTD of AEE, %	49.3	65.2	63.5	65.3	3.3	0.001	0.047
Full-fat soybeans							
AEE ileal output, g/kg DMI	7.1	11.2	11.7	18.5	1.3	<0.001	0.337
AEE ileal digested, g/kg DMI	7.5	25.8	49.2	67.1	1.3	<0.001	0.275
AID of AEE, %	51.5	69.7	80.8	78.4	3.5	<0.001	0.003
AEE fecal output, g/kg DMI	7.4	13.0	16.9	22.2	1.0	<0.001	0.715
AEE total tract digested, g/kg DMI	7.2	24.0	44.1	63.3	1.0	<0.001	0.846
ATTD of AEE, %	49.3	64.9	72.3	74.0	3.2	<0.001	0.019

[1]Each least squares mean represents 11 observations.

[2]Added 3 levels of extracted corn oil (2.00, 4.00, or 6.00%), high-oil corn (24.00, 48.00, or 72.00%), DDGS (17.00, 34.00, or 51.00%), corn germ (11.00, 22.00, or 33.00%), HP DDG (16.00, 32.00, or 48.00%), or full-fat soybeans (9.34, 18.68, or 28.02%) to the basal diet at the expense of corn starch, casein, and corn bran.

soybeans (6.11, 4.20, and 4.85 g/kg DMI, respectively; $P < 0.01$). The TID of AEE that were calculated as the slopes of the regression lines were greater ($P < 0.05$) for extracted corn oil (95.4%) than other ingredients and the TID of AEE in HP DDG was greater ($P < 0.05$) than in high-oil corn, DDGS, and corn germ (76.5 vs. 53.0, 62.1, and 50.1%). The TID of AEE in full-fat soybeans (85.2%) was also greater ($P < 0.05$) than in high-oil corn, DDGS, and corn germ, but not different from the TID of AEE in HP DDG.

Table 5. Endogenous loss and the true digestibility of acid-hydrolyzed ether extract (AEE) in extracted corn oil, high-oil corn, distillers dried grains with solubles (DDGS), high protein distillers dried grains (HP DDG), and full-fat soybeans fed to growing pigs

			Endogenous loss of AEE, g/kg DMI			True digestibility of AEE[1], %		
Item	Regression equation	r^2	Estimate	SE	*P*-value	Estimate[1]	SE	*P*-value
Ileal basis								
Corn oil	y = –6.11 + 0.954x	0.988	6.11	1.09	<0.001	95.4[a]	1.8	<0.001
High-oil corn	y = –1.77 + 0.530x	0.787	1.77	2.12	0.411	53.0[c]	5.0	<0.001
DDGS	y = –1.27 + 0.621x	0.893	1.27	1.84	0.492	62.1[c]	3.6	<0.001
Corn germ	y = 0.29 + 0.501x	0.775	–0.29	2.43	0.907	50.1[c]	5.1	<0.001
HP DDG	y = –4.20 + 0.765x	0.940	4.20	1.48	0.008	76.5[b]	3.5	<0.001
Full-fat soybeans	y = –4.85 + 0.852x	0.977	4.85	1.37	0.001	85.2[b]	2.4	<0.001
Total tract basis								
Corn oil	y = –6.51 + 0.943x	0.970	6.51	1.73	<0.001	94.3[a]	2.8	<0.001
High-oil corn	y = 0.11 + 0.414x	0.771	–0.11	1.73	0.948	41.4[d]	4.1	<0.001
DDGS	y = 0.87 + 0.519x	0.887	–0.87	1.59	0.589	51.9[d]	3.1	<0.001
Corn germ	y = 1.33 + 0.439x	0.863	–1.33	1.57	0.407	43.9[d]	3.3	<0.001
HP DDG	y = –2.62 + 0.702x	0.951	2.62	1.22	0.040	70.2[c]	2.9	<0.001
Full-fat soybeans	y = –4.85 + 0.797x	0.985	4.85	1.02	<0.001	79.7[b]	1.8	<0.001

[a–d]Within a column and site of collection, means lacking a common superscript letters are different ($P < 0.05$).

[1]Values for both ileal and total tract true digestibility of AEE were calculated and compared, but because no differences ($P > 0.05$) were observed for any of the ingredients, only the average values for the true digestibility of AEE are presented.

The regression of total tract output of AEE against the intake of AEE was also significant ($P < 0.001$; $r^2 > 0.77$) for all ingredients. However, the *y*-intercept was different from 0 only for extracted corn oil, HP DDG, and full-fat soybeans (6.51, 2.62, and 4.85 g/kg DMI, respectively; $P < 0.05$). The TTTD of AEE was greater ($P < 0.05$) for extracted corn oil (94.3%) than for all other ingredients. The TTTD of AEE in HP DDG was greater ($P < 0.05$) than in high-oil corn, DDGS, and corn germ (70.2 vs. 41.4, 51.9, and 43.9%) but less ($P < 0.05$) than the TTTD of AEE in full-fat soybeans (79.7%).

The TTTD of AEE was less ($P < 0.05$) than the TID of AEE in high-oil corn, DDGS, corn germ, and HP DDG. However, for extracted corn oil and full-fat soybeans, no differences between TTTD and TID values were observed.

DISCUSSION

Digestibility values were calculated based on values for AEE in this experiment whereas values for the digestibility of crude fat without acid hydrolysis before ether extraction have been reported by others (Htoo et al., 2008; Seneviratne et al., 2011). Because digestibility values for AEE are different from digestibility values for crude fat determined without acid hydrolysis (Ji et al., 2008), it is important that the procedures used for fat analyses are specified.

Values for the ATTD of AEE in extracted corn oil and full-fat soybeans obtained in the present experiment are in good agreement with values reported by Adams and Jensen (1984), but values for the ATTD of AEE in DDGS observed in this experiment are less than the values for the ATTD of crude fat in DDGS reported by Stein et al. (2009). The ATTD of AEE in high-oil corn obtained in this experiment is also less than the value reported by Adams and Jensen (1984), but closer to the values obtained by Adeola and Bajjalieh (1997). It has also been demonstrated that there are differences in the ATTD of fat among sources of high oil-corn (Adeola and Bajjalieh, 1997), which may be a consequence of differences in fat encapsulation among hybrids.

The reason for the reduced ATTD and TTTD of the oil in high oil corn and the corn co-products compared with the extracted oil is most likely that some of the oil in corn and the corn co-products is bound or encapsulated in cell membranes or fiber compounds in the ingredients (Adams and Jensen, 1984). Heating of sunflower oil reduces the ATTD of fat by approximately 25% units when fed to rats (González-Muñoz et al., 2003) because of oxidation and polymeration of the fatty acids in the oil. It is, therefore, possible that the heating taking place when DDGS and HP DDG are dried during the dehydration process contributes to the reduced digestibility of AEE in these ingredients compared with extracted oil. To our knowledge, there is, however, no information about the effect of heating on the digestibility of AEE in ingredients fed to pigs.

The concentration and source of dietary fiber in a diet may affect the digestibility of fat (Just et al., 1980; Hansen et al., 2006; Kil et al., 2010). In the present experiment, corn bran was included in the diets in an attempt to equalize the concentration of fiber among diets. Although the concentration of NDF varied somewhat among diets, most values were within a relatively narrow range. However, addition of fiber to diets may have a different effect on fat digestibility than fiber present in a high-fiber ingredient because of the encapsulation of fat that may take place in high-fiber ingredients. Synthetic fiber does not have the same effect on the digestibility of fat as intact corn fiber (Kil et al., 2010), which was the reason corn bran was used in the present experiment to attempt to equalize fiber levels among diets. However, corn bran does contain a small amount of fat and by including different amounts of corn bran in the diets, small amounts (between 0 and 0.45%) of fat from corn bran was included in the diets. It was not possible to account for the fat provided from corn bran in the calculations of ATTD values for AEE in the diets and it was assumed that the small quantities of fat from corn bran did not influence the results of the experiment.

The linear and quadratic increase in the AID and ATTD of AEE that was observed as the dietary inclusion of extracted corn oil increased was anticipated and in agreement with data from research with extracted oils such as animal fat (Just et al., 1980), soybean oil (Jørgensen et al., 1993), rapeseed oil (Jørgensen et al., 1996), and corn oil (Kil et al., 2010). The reason for this curvilinear response is that the endogenous loss of AEE contributes a relatively larger proportion to the total AEE output in diets with less AEE concentrations than in diets with greater AEE concentrations (Kil et al., 2010). The reason the digestibility values for AEE from high-oil corn, DDGS, and corn germ were unaffected by the level of AEE in the diets is most likely that these diets had a greater AEE output in the digesta and feces because of the low AEE digestibility compared with diets containing extracted corn oil or full-fat soybeans. The contribution of endogenous AEE to the AEE output was, therefore, much less in pigs fed these diets compared with pigs fed the diets containing extracted corn oil or soybean oil. The estimates of endogenous AEE loss in pigs fed diets containing high oil corn, DDGS, or corn germ also had greater variation than the estimates for pigs fed extracted corn oil or full-fat soybeans.

The regression procedure was used to estimate endogenous losses in the present experiment. This procedure yields the total, not the basal, endogenous losses of AEE (NRC, 2012). As a consequence, true digestibility values rather than standardized digestibility values were calculated. The ileal and total tract endogenous losses of AEE for corn oil that were determined in this experiment are in good agreement with recent values reported by Kil et al. (2010) and also in agreement with values reported for soybean oil (Jørgensen et al., 1993). The fact that the estimated endogenous loss of AEE from some of the other diets was not different from 0 is a reflection of the relatively large variability that is observed in endogenous losses of AEE (Jørgensen et al., 1993).

The greater TID and TTTD of AEE in extracted corn oil compared with oil in high-oil corn that was observed in this experiment are in agreement with previous research (Adams and Jensen, 1984; Agunbiade et al., 1992; Kil et al., 2010). This observation may be attributed to insufficient digestive capacity of pigs to liberate all oil from the intact forms of oil. The TID of AEE in extracted corn oil that was determined in the present experiment is comparable to the TID recently reported for extracted corn oil (Kil et al., 2010). The fact that the TID and the TTTD of AEE in full-fat soybeans was much greater than in high-oil corn, DDGS, corn germ, and HP DDGS indicates that the oil in soybeans is more accessible to digestive enzymes than the oil in high-oil corn, DDGS, corn germ, and HP DDG. The reason for this observation may be that oil is the primary storage form of energy in soybeans whereas starch is the primary storage form of energy in corn. The digestibility of extracted corn oil is, however, close to 95%, as demonstrated in this and in previous experiments (Adams and Jensen, 1984; Kil et al., 2010), which indicates that the difference in TID and TTTD of AEE between full-fat soybeans and high-oil corn and corn co-products is not a result of a low digestibility of corn oil as such. It is, therefore, likely that the main reason for the reduced digestibility of AEE in high-oil corn and corn co-products compared with full-fat soybeans is a result of the way the oil is stored in the ingredients.

Corn germ contains over 90% of the total amount of AEE in corn and DDGS contains all the AEE in corn, which is likely the reason for the lack of differences in the digestibility of AEE among corn germ, DDGS, and high-oil corn. In contrast, HP DDG contains only a portion of the AEE in corn because it is produced from fermentation of endosperm that is left after removal of bran and germ from the corn grain (Widmer et al., 2007), and this is likely the reason for the greater digestibility of AEE in HP DDG than in the other sources of intact corn oil.

The relatively low TID and TTTD of AEE in corn germ explains why the total DE in corn germ is not greater than in corn despite the high concentration of AEE in corn germ (Widmer et al., 2007). However, the energy value of corn germ will likely be improved if technological treatments that will improve the digestibility of AEE in corn germ can be identified. Research in this area is, therefore, needed. Likewise, the low digestibility of AEE in DDGS indicates that it may be possible to improve the energy value of DDGS if procedures to improve the TID and the TTTD of AEE in DDGS can be identified.

The reduced digestibility of AEE in corn and corn co-products compared with extracted corn oil has implications in terms of calculating energy values of feed ingredients. In calculations of energy values for pigs, an average digestibility value for fat in feed ingredients of 82% minus [0.2 × NDF (%, DM) – 0.7] in the ingredient has been suggested (Sauvant et al., 2004). However, the present data indicate that some sources of fat have digestibility values that are much less than the value calculated from this equation, which indicates that the energy value of ingredients with high concentrations of fat may be less than previously assumed. The current data, therefore, indicate that the digestibility of fat needs to be determined in all feed ingredients that are used in diets fed to pigs and that the actual digestibility value for each ingredient should be used when the NE value of an ingredient is calculated.

The fact that values for TID of AEE were greater than values for TTTD of AEE in high oil corn, DDGS, corn germ, and HP DDG is in agreement with previous values obtained for fiber containing ingredients (Kil et al., 2010). This is most likely a result of microbial synthesis of fat in the hindgut because endogenous losses of fat determined over the total intestinal tract are greater than values determined at the end of the ileum (Kil et al., 2010). It is, however, not clear why TID and TTTD values for AEE in corn oil and in full fat soybeans were not different because the concentration of fiber was equalized among diets. This observation indicates that, in addition to dietary fiber, there are other factors that influence endogenous losses of fat in pigs.

Conclusion

The AEE in extracted corn oil is more digestible than oil from high-oil corn, DDGS, corn germ, and HP DDG, and the digestibility of AEE in oil from corn and corn co-products is less than in intact soybean oil. There is, however, relatively great variability in the digestibility of fat among corn co-products, and a common value for fat digestibility among ingredients should not be used. Research to investigate the possibility of enhancing the digestibility of AEE is needed to improve the energy values of feed ingredients.

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