Effects of reduced-oil corn distillers dried grains with solubles composition on digestible and metabolizable energy value and prediction in growing pigs[1]

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ABSTRACT: Two experiments were conducted to determine the DE and ME content of corn distillers dried grains with solubles (corn-DDGS) containing variable ether extract (EE) concentrations and to develop DE and ME prediction equations based on chemical composition. Ether extract content of corn-DDGS ranged from 4.88 to 10.88% (DM basis) among 4 corn-DDGS samples in Exp. 1 and from 8.56 to 13.23% (DM basis) among 11 corn-DDGS samples in Exp. 2. The difference in concentration of total dietary fiber (TDF) and NDF among the 4 corn-DDGS sources was 2.25 and 3.40 percentage units, respectively, in Exp. 1 but was greater among the 11 corn-DDGS sources evaluated in Exp. 2, where they differed by 6.46 and 15.18 percentage units, respectively. The range in CP and ash were from 28.97 to 31.19% and 5.37 to 6.14%, respectively, in Exp. 1 and from 27.69 to 32.93% and 4.32 to 5.31%, respectively, in Exp. 2. Gross energy content among corn-DDGS samples varied from 4,780 to 5,113 kcal/kg DM in Exp. 1 and from 4,897 to 5,167 kcal/kg DM in Exp. 2. In Exp. 1, the range in DE content was from 3,500 to 3,870 kcal/kg DM and ME content varied from 3,266 to 3,696 kcal/kg DM. There were no differences in ME:DE content among the 4 corn-DDGS sources in Exp. 1, but ME:GE content differed ($P = 0.04$) among sources (66.82 to 74.56%). In Exp. 2, the range in DE content among the 11 corn-DDGS sources was from 3,474 to 3,807 kcal/kg DM and ME content varied from 3,277 to 3,603 kcal/kg DM. However, there were no differences in DE:GE, ME:DE, or ME:GE among sources in Exp. 2. In Exp. 1, no ingredient physical or chemical measurement [bulk density (BD), particle size, GE, CP, starch, TDF, NDF, ADF, hemicellulose, EE, or ash)] was statistically significant at $P \leq 0.15$ to predict DE or ME content in corn-DDGS. In Exp. 2, the best fit DE equation was DE (kcal/kg DM) = 1,601 – (54.48 × % TDF) + (0.69 × % GE) + (731.5 × BD) [$R^2 = 0.91$, SE = 41.25]. The best fit ME equation was ME (kcal/kg DM) = 4,558 + (52.26 × % EE) – (50.08 × % TDF) [$R^2 = 0.85$, SE = 48.74]. Apparent total tract digestibility of several nutritional components such as ADF, EE, and N were quite variable among corn-DDGS sources in both experiments. These results indicate that although EE may be a good predictor of GE content in corn-DDGS, it is not a primary factor for predicting DE or ME content. Measures of dietary fiber, such as ADF or TDF, are more important than EE in determining the DE or ME content of corn-DDGS for growing pigs.

Key words: corn-distillers grains with solubles, energy, energy prediction, ether extract, growing–finishing pigs

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INTRODUCTION

Corn dried distillers grains with solubles (**corn-DDGS**) have typically contained 10 to 11% ether extract (**EE**) with a ME content similar to corn (Stein and Shurson, 2009). However, the majority of United States ethanol plants have recently implemented oil extraction technology that has led to the production of corn-DDGS with a wider range of EE (5 to 12%). Because oil contains 2.25 times more energy than

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carbohydrates, removal of oil likely reduces the ME content in corn-DDGS, which can affect its economic value and dietary inclusion rates.

Four studies have been published (Stein et al., 2006, 2009; Pedersen et al., 2007; Anderson et al., 2012) that determined the DE and ME content of 30 sources of corn-DDGS varying in EE from 9.6 to 14.3% (DM basis). Studies by Pedersen et al. (2007) and Anderson et al. (2012) also included prediction equations based on chemical analysis to estimate DE and ME content. In contrast, only 3 studies that estimated the effect of reduced-oil corn-DDGS on ME content have been published (Dahlen et al., 2011; Jacela et al., 2011; Anderson et al., 2012). In the studies by Jacela et al. (2011) and Anderson et al. (2012), oil was removed by hexane extraction whereas Dahlen et al. (2011) evaluated a dried distillers grains co-product without solubles. The processes used to produce reduced-oil corn-DDGS in these studies are different than the centrifugation technologies used by ethanol plants to produce reduced-oil corn-DDGS today.

Interestingly, the EE content of the reduced-oil distillers dried grains with solubles (**DDGS**) evaluated by Jacela et al. (2011) and Anderson et al. (2012) was similar, yet different estimates of DE and ME were obtained, indicating that these results may not be fully applicable for estimating the ME content of reduced-oil corn-DDGS. The objectives of this study were to obtain sources of corn-DDGS varying in EE content, from which to determine DE and ME content, and to develop DE and ME prediction equations based on corn-DDGS composition.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at Iowa State University (Ames, IA) approved all experimental protocols.

Animal Management

Two experiments (Exp. 1 and Exp. 2) were conducted using gilts that were offspring from PIC Camborough 22 sows × L337 boars (Pig Improvement Company, Hendersonville, TN). Both experiments were conducted over a 4-mo period (May through September, 2011) at the Iowa State University Swine Nutrition Farm (Ames, IA). Three groups of 24 gilts (n = 72; BW = 105.6 ± 9.1 kg) were used in Exp. 1, and 6 groups of 24 gilts (n = 144; BW = 83.7 ± 8.3 kg) were used in Exp. 2. Gilts were housed individually in metabolism crates (Exp. 1: 1.2 by 2.4 m; Exp. 2: 0.7 by 1.5 m) that allowed for separate but total collection of feces and urine. Crates were equipped with a stainless steel feeder and a nipple waterer, to which the pigs had ad libitum access. Gilts were randomly assigned to either a basal or corn-DDGS-containing diet, resulting in 12 replications for pigs fed the basal diet and 15 replications for pigs fed each corn-DDGS source in Exp. 1 or 12 replications for pigs fed the basal diet or each corn-DDGS source in Exp. 2.

Table 1. Ingredient composition of basal diet, as-fed basis[1]

Ingredient	Concentration, %
Corn	96.70
Monoammonium phosphate	0.75
Limestone	1.30
Sodium chloride	0.35
Titanium dioxide[2]	0.50
Vitamin mix[3]	0.20
Trace mineral mix[4]	0.20

[1]Formulated to contain 0.50% Ca and 0.45% P.

[2]Indigestible marker.

[3]Provided per kilogram of diet: vitamin A, 6,125 IU; vitamin D_3, 700 IU; vitamin E, 50 IU; vitamin K, 30 mg; vitamin B_{12}, 0.05 mg; riboflavin, 11 mg; niacin, 56 mg; and pantothenic acid, 27 mg.

[4]Provided per kilogram of diet: Cu (as $CuSO_4$), 22 mg; Fe (as $FeSO_4$), 220 mg; I (as $Ca(IO_3)_2$), 0.4 mg; Mn (as $MnSO_4$), 52 mg; Zn (as $ZnSO_4$), 220 mg; and Se (Na_2SeO_3), 0.4 mg.

Diets

Gilts were fed a standard corn–soybean meal-based diet before experimentation and were weighed at the beginning and end of each metabolism trial. For each trial, the same basal diet was fed, which contained 96.7% corn and supplemental vitamins and minerals, with corn being the sole energy-containing ingredient (Table 1). In Exp. 1, 4 corn-DDGS samples varying in EE content from 4.88 to 10.88% (DM basis) were evaluated whereas in Exp. 2, 11 corn-DDGS samples with EE content varying from 8.56 to 13.23% (DM basis) were evaluated. Particle size of corn-DDGS sources varied from 294 to 379 μm in Exp. 1 and from 568 to 1,078 μm in Exp. 2. In both experiments, pigs were either fed 100% of the basal diet or test diets that contained 70% of the basal diet and 30% of a specific corn-DDGS sample. All diets were fed in a meal form. Test ingredients were not ground to a constant particle size to determine if particle size was an important factor in equations to predict DE and ME content and to represent a typical range in particle size as would be fed commercially. Corn-DDGS sources were included in the test diets at 30% (70% basal diet) for several reasons: 1) to include as much of the test ingredients as possible to improve accuracy of DE and ME estimates, 2) to reduce the risk of feed refusals, and 3) to use dietary inclusion rates that are representative of those used commercially in the swine industry. Feed was offered at approximately 3% of BW during the 9-d adaption and 4-d collection periods. Only pigs with constant and complete feed consumption during the adaptation period were used for the 4-d collection period. Pigs refusing greater than 20% of their diet compared with other pigs within the same feeding group were removed from the study.

Sample Collection

During the time-based 4-d total fecal and urine collection period, stainless steel screens were placed under each metabolism crate for total fecal collection and stainless steel buckets containing 30 mL of 6 *N* HCl were placed under each crate for the total urine collection. Feces and urine were collected twice daily and stored at 0°C until the end of the collection period. Feces were pooled by pig over the 4-d period, dried in a 70°C forced-air oven, weighed, and ground through a 1-mm screen with a subsample taken for analysis. Likewise, urine samples were pooled by pig over the 4-d period, thawed at the end of the collection period, and weighed with a subsample collected for analysis.

Chemical Analysis and Calculations

All corn-DDGS samples were ground through a 1-mm screen before chemical analysis. Samples were analyzed at various laboratories as described in Table 2, with the analyzed composition of the basal diet summarized in Table 3, and the composition of the corn-DDGS samples summarized in Tables 4 and 5 for Exp. 1 and 2, respectively. To determine DE and ME content, GE of the feedstuffs, feces, and urine samples were determined using an isoperibol bomb calorimeter (Model 1282, Parr Instrument Company, Moline, IL) with benzoic acid used as a standard. For urine, 1 mL of filtered subsample urine was added to 0.5 g of dried cellulose and subsequently dried at 50°C for 24 h. Urine addition and subsequent drying was repeated 3 times, for a total of 3 mL of filtered urine, over a 72-h period before urinary GE determination. Gross energy in cellulose was also determined and urinary GE was calculated by subtracting the GE in cellulose from the GE in the samples containing both urine and cellulose.

Gross energy intake was calculated as the product of GE content of the treatment diet and the actual feed intake over the 4-d collection period. Within a specific assay diet, the DE and ME of each test ingredient was calculated by subtracting the DE or ME contributed by the basal diet from the DE or ME of the diet containing a particular corn-DDGS source. Because corn was the only energy-containing ingredient in the basal diet, the energy concentration of corn was calculated by dividing the DE or ME of the basal diet by 0.967. All energy values are reported on a DM basis.

Similar to the calculations for energy, apparent total tract digestibility (**ATTD**) of ADF, C, DM, GE, EE, NDF, N, P, and S of each test ingredient were calculated by subtracting the respective component contributed by the basal diet from the similar component of the diet containing that particular corn-DDGS source within a specific assay. Digestibility coefficients were then determined by dividing grams of component digested by the grams of component consumed and reported on a percentage basis.

Table 2. Methods of analysis

Measurement	Method
Bulk density[1]	USDA (1953)
GE[1]	Isoperibol bomb calorimeter (Model 1281; Parr Instrument Co., Moline, IL)
Particle size[1]	Baker and Herrman (2002)
ADF[2]	AOAC International (2005) official method 973.18 (A–D)
Ash[2]	AOAC International (2005) official method 942.05
CP[2]	AOAC International (2005) official method 990.03
DM[2]	AOAC International (2005) official method 934.01
Ether extract[2]	AOAC International (2005) official method 920.39 (A), petroleum ether
Fatty acids[2]	AOAC International (2005) official method 969.33; 963.22
FFA	AOAC International (2005) official method 940.28
Lysine[2]	AOAC International (2005) official method 982.30 E (a)
Minerals[2]	AOAC International (2005) official method 985.01 (A–D)
NDF[2]	Holst (1973)
Peroxide value[2]	AOAC International (2005) official method 940.28
Thiobarbituric acid[2]	American Oil Chemists' Society (AOCS, 2011) official method Cd 19-90
Total starch[2]	AACC International (1976); approved method 76-13.01; modified: starch assay kit (Kit STA-20; Sigma, St. Louis, MO)
Total dietary fiber[3]	AOAC International (2005) official method 991.43
Aflatoxin B1, B2, G1, G2[4]	AOAC International (2005) official method 994.08
Deoxynivalenol[4]	Trucksess et al. (1998)
Fumonisin B1, B2, B3[4]	AOAC International (2005) official method 995.15
Ochratoxin A[4]	AOAC International (2005) official method 2000.3
T-2 Toxin[4]	Croteau et al. (1994)
Zearalenone[4]	MacDonald et al. (2005)

[1]Analyzed by USDA-ARS, Ames, IA.
[2]Analyzed by University of Missouri, Columbia, MO.
[3]Analyzed by Eurofins, Des Moines, IA.
[4]Analyzed by Trilogy Analytical Laboratory, Washington, MO.

Statistical Analysis

Using the individual pig as the experimental unit, data were subjected to ANOVA using Proc GLM with group and treatment in the model (SAS Inst. Inc., Cary,

Table 3. Composition of corn basal diet used in Exp. 1 and 2, DM basis

Item	Basal
Bulk density, g/cm^3	–
Particle size, µm	–
DM, %	85.88
GE, kcal/kg	4,025
CP, %	8.28
Lys, %	0.28
Total starch, %	55.29
Total dietary fiber, %	7.10
NDF, %	10.65
ADF, %	2.90
Hemicellulose, %[1]	7.75
Ash, %	4.44
Cl, %	0.29
P, %	0.42
K, %	0.40
Na, %	0.15
S, %	0.16
Ether extract, %	2.84
Fatty acid, % of total fat	
Myristic, 14:0	ND[2]
Palmitic, 16:0	15.06
Palmitioleic, 16:1	0.13
Stearic, 18:0	1.89
Oleic, 18:1	27.28
Linoleic, 18:2	53.04
Linolenic, 18:3	1.45
Arachidonic, 20:4	ND
Eicosapentaenoic, 20:5	ND
Docosapentaenoic, 22:5	ND
Docosahexaenoic, 22:6	ND
Lipid peroxidation	
Free fatty acids, %	1.79
Thiobarbituric acid, absorbance (532 nm)	11.91
Peroxide value, mEq/kg	58.22
Mycotoxins	
Aflatoxin B_1, µg/kg	ND
Aflatoxin B_2, µg/kg	ND
Aflatoxin G_1, µg/kg	ND
Aflatoxin G_2, µg/kg	ND
Deoxynivalenol, mg/kg	0.23
Fumonisin B_1, mg/kg	ND
Fumonisin B_2, mg/kg	ND
Fumonisin B_3, mg/kg	ND
Ochratoxin A, µg/kg	ND
T-2 Toxin, µg/kg	ND
Zearalenone, µg/kg	ND

[1]Calculated as NDF – ADF.

[2]ND = not detected or below detection limit.

Table 4. Composition of corn distillers dried grains with solubles used in Exp. 1, DM basis

	Source			
Item	1	2	3	4
Bulk density, g/cm^3	0.597	0.660	0.608	0.556
Particle size, µm	379	362	294	316
DM, %	88.87	88.77	89.98	89.93
GE, kcal/kg	4,780	4,841	4,943	5,113
CP, %	31.19	30.56	30.80	28.97
Lys, %	1.14	1.09	1.06	1.06
Total starch, %	3.26	3.26	2.53	3.26
Total dietary fiber, %	35.56	36.05	36.01	33.80
NDF, %	30.49	31.58	33.89	31.64
ADF, %	9.42	10.05	10.59	9.01
Hemicellulose, %[1]	21.07	21.53	23.30	22.63
Ash, %	5.82	6.14	5.67	5.37
Cl, %	0.19	0.18	0.17	0.17
P, %	0.91	0.91	0.87	0.90
K, %	1.31	1.22	1.18	1.31
Na, %	0.23	0.35	0.41	0.16
S, %	1.31	1.27	1.39	1.16
Ether extract, %	4.88	5.61	7.45	10.88
Fatty acid, % of total fat				
Myristic, 14:0	ND[2]	ND	ND	0.06
Palmitic, 16:0	14.46	14.34	13.96	13.73
Palmitioleic, 16:1	0.15	0.14	ND	0.14
Stearic, 18:0	2.33	2.29	2.26	2.27
Oleic, 18:1	26.51	26.51	27.16	27.30
Linoleic, 18:2	53.55	53.33	53.71	53.36
Linolenic, 18:3	1.65	1.63	1.57	1.52
Arachidonic, 20:4	ND	ND	ND	ND
Eicosapentaenoic, 20:5	ND	ND	ND	ND
Docosapentaenoic, 22:5	ND	ND	ND	ND
Docosahexaenoic, 22:6	0.20	0.25	0.25	0.17
Lipid peroxidation				
Free fatty acids, %	0.64	0.57	0.87	1.09
Thiobarbituric acid, absorbance (532 nm)	17.07	19.39	6.69	6.03
Peroxide value, mEq/kg	6.75	14.17	10.41	6.55
Mycotoxins				
Aflatoxin B_1, µg/kg	ND	ND	ND	ND
Aflatoxin B_2, µg/kg	ND	ND	ND	ND
Aflatoxin G_1, µg/kg	ND	ND	ND	ND
Aflatoxin G_2, µg/kg	ND	ND	ND	ND
Deoxynivalenol, mg/kg	1.46	1.46	1.44	1.33
Fumonisin B_1, mg/kg	1.80	1.13	1.22	1.22
Fumonisin B_2, mg/kg	0.34	0.11	0.33	0.33
Fumonisin B_3, mg/kg	0.11	ND	ND	ND
Ochratoxin A, µg/kg	ND	ND	ND	ND
T-2 Toxin, µg/kg	ND	ND	ND	ND
Zearalenone, µg/kg	57.61	ND	ND	ND

[1]Calculated as NDF – ADF.

[2]ND = not detected or below detection limit.

Table 5. Composition of corn distillers dried grains with solubles used in Exp. 2, DM basis

	Source										
Item	1	2	3	4	5	6	7	8	9	10	11
Bulk density, g/cm^3	0.597	0.566	0.574	0.612	0.521	0.573	0.553	0.541	0.549	0.573	0.621
Particle size, µm	863	622	1,054	1,078	689	766	710	645	757	945	568
DM, %	88.40	88.47	87.47	85.60	89.18	87.56	86.43	84.79	86.53	85.54	86.98
GE, kcal/kg	5,077	5,075	5,066	4,897	5,043	4,963	4,938	5,167	4,963	4,948	5,130
CP, %	27.69	29.67	29.67	32.93	30.97	30.15	30.31	30.61	29.77	32.71	32.10
Lys, %	1.06	1.03	1.06	1.20	1.13	1.13	1.11	1.20	1.05	1.19	1.06
Total starch, %	1.76	3.89	1.61	0.84	0.89	3.38	2.20	1.26	2.84	0.97	1.09
TDF,[1] %	37.78	33.91	35.33	32.48	35.66	30.84	33.90	32.43	31.32	33.90	33.46
NDF, %	43.97	36.49	38.62	35.70	38.89	33.30	38.23	34.00	28.79	35.85	38.92
ADF, %	14.02	12.14	13.92	13.40	12.90	10.47	12.45	9.87	10.33	13.71	13.29
Hemicellulose, %[2]	29.95	24.35	24.70	22.30	25.99	22.83	25.78	24.13	18.46	22.14	25.63
Ash, %	4.42	4.32	4.58	5.12	4.91	4.87	5.03	5.30	5.04	5.31	4.89
Cl, %	0.15	0.11	0.15	0.16	0.17	0.16	0.16	0.17	0.13	0.16	0.16
P, %	0.75	0.71	0.80	0.88	0.74	0.80	0.89	0.89	0.83	0.91	0.77
K, %	1.09	1.03	1.09	1.34	1.23	1.18	1.21	1.30	1.09	1.15	1.15
Na, %	0.18	0.09	0.17	0.04	0.18	0.11	0.22	0.22	0.25	0.26	0.18
S, %	0.59	0.46	0.78	1.03	0.78	0.72	0.66	0.57	0.87	1.15	0.93
Ether extract, %	11.20	11.13	10.79	8.56	10.82	9.62	10.05	13.23	9.65	9.96	11.83
Fatty acid, % of total fat											
Myristic, 14:0	0.07	0.07	0.07	0.08	0.06	0.08	0.08	0.06	0.07	0.07	0.06
Palmitic, 16:0	13.97	15.38	14.65	14.56	14.38	14.27	14.08	14.07	14.04	14.10	13.58
Palmitioleic, 16:1	0.14	0.12	0.14	0.15	0.16	0.14	0.14	0.13	0.15	0.13	0.13
Stearic, 18:0	2.09	2.01	2.62	2.06	2.08	2.08	2.03	2.05	2.09	2.12	2.05
Oleic, 18:1	25.94	24.96	27.03	25.16	24.81	25.78	25.53	26.69	25.80	26.22	25.65
Linoleic, 18:2	54.44	54.01	51.92	54.23	54.98	54.20	54.76	53.51	54.51	53.93	54.92
Linolenic, 18:3	1.60	1.72	1.35	1.76	1.66	1.64	1.64	1.57	1.58	1.59	1.76
Arachidonic, 20:4	ND[3]	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Eicosapentaenoic, 20:5	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Docosapentaenoic, 22:5	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Docosahexaenoic, 22:6	0.16	0.16	0.27	0.26	0.17	0.18	0.16	0.16	0.16	0.16	0.15
Lipid peroxidation											
FFA, %	2.01	1.41	1.53	1.36	1.46	1.69	1.48	2.38	1.39	1.47	1.87
Thiobarbituric acid, absorbance (532 nm)	7.14	8.55	9.00	12.76	5.67	6.36	6.90	11.78	5.33	6.90	7.60
Peroxide value, mEq/kg	8.23	0.24	2.61	17.50	19.03	0.58	0.45	2.39	1.42	2.78	3.47
Mycotoxins											
Aflatoxin B_1, µg/kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Aflatoxin B_2, µg/kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Aflatoxin G_1, µg/kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Aflatoxin G_2, µg/kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Deoxynivalenol,mg/kg	0.68	0.34	0.34	2.10	0.89	1.60	1.97	1.06	1.62	1.64	0.34
Fumonisin B_1, mg/kg	0.90	0.34	0.34	0.35	0.34	0.91	0.93	ND	1.73	0.47	0.11
Fumonisin B_2, mg/kg	0.11	ND	ND	ND	ND	0.11	0.12	ND	0.35	ND	ND
Fumonisin B_3, mg/kg	ND	ND	ND	ND	ND	ND	ND	ND	0.12	ND	ND
Ochratoxin A, µg/kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
T-2 Toxin, µg/kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Zearalenone, µg/kg	74.55	ND	ND	113.55	ND	98.68	ND	65.81	61.48	100.07	ND

[1]TDF = total dietary fiber.

[2]Calculated as NDF – ADF.

[3]ND = not detected or below detection limit.

NC), with treatment means reported as least squares means. The experiment was conducted as a completely randomized design with DE and ME of the basal diet used as a covariate to determine DE and ME values, respectively, among all groups of pigs. Using Proc REG, stepwise regression was used to determine the effect of nutrient composition among corn-DDGS sources on apparent GE, DE, ME, and DE:ME, ME:GE, and ME:GE, and variables with *P*-values ≤ 0.15 were retained in the model. The R^2, the SE of the estimate, and the Mallows statistic [**C(p)**] were used to define the best fit equation. Similar to the analysis of energy, the digestibility of each component in the basal diet was used as a covariate to determine the digestibility of each component in the test diets.

RESULTS AND DISCUSSION

General and Compositional Evaluation

In our previous work (Anderson et al., 2012), justification for using a corn-only basal diet, inclusion of 30% corn-DDGS in the test diet, use of a default *P*-value of 0.15 in the selection and elimination of regression variables in stepwise regression, and not allowing the model to contain multiple measures of a similar component (e.g., multiple fiber measures, multiple minerals in addition to ash, and fatty acids in addition to EE) was discussed in detail. As a result, these same procedures were used in the current study. Although particle size has an impact on energy and nutrient digestibility (Nuzback et al., 1984; Yanez et al., 2011), corn-DDGS samples were not to ground to a common particle size because they are representative of the variability in particle size among corn-DDGS sources in the industry and particle size was used as a variable in stepwise regression analysis to develop prediction equations.

For digestibility trials, feces may be collected using a “time-based” approach, as used in the current study as well as in previous studies (Lammers et al., 2008; Anderson et al., 2012), or by using colored markers that are added to feed to mark the beginning and end of fecal collection (Adedokun and Adeola, 2005; Pedersen et al., 2007). With the “marker-to-marker” method, it must be assumed that the marker moves at the same rate as the digesta in the lumen of the gastrointestinal tract does not diffuse into adjacent unmarked digesta and pigs have no aversion to feed containing a marker. Furthermore, the time of marker appearance and disappearance in feces can be somewhat subjective. Therefore, we chose to use the time-based approach for fecal collection, reasoning that it is an acceptable method if a constant daily feed intake over an extended adaptation period (9 d in the current study) is achieved and that feces are then collected for several days (4 d in the current study).

Three pigs in Exp. 1 (corn-DDGS sources 2, 3, and 4) and 7 pigs in Exp. 2 (1 pig each in the basal and corn-DDGS sources 1, 2, and 5 and 3 pigs in corn-DDGS source 3) refused greater than 20% of their diet compared with other pigs within the same feeding group and were, therefore, removed from the study. There was no apparent reason for pigs fed corn-DDGS source 3 in Exp. 2 to have the most number of pigs removed, as evaluation of the corn-DDGS composition (Table 5) fed to these pigs showed no overtly high levels of lipid peroxidation, peroxide value, or mycotoxins. With these pigs removed, there was no difference in ADFI among treatments within an experiment, with ADFI averaging 2,693 ± 352 g/d in Exp. 1 and 2,399 ± 303 g/d in Exp. 2. The small difference in ADFI between Exp. 1 and Exp. 2 was expected, given that pigs in Exp. 1 and 2 had final BW of 105.6 and 83.7 kg, respectively. In addition, pigs in Exp. 1 were housed at a lower effective environmental temperature (20.8°C with 61.6% relative humidity) compared with pigs in Exp. 2 (25.0°C with 64.4% relative humidity), but both environments were within the thermal neutral zone for pigs of this BW.

One of the main objectives of this study was to obtain corn-DDGS samples with a range of EE content, from which to relate ingredient composition to in vivo DE and ME content. Relative to this objective, EE ranged from 4.88 to 10.88% (Table 4) in Exp. 1 and from 8.56 to 13.23% in Exp. 2 (Table 5). The difference in concentration of total dietary fiber (**TDF**) and NDF among corn-DDGS sources was 2.25 and 3.40 percentage units, respectively, in Exp. 1 but was greater in Exp. 2, where they differed by 6.46 and 15.18 percentage units, respectively. This is noteworthy because Pedersen et al. (2007) and Anderson et al. (2012) showed that a measure of fiber and EE content are often included in DE and ME prediction equations for corn-DDGS. Ash and CP are also primary variables in DE and ME prediction equations (Noblet and Perez, 1993; Pedersen et al., 2007; Anderson et al., 2012). In the current study, the range in CP and ash were from 28.97 to 31.19% and 5.37 to 6.14%, respectively, in Exp. 1 and from 27.69 to 32.93% and 4.32 to 5.31%, respectively, in Exp. 2. Although the range in nutrient composition was not as great as found in the diverse collection of 20 corn co-products obtained from wet-mill and dry-grind ethanol plants reported by Anderson et al. (2012), it is equal to or greater than the ranges in corn-DDGS composition reported by others (Spiehs et al., 2002; Stein et al., 2006, 2009; Pedersen et al., 2007). Other nutrient composition data (fatty acids, minerals, starch, etc.) of the corn-DDGS sources evaluated in the current study are listed in Tables 4 and 5, because these data are lacking in the literature (NRC, 2012) and may be important relative to other research topics, such as the impact of feeding corn-DDGS varying in EE content on carcass pork fat quality (Xu et al., 2010a,b; McClelland et al., 2012).

Energy Content of Corn and Corn Dried Distillers Grains with Solubles

Because corn was the sole energy-containing ingredient in the basal diet (Table 1), dividing the DE and ME content determined with pigs fed the basal diet by 0.967 allowed for estimation of DE and ME content in corn. The DE value of corn in Exp. 1 and Exp. 2 was 3,696 and 3,672 kcal/kg DM, respectively, and the ME content was 3,620 and 3,595 kcal/kg DM, respectively. These values are slightly lower that the 3,908 kcal DE/kg DM and 3,844 kcal ME/kg DM reported by the NRC (2012) and a recent summary of several corn DE and ME values reported by Anderson et al. (2012) but are still within the range of corn energy values reported elsewhere (Jones et al., 2011).

Gross energy content among corn-DDGS samples varied from 4,780 to 5,113 kcal/kg DM in Exp. 1 and from 4,897 to 5,167 kcal/kg DM in Exp. 2. In Exp. 1, the range in DE content among the 4 corn-DDGS sources was from 3,500 to 3,870 kcal/kg DM and ME content varied from 3,266 to 3,696 kcal/kg DM. In Exp. 2, the range in DE content among the 11 corn-DDGS sources was from 3,474 to 3,807 kcal/kg DM and ME content varied from 3,277 to 3,603 kcal/kg DM. Average DE and ME values for the corn-DDGS were 3,692 and 3,463 kcal/kg DM, respectively, for Exp. 1 (Table 6) and 3,635 and 3,425 kcal/kg DM, respectively, for Exp. 2 (Table 7). Small differences in DE and ME content between Exp. 1 and Exp. 2 may be due to the differences in pig BW, which has been reported to affect energy digestibility (Noblet et al., 1994; Le Goff et al., 2002) but may also be due to differences in corn-DDGS particle size that averaged 338 μm in Exp. 1 compared with 791 μm in Exp. 2, which is also known to have an impact on energy digestibility (Nuzback et al., 1984; Yanez et al., 2011; Liu et al., 2012). The DE and ME content of the corn-DDGS sources evaluated in the current study compare favorably to values reported by others (Stein et al., 2006, 2009; Pedersen et al., 2007; Anderson et al., 2012) and the NRC (2012) for "normal" corn-DDGS samples. In contrast, Jacela et al. (2011) and Anderson et al. (2012) evaluated a hexane-extracted corn-DDGS with dramatically lower (4.56 and 3.15%, respectively) EE content than the EE content of the corn-DDGS samples used in the current experiments and reported a DE content of 3,100 and 3,868 kcal/kg DM, respectively. Jacela et al. (2011) calculated the ME content of their low-oil corn-DDGS source to be 2,858 kcal/kg DM using an equation developed by Noblet and Perez (1993). However, the applicability of using this equation to estimate ME content of corn-DDGS may be questionable because those equations were developed for complete diets and not for a specific feedstuff. Anderson et al. (2012) directly determined the ME content of low-oil corn-DDGS to be 3,650 kcal/kg DM, which is greater than ME content of several of the corn-DDGS sources with greater EE content in the current study. Based on this comparison, it appears that EE content may not be strongly associated with ME content of corn-DDGS. Furthermore, a corn-distillers dried grains (**DDG**) co-product without solubles (8.8% EE) was also evaluated by Dahlen et al. (2011) and found to contain 3,232 and 2,959 kcal/kg DM of DE and ME, respectively. By comparison, these DE and ME values are considerably less than values from corn-DDGS with less EE content in the current study. Among the corn-DDGS sources evaluated in the current study, corn oil was partially removed by centrifugation from samples with reduced EE (<11% DM basis) content. Large differences in composition in corn-DDGS result from differences in the design of dry-grind at ethanol plant, oil extraction equipment, and efficiencies of oil extraction, which makes estimating DE and ME content among different sources challenging. Therefore, the development and use of prediction equations based on nutrient composition to estimate energy content in feeds such as barley (Fairbairn et al., 1999), meat and bone meal

Table 6. Apparent total tract digestibility (ATTD) and energy content of corn distillers dried grains with solubles in Exp. 1, DM basis

		Source				Statistics	
Item	Basal	1	2	3	4	SD	*P*-value
Observations	12	15	14	14	14	–	–
ATTD,[1] %							
ADF	59.12	58.59	70.19	55.15	60.92	11.20	0.01
C	89.66	73.62	78.05	69.01	74.07	8.03	0.05
DM	89.85	72.44	77.29	67.71	72.48	8.29	0.04
GE	88.63	74.65	79.11	70.77	75.70	7.66	0.05
Ether extract	33.49	65.68	69.80	72.71	81.24	9.47	0.01
NDF	56.15	49.79	57.36	44.45	45.82	13.21	0.07
N	81.57	82.58	83.44	77.96	80.47	5.52	0.06
P	39.53	61.37	66.48	59.12	58.64	15.45	0.58
S	79.98	89.05	89.87	86.98	88.61	3.40	0.18
Energy content[2]							
GE, kcal/kg	4,025	4,780	4,841	4,944	5,113	–	–
DE, kcal/kg	3,574	3,568	3,829	3,500	3,870	375	0.03
ME, kcal/kg	3,501	3,286	3,604	3,266	3,696	381	0.01
DE:GE	88.78	74.72	79.19	70.90	76.08	7.71	0.06
ME:DE	97.95	93.38	94.04	93.40	94.33	2.35	0.68
ME:GE	86.96	68.82	74.56	66.18	72.82	7.84	0.04

[1]Digestibility of the basal diet was used as a covariate in analysis of subsequent digestibility values.

[2]Digestible energy and ME value of the basal diet was used as a covariate for analysis of subsequent DE and ME values for each corn distillers dried grains with solubles sample. Final BW and ADFI averaged 105.6 kg and 2,693 g/d, respectively.

Table 7. Apparent total tract digestibility (ATTD) and energy content of corn distillers dried grains with solubles in Exp. 2, DM basis

		Source											Statistics	
Item[1]	Basal	1	2	3	4	5	6	7	8	9	10	11	SD	*P*-value
Observations	11	11	11	9	12	11	12	12	12	12	12	12		
ATTD,[1] %														
ADF	55.50	69.87	69.87	74.57	72.17	66.77	74.94	76.74	68.24	72.75	73.53	70.14	6.73	0.02
C	89.71	67.93	71.04	70.18	72.25	68.27	74.34	73.16	73.01	74.70	70.50	72.37	7.31	0.39
DM	89.69	66.80	70.52	69.64	73.30	67.41	74.18	71.89	71.57	73.78	70.35	70.38	7.89	0.41
GE	88.50	68.32	71.20	70.85	74.78	69.12	74.69	73.26	73.71	75.20	71.31	73.47	7.10	0.29
Ether extract	38.82	54.82	57.20	54.70	67.13	59.42	53.34	52.69	68.53	58.13	57.59	65.80	12.11	0.01
NDF	55.89	56.26	57.39	58.18	51.81	54.15	60.56	61.54	57.05	55.17	57.16	53.26	11.66	0.69
N	80.95	76.89	79.73	81.79	77.02	82.12	82.78	80.61	80.99	84.80	81.83	82.48	5.63	0.03
P	47.09	52.37	66.31	64.65	54.54	53.06	61.37	52.33	57.08	56.28	62.23	63.54	13.93	0.18
S	79.18	79.63	77.19	84.55	83.55	82.42	84.54	83.24	81.05	87.44	87.06	85.99	5.16	0.01
Energy content[2]														
GE, kcal/kg	4,025	5,077	5,075	5,066	4,897	5,043	4,963	4,938	5,167	4,963	4,948	5,130	–	–
DE, kcal/kg	3,551	3,474	3,619	3,584	3,663	3,484	3,706	3,617	3,807	3,731	3,527	3,768	350	0.31
ME, kcal/kg	3,477	3,302	3,400	3,360	3,362	3,277	3,513	3,423	3,603	3,550	3,327	3,553	346	0.30
DE:GE	88.24	68.44	71.32	70.74	74.81	69.08	74.67	73.24	73.69	75.18	71.29	73.45	6.99	0.27
ME:DE	97.91	94.92	93.70	93.78	93.64	94.02	94.74	94.52	94.75	95.08	94.10	94.21	1.70	0.46
ME:GE	86.47	65.00	66.95	66.37	68.69	64.98	70.79	69.32	69.72	71.55	67.24	69.28	6.95	0.33

[1]Digestibility of the basal diet was used as a covariate in analysis of subsequent digestibility values.

[2]Digestible energy and ME value of the basal diet was used as a covariate for analysis of subsequent DE and ME values of each corn distillers dried grains with solubles sample. Final BW and ADFI averaged 83.7 kg and 2,399 g/d, respectively.

(Adedokun and Adeola, 2005; Olukosi and Adeola, 2009), corn-DDGS (Pedersen et al., 2007; Anderson et al., 2012), and wheat-dried distillers grains with solubles (**wheat-DDGS**; Cozannet et al., 2010), such as those developed for complete diets (Just et al., 1984; Noblet and Perez, 1993), is a noteworthy task.

Digestible Energy and ME Prediction Equations

In Exp. 1, no physical or chemical measurement [bulk density (**BD**), particle size, GE, CP, starch, TDF, NDF, ADF, hemicellulose, EE, or ash] was statistically significant at $P \leq 0.15$ to predict DE or ME content in corn-DDGS. Likewise, neither DE nor ME as a percentage of GE could be predicted by any measured variable. The best fit equation for ME as a percentage of DE was:107.61 – (0.64 × % CP) + (0.96 × % ash) [R^2 = 0.99, SE = 0.67]. The inability of these physical and chemical measurements to predict DE, ME, or ME as a percentage of GE was surprising because we expected that the relatively large differences in several variables among the corn-DDGS samples evaluated would have been great enough to develop regression equations among these 4 corn-DDGS sources. Although Pedersen et al. (2007) did not evaluate reduced-oil corn-DDGS sources per se, the range in EE content in their experiment (4.66 percentage units on a DM basis) was less than the corn-DDGS samples used in the Exp. 1 (6.00 percentage units on a DM basis) of the current study but the ranges in NDF (6.55 percentage units) and ash (1.47 percentage units) content were greater than the current experiment (3.40 and 0.77 percentage units, respectively). Interestingly, GE differences among corn-DDGS samples between the current Exp. 1 and that of Pedersen et al. (2007) were similar (333 and 317 kcal/kg DM, respectively).

For Exp. 2, stepwise regression and chemical analysis were useful in generating a series of prediction equations for DE (Table 8). The initial regression (Eq. [1]) included TDF as the most important component to predict DE followed by Eq. [2], which included both TDF and GE, and ultimately resulting in the best fit equation (Eq. [3]): DE (kcal/kg DM) = 1,601 – (54.48 × % TDF) + (0.69 × % GE) + (731.5 × BD) [R^2 = 0.91, SE = 41.25]. Eq. [3]. However, because TDF analysis can be costly, time consuming, and less automated, we elected to exclude TDF from the variables included in the model. As a result, ADF became the most important predictor in the model (Eq. [4]) followed by BD, resulting in the best fit question (Eq. [5]): DE (kcal/kg DM) = 3,343 – (73.15 × % ADF) + (2,276 × BD) [R^2 = 0.76, SE = 61.81]. Eq.[5] By not including TDF in the model and comparing the best fit models (Eq. [5] vs. Eq. [3]), the SE of the estimate increased and the R^2 decreased, indicating loss in prediction confidence. It was surprising that BD was a significant factor in these models because the range in BD was only 0.1 g/cm^3 (Table 5) among corn-DDGS samples. However, Kingsly et al. (2010) showed that increasing the amount of condensed

Table 8. Stepwise regression equations for DE in corn distillers dried grains with solubles, Exp. 2

	Regression coefficient[1]					Statistics[2]		
Item	Intercept	TDF	GE	BD	ADF	SE	R^2	C(p)
Equation 1	5,126	–44.22	–	–	–	72.38	0.63	3.94
SE[3]	385	11.41	–	–	–	–	–	–
P-value[3]	0.01	0.01	–	–	–	–	–	–
Equation 2	2,084	–53.65	0.67	–	–	45.75	0.86	–1.12
SE	835	7.62	0.18	–	–	–	–	–
P-value	0.04	0.01	0.01	–	–	–	–	–
Equation 3	1,601	–54.48	0.69	731.5	NA	41.25	0.91	–0.24
SE	805	6.89	0.16	433.9	NA	–	–	
P-value	0.09	0.01	0.01	0.14	NA	–	–	–
Equation 4	4,265	NA	–	–	–50.77	85.73	0.48	2.67
SE	223	NA	–	–	17.81	–	–	
P-value	0.01	NA	–	–	0.02	–	–	–
Equation 5	3,343	NA	–	2,276	–73.15	61.81	0.76	–0.53
SE	371	NA	–	746	14.79	–	–	–
P-value	0.01	NA	–	0.02	0.01	–	–	–

[1]Equations based on analyzed nutrient content expressed on a DM basis. Units are kilocalories per kilogram DM for GE and DE, percent for ADF and total digestible fiber (TDF), and grams per cubic centimeter for bulk density (BD). NA = not applicable.

[2]SE = SE of the regression estimate defined as the root of the mean square error; C(p) = the Mallows statistic.

[3]SE and *P*-values of the corresponding regression coefficient.

solubles added to the grains fraction before producing corn-DDGS linearly increased several chemicals (e.g., EE) and physical properties of corn-DDGS, including particle size and bulk density. Because the ethanol plants vary in the rate of condensed distillers solubles added to the grains fraction to produce corn-DDGS and partial oil extraction occurs in the thin stillage fraction before dehydrating to produce condensed distillers solubles, it is plausible that bulk density is a meaningful variable for prediction of the DE content in corn-DDGS. Bulk density can be excluded from Eq. [3] and Eq. [5]; however, in both instances, the SE of the estimate increased and the R^2 decreased (Eq. [2] and [4], respectively). Equation [2] appears to predict DE relatively well (R^2 = 0.86 and SE = 45.75 kcal/kg DM), but Eq. [4] does not (R^2 = 0.48 and SE = 85.73 kcal/kg DM). Our data are similar to others where fiber is a central component in regression equations to predict DE, whether it be for a complete diet (Noblet and Perez, 1993), wheat-DDGS (Cozannet et al., 2010), or corn-DDGS (Pedersen et al., 2007; Anderson et al., 2012). Furthermore, removing TDF from the equation and replacing it with NDF (Anderson et al., 2012) or ADF (current study) reasonably predicts DE, but this is not unexpected because there is not a large difference between TDF and NDF in corn-based co-products (Tables 4 and 5; Anderson et al., 2012). Corn dried distillers grains with solubles does, however, contain an appreciable amount of β-glucans derived from yeast, where it has been estimated that 20% of the weight of corn-DDGS is dried yeast (Han and Liu, 2010; Liu, 2011). Unlike NDF, measurement of TDF includes β-glucans (NRC, 2012). Therefore, it would be expected that TDF is a better variable to use in DE and ME prediction models than NDF because TDF provides a more complete estimate of fiber in corn-DDGS. This issue may become more important as more corn oil is removed from corn-DDGS, thereby concentrating all other nutritional compounds, including β-glucans.

A series of prediction equations was also generated for the ME content of corn-DDGS (Table 9). The initial regression (Eq. [1]) included ADF as the most important component to predict ME followed by ADF and BD (Eq. [2]) and lastly by ADF, BD, and EE (Eq. [3]), resulting in the best fit equation (Eq. [4]): ME (kcal/kg DM) = 4,558 + (52.26 × % EE) – (50.08 × % TDF) [R^2 = 0.85, SE = 48.74]. Similar to DE, a fiber component, in this instance ADF, was the initial variable included in the regression model, indicating that fiber is a primary factor affecting the ME content of corn-DDGS. This is not surprising given that DE and ME content are highly correlated. We were surprised that BD was a primary variable in the model although it did not remain in the final best fit model (Eq. [4]). The fact that TDF was in the final model indicates that analysis of feedstuffs for TDF, especially in corn co-products, should be conducted based on our previous work (Anderson et al., 2012) and because fermented co-products may contain appreciable amounts of β-glucans (Han and Liu, 2010; Liu, 2011). It is not known whether TDF would have been an important factor in models generated by others (Noblet and Perez, 1993; Fairbairn et al., 1999; Pedersen et al., 2007; Cozannet et al., 2010) because TDF was not measured in those feedstuffs. Compared with prediction equations derived for complete feeds (Noblet and Perez, 1993) or corn-DDGS (Pedersen et al., 2007), ash was not an important

Table 9. Stepwise regression equations for ME in corn distillers dried grains with solubles, Exp. 2

	Regression coefficient[1]					Statistics[2]		
Item	Intercept	ADF	BD	EE	TDF	SE	R^2	C(p)
Equation 1	4,132	–57.05	–	–	–	75.63	0.59	20.54
SE[3]	196	15.71	–	–	–	–	–	–
P-value[3]	0.01	0.01	–	–	–	–	–	–
Equation 2	3,291	–75.47	1,874	–	–	58.48	0.78	9.64
SE	351	13.98	706	–	–	–	–	–
P-value	0.01	0.01	0.03	–	–	–	–	–
Equation 3	2,939	–73.30	2,004	23.65	–	51.91	0.85	7.09
SE	370	12.48	631	13.32	–	–	–	–
P-value	0.01	0.01	0.02	0.12	–	–	–	–
Equation 4	4,558	–	–	52.26	–50.08	48.74	0.85	3.09
SE	267	–	–	12.72	7.99	–	–	–
P-value	0.01	–	–	0.01	0.01	–	–	–

[1]Equations based on analyzed nutrient content expressed on a DM basis. Units are kilocalories per kilogram DM for ME, percent for ADF, ether extract (EE), and total digestible fiber (TDF), and grams per cubic centimeter for bulk density (BD).

[2]SE = SE of the regression estimate defined as the root of the mean square error; C(p) = the Mallows statistic.

[3]SE and *P*-values of the corresponding regression coefficient.

variable in our DE or ME prediction equations. Similarly, ash was not a primary measure in the DE or ME equations reported by Anderson et al. (2012), but it was a regression variable for ME when TDF was not offered in the list of variables (Anderson et al., 2012).

As expected, predicting DE as a percentage of GE followed a similar pattern of predicting DE, where TDF was a primary component in the regression model (Eq. [1] and [2]; Table 10). Likewise, if TDF was not offered as a regression variable, another fiber measure, in this instance, NDF, was used (Eq. [3]), and NDF as well as BD was used in the final model (Eq. [4]). Not allowing TDF to be used in the stepwise regression analysis resulted in NDF being retained in the regression model, but the resultant equations had greater SE and reduced R^2, resulting in less confidence in their ability to predict DE as a percentage of GE. We suspect that this may be due to corn-DDGS having appreciable amounts of β-glucans, which is measured by the TDF assay but not by the NDF assay.

Metabolizable energy as a percentage of DE was negatively affected by ADF content (Eq. [1]), with subsequent equations excluding ADF and including a negative effect of CP and positive effects of ash and BD (Table 11). Although Fairbairn et al. (1999) and Pedersen et al. (2007) did not measure ME as a percentage of DE, previous work (Noblet and Perez, 1993; Anderson et al., 2012) supports the notion that CP has a negative effect on ME as a percentage of DE in complete feeds or corn co-products. The positive coefficient for ash was not expected, given that ash typically has a negative effect on DE or ME (Noblet and Perez, 1993; Adedokun and

Table 10. Stepwise regression equations for DE as a percentage of GE in corn dried distillers grains with solubles, Exp. 2

	Regression coefficient[1]				Statistics[2]		
Item	Intercept	TDF	BD	NDF	SE	R^2	C(p)
Equation 1	108.89	–1.08	–	–	0.87	0.87	–3.03
SE[3]	4.64	0.14	–	–	–	–	–
P-value[3]	0.01	0.01	–	–	–	–	–
Equation 2	100.74	–1.10	14.97	NA	0.76	0.91	–2.21
SE	6.06	0.12	8.14	NA	–	–	–
P-value	0.01	0.01	0.10	NA	–	–	–
Equation 3	89.29	NA	–	–0.46	1.55	0.60	1.37
SE	4.63	NA	–	0.13	–	–	–
P-value	0.01	NA	–	0.01	–	–	–
Equation 4	73.11	NA	33.67	–0.55	1.24	0.77	–0.22
SE	7.57	NA	13.74	0.11	–	–	–
P-value	0.01	NA	0.04	0.01	–	–	–

[1]Equations based on analyzed nutrient content expressed on a DM basis. Units are kilocalories per kilogram DM for ME, percent for ADF, ether extract (EE), and total digestible fiber (TDF), and grams per cubic centimeter for bulk density (BD). NA = not applicable.

[2]SE = SE of the regression estimate defined as the root of the mean square error; C(p) = the Mallows statistic.

[3]SE and *P*-values of the corresponding regression coefficient.

Table 11. Stepwise regression equations for ME as a percentage of DE in corn distillers dried grains with solubles, Exp. 2

	Regression coefficient[1]					Statistics[2]		
Item	Intercept	ADF	CP	Ash	BD	SE	R^2	C(p)
Equation 1	96.65	–0.19	–	–	–	0.45	0.31	17.37
SE[3]	1.16	0.09	–	–	–	–	–	–
P-value[3]	0.01	0.07	–	–	–	–	–	–
Equation 2	100.73	–0.17	–0.14	–	–	0.41	0.49	13.17
SE	2.68	0.09	0.09	–	–	–	–	–
P-value	0.01	0.09	0.14	–	–	–	–	–
Equation 3	98.80	–	–0.39	1.52	–	0.29	0.74	4.15
SE	1.85	–	0.08	0.38	–	–	–	–
P-value	0.01	–	0.01	0.01	–	–	–	–
Equation 4	96.30	–	–0.46	1.84	5.47	0.26	0.82	3.52
SE	2.23	–	0.09	0.40	3.25	–	–	–
P-value	0.01	–	0.01	0.01	0.14	–	–	–

[1]Equations based on analyzed nutrient content expressed on a DM basis. Units are kilocalories per kilogram DM for ME, percent for ADF, ether extract (EE), and total digestible fiber (TDF), and grams per cubic centimeter for bulk density (BD).

[2]SE = SE of the regression estimate defined as the root of the mean square error; C(p) = the Mallows statistic.

[3]SE and *P*-values of the corresponding regression coefficient.

Adeola, 2005; Pedersen et al., 2007; Olukosi and Adeola, 2009; Cozannet et al., 2010; Anderson et al., 2012). We have no explanation for this effect, but Fairbairn et al. (1999) also reported a positive coefficient for ash in estimating DE content.

Another approach for estimating ME content of corn-DDGS is to predict GE from nutrient composition and then calculating ME as a percentage of GE. Because the chemical and physical composition analysis of corn-DDGS from Exp. 1 and 2 were independent of animal experimentation, compositional data from these samples can be combined and used in stepwise regression to predict GE. The results of this analysis are presented in Table 12 and indicate that EE has the greatest impact on the GE of corn-DDGS (Eq. [1]), with particle size having a secondary (Eq. [2]) effect. The fact that EE was included in the model but CP, starch, and a fiber component were not included in the model is not surprising, given the fact that lipids contain approximately 2.25 times the energy of carbohydrates and various carbohydrates and CP are of a somewhat similar GE content. However, the negative coefficient associated with particle size on GE is counterintuitive because all samples were ground to a common particle size before GE analysis. Even though equating ME as a percentage of GE is not a common practice in the nutritional literature (Noblet et al., 1994; Pedersen et al., 2007; Anderson et al., 2012), it could potentially be used with an estimated GE to predict ME. Unfortunately, ME as a percentage of GE could not be predicted from data obtained from pigs used in Exp. 1, but data from pigs in Exp. 2 indicate that either TDF [ME (% of GE) = 102.3 – (1.01 × % TDF); R^2 = 0.84, SE = 0.95] or NDF [ME (% of GE) = 84.7 – (0.45 × % NDF); R^2 = 0.63, SE = 1.43] can be used as prediction equations.

Table 12. Stepwise regression equations for GE in corn distillers dried grain with solubles (Exp. 1 and Exp. 2 samples combined)

	Regression coefficient[1]			Statistics[2]		
Item	Intercept	EE	PS	SE	R^2	C(p)
Equation 1	4,553	45.63	–	41.84	0.87	30.52
SE[3]	49	4.94	–	–	–	–
P-value[3]	0.01	0.01	–	–	–	–
Equation 2	4,583	50.61	–0.12	31.87	0.93	13.23
SE	39	4.07	0.04	–	–	–
P-value	0.01	0.01	0.01	–	–	–

[1]Equations based on analyzed nutrient content expressed on a DM basis. Units are kilocalories per kilogram DM for GE, percent for ether extract (EE), and micrometers for particle size (PS).

[2]SE = SE of the regression estimate defined as the root of the mean square error; C(p) = the Mallows statistic.

[3]SE and *P*-values of the corresponding regression coefficient.

Although it may be reasonable to expect that EE by itself should be a primary factor in predicting DE and ME content of corn-DDGS because of the greater energy concentration in lipids compared with carbohydrates, it was not included in DE prediction equations (Table 8) and had only a secondary effect in ME prediction equations (Table 9). Likewise, directly relating the EE content of corn-DDGS to DE and ME using simple linear regression models resulted in a poor fit and was not found to be significant [Exp. 1: DE (kcal/kg DM) = 3,461 + (31.83 × % EE), R^2 = 0.22, P = 0.54; and ME (kcal/kg DM) = 3,130 + (46.23 × % EE), R^2 = 0.32, P = 0.43; Exp. 2: DE (kcal/kg DM) = 3,414 + (20.72 × % EE), R^2 = 0.05, P = 0.49; and ME (kcal/kg DM) = 3,103 + (30.28 × % EE), R^2 = 0.11, P = 0.31]. This finding is supported by Pedersen et al. (2007) and Anderson et al. (2012) where it was reported that a fiber measure (e.g., TDF, NDF, ADF, hemicellulose) was a more important variable and was included before EE in prediction models. We speculate that because fiber represents a much greater percentage of corn-DDGS than EE (3.6-fold greater among the 15 corn-DDGS samples in the current experiment) and because fiber has a large impact on energy digestibility (Fernandez and Jorgensen, 1986; Chabeauti et al., 1991), including effects on lipid digestion (Degen et al., 2007), this poor relationship could be expected.

Apparent Total Tract Digestibility of Nutritional Components

Apparent total tract digestibility of ADF, C, DM, GE, EE, NDF, N, P, and S for pigs fed the basal diet and each corn-DDGS source evaluated in Exp. 1 and Exp. 2 are also shown in Tables 6 and 7, respectively. Average ATTD of ADF, C, DM, GE, EE, NDF, N, P, and S for pigs fed the corn-DDGS samples (ADF, 61.21 vs. 71.78; C, 73.69 vs. 71.61; DM, 72.48 vs. 70.89; GE, 75.06 vs. 72.36; EE, 72.36 vs. 59.03; NDF, 49.36 vs. 56.59; N, 81.11 vs. 81.00; P, 61.40 vs. 58.52; and S, 88.63 vs. 83.33 for Exp. 1 and 2, respectively) varied somewhat between the 2 experiments. In comparison, Pedersen et al. (2007) reported an average ATTD of GE, N, and P of 82.9, 82.7, and 50.8%, respectively, for 10 corn-DDGS samples whereas Stein et al. (2009) reported an average ATTD of ADF, DM, GE, EE, NDF, N, and P for 4 corn-DDGS samples of 70.2, 75.1, 75.1, 72.5, 69.6, 84.9, and 56.0%, respectively. Urriola et al. (2010) reported an average ATTD of ADF and NDF of 60.7 and 59.3%, respectively. Widyaratne and Zijlstra (2007) reported ATTD of GE and P in a single corn-DDGS sample of 78.7 and 55.5%, respectively, whereas Almeida and Stein (2010) reported an ATTD of P in a single corn-DDGS sample of 68.6%. Consequently, digestibility of various components among corn-DDGS sources can be quite variable and may contribute to the accuracy of estimating DE and ME content. It may be possible to develop accurate prediction equations for DE, ME, DE as a percentage of GE, ME as a percentage of DE, and ME as a percentage of GE using various total tract digestibility coefficients of nutrient, as has been done by others (Noblet and Perez, 1993). However, this analysis is beyond the scope and aim of this study, and it requires conducting animal experiments with the objective of predicting energy (DE, ME, or various relationships) from the composition of an ingredient.

Given the time and expense of animal experimentation, development and use of prediction equations to estimate energy content of feed ingredient based on nutrient composition is needed for accurate, inexpensive, and rapid determination of highly variable feed ingredients in the feed industry. Although EE may be a good indicator of the GE in corn-DDGS samples evaluated in this study, it is not a primary indicator of DE or ME content. Dietary fiber, namely ADF or TDF, is the most important variable in determining the DE or ME content of corn-DDGS with variable EE content in growing pigs.

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