Digestibility of amino acids, energy, acid hydrolyzed ether extract, and neutral detergent fiber, and concentration of digestible and metabolizable energy in low-oil distillers dried grains with solubles fed to growing pigs[1]

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ABSTRACT: Two experiments were conducted to test the hypothesis that digestibility of amino acids (AA), gross energy (GE), acid hydrolyzed ether extract (AEE), and neutral detergent fiber (NDF), and values for metabolizable energy (ME) in low-oil distillers dried grains with solubles (DDGS) vary among suppliers. In Exp. 1, the apparent total tract digestibility (ATTD) of GE, AEE, and NDF, and concentration of ME were determined in eight sources of DDGS (sources A, B, C, D, E, G, H, and I). A corn-based basal diet and eight diets containing corn and each source of DDGS were fed to 72 barrows (initial body weight = 18.1 ± 1.3 kg) with eight pigs per diet. Feces and urine were collected for 5 d after 7 d of adaptation. The ME did not differ among the eight sources of DDGS with the exception that DDGS source E contained less ($P < 0.05$) ME than DDGS source D. The ATTD of GE did also not differ among the eight sources of DDGS, but ME and ATTD of GE in corn were greater ($P < 0.05$) than in the eight sources of DDGS. However, the ATTD of AEE in corn and the eight sources of DDGS was not different, but the ATTD of AEE in DDGS source E was greater ($P < 0.05$) than in DDGS source A. The ATTD of NDF in DDGS source D was also greater ($P < 0.05$) than in DDGS sources E, G, and H, but ATTD of NDF did not differ between corn and the eight sources of DDGS. In Exp. 2, standardized ileal digestibility (SID) of AA was determined in seven sources of DDGS (sources A, B, C, D, E, G, and H). Twenty-four barrows (initial body weight = 63.4 ± 3.4 kg) that had a T-cannula installed in the distal ileum were allotted to a two-period incomplete Latin square design with eight diets. Seven diets were formulated to contain each of the seven sources of DDGS and an N-free diet was also used. Ileal digesta were collected for 2 d after 5 d of adaptation. There were no differences between pigs fed DDGS sources A and B in SID of AA, and the SID of Lys, Met, and Trp did not differ among DDGS sources A, B, and E. However, SID of most indispensable and dispensable AA except Gly were greater ($P < 0.05$) in DDGS source B than in DDGS sources C, D, E, G, and H. In conclusion, variability in SID of AA, ATTD of NDF and AEE, and ME were observed among the sources of DDGS used in this experiment.

Key words: amino acids, digestibility, distillers dried grains with solubles, energy, pig

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INTRODUCTION

Distillers dried grains with solubles (DDGS) is a coproduct from ethanol production and has

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been successfully included in diets fed to ruminants, pigs, and poultry (Stein and Shurson, 2009; Liu and Han, 2011). Conventional DDGS contains 10% to 14% fat (NRC, 2012), but the majority of ethanol plants now collect fat from the solubles, which results in the production of low-oil DDGS that contains between 6% and 9% fat (NRC, 2012; Kerr et al., 2013). Addition of fat to diets fed to pigs often increases the digestibility of amino acids (AA; Cervantes-Pahm and Stein, 2008; Kil and Stein, 2011), and it is, therefore, possible that removal of fat from DDGS influences the digestibility of AA in DDGS. Indeed, compared with conventional DDGS, the apparent ileal digestibility (AID) and the standardized ileal digestibility (SID) of AA were reduced in two sources of low-oil DDGS that were produced by one ethanol plant (Curry et al., 2014). However, it is not known if this effect is something that is generally observed in low-oil DDGS or if it can be attributed to a specific supplier.

Values for digestible energy (DE) and metabolizable energy (ME) in low-oil DDGS produced in and around Illinois are reduced compared with conventional DDGS (Curry et al., 2016), but the concentration of fat in DDGS is not always correlated with the ME of DDGS (Kerr et al., 2013). In addition to the differences in fat removal procedures among ethanol plants, different plants also use different enzymes in the production. This may result in some of the neutral detergent fiber (NDF) being degraded, which may result in differences in the fermentability by pigs of the NDF in different sources of DDGS, but this hypothesis has not been verified. It was, therefore, the objective of this research to test the hypothesis that the digestibility of crude protein (CP), AA, gross energy (GE), acid hydrolyzed ether extract (AEE), and NDF, and the concentration of ME in low-oil DDGS vary among suppliers of DDGS due to differences in production processes.

MATERIALS AND METHODS

Two experiments were conducted, and protocols for both experiments were reviewed and approved by the Institutional Animal Care and Use Committee at the University of Illinois before animal work was initiated. In both experiments, castrated male pigs that were the offspring of Line 359 boars and Camborough females were used. Eight sources DDGS were procured from feed mills located in the Midwest in the United States. No requirements to the composition of the DDGS was made from the feed mills, but all eight suppliers used low-oil DDGS. One of the sources of DDGS was provided in a quantity that only allowed it to be used in one of the two experiments, so there were eight sources used in Exp. 1 and only seven sources in Exp. 2.

Exp. 1: Digestibility of Energy, Acid Hydrolyzed Ether Extract, and Neutral Detergent Fiber

In Exp. 1, the apparent total tract digestibility (ATTD) of nutrients and DE and ME was determined in eight sources of low-oil DDGS. A corn-based basal diet and eight diets containing each source of DDGS were formulated (Tables 3 and 4). Vitamins and minerals were included in all diets to meet or exceed current requirement estimates (NRC, 2012).

Seventy-two barrows (initial body weight = 18.1 ± 1.3 kg) were randomly allotted to the nine diets in a randomized complete block design with two blocks. There were 36 pigs per block and four replicate pigs per diet within each block for a total of eight replicate pigs per diet in the two blocks. Pigs were housed individually in metabolism crates that were equipped with a self-feeder, a nipple waterer, and a slatted floor. A screen and a urine pan were placed under the slatted floor to allow for the total, but separate, collection of urine and fecal materials. Metabolism crates were placed in an environmentally controlled room with the minimum temperature established at 24 °C. Pigs were fed at three times the energy requirement for maintenance (i.e., 197 kcal/kg × $BW^{0.60}$; NRC, 2012), which were provided each day in two equal meals at 0800 and 1600 h. Throughout the study, pigs had ad libitum access to water. Feed consumption was recorded daily and pigs were fed experimental diets for 14 d. The initial 7 d were considered the adaptation period to the diet. A color marker was included in the diet provided in the morning of day 8 and again in the diet provided in the morning of day 13. Fecal collections were initiated upon appearance of the first marker and ceased when the second marker appeared to ensure that feces that originated from the feed provided from day 8 to day 13 were collected (Adeola, 2001). Urine samples were collected in urine buckets over a preservative of 50 mL of 3*N* HCl, and urine collection started on day 8 in the morning and ceased on day 13 in the morning. 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 pooled within animal, and a subsample was lyophilized before analysis (Kim et al., 2009).

At the conclusion of the experiment, fecal samples were thawed and mixed within pig and diet and then dried to approximately 95% dry matter (DM) in a 50 °C forced-air drying oven prior to analysis. Fecal samples were finely ground through a 1-mm screen in a Wiley mill (Model 4; Thomas Scientific, Swedesboro, NJ). Ingredients, diets, and fecal samples were analyzed for DM (Method 930.15; AOAC Int., 2007). These samples were also analyzed for GE using an isoperibol bomb calorimeter (Model 6300, Parr Instruments, Moline, IL) and for AEE by acid hydrolysis using 3*N* HCl (Ankom HCl hydrolysis system, Ankom Technology, Macedon, NY) followed by fat extraction (Ankom XT-15 Extractor, Ankom Technology) and NDF (Ankom^{2000} fiber analyzer, Ankom Technology). Diets and ingredients were also analyzed for CP (Method 990.03; AOAC Int., 2007) and ash (Method 942.05; AOAC Int., 2007). Ingredients were also analyzed for acid detergent fiber (ADF) using an Ankom^{2000} fiber analyzer and insoluble dietary fiber and soluble dietary fiber according to method 991.43 (AOAC Int., 2007) using the Ankom^{TDF} Dietary Fiber Analyzer (Ankom Technology, Macedon, NY). Total dietary fiber was calculated as the sum of insoluble dietary fiber and soluble dietary fiber. Minerals in the eight sources of DDGS and in corn were analyzed by inductively coupled plasma optical emissions spectrometry using an internally validated method (Method 985.01 a, b, and c; AOAC Int., 2007) after wet ash sample preparation (Method 975.03 B[b]; AOAC Int., 2007). Ingredients were also analyzed for phytic acid (Ellis et al., 1977), sugars including glucose, fructose, maltose, sucrose, stachyose, and raffinose (Method 977.2, AOAC Int., 2007), and fructo-oligosaccharides using refractive index high-performance liquid chromatography (Campbell et al., 1997). Starch was analyzed in corn and each source of DDGS using the glucoamylase procedure (Method 979.10; AOAC Int., 2007). Objective L^*, a^*, and b^* values for the DDGS sources were determined to analyze color using a Konica Minolta cr-400 (Konica Minolta Sensing Americas, Inc., William Drive Ramsey, NJ) utilizing a D65 light source, a 0° observer, and an aperture size of 8 mm (Tavárez et al., 2011). Bulk density (Cromwell et al., 2000) and particle size (ASABE, 2008; De Jong et al., 2016) of each source of DDGS were also determined.

Following chemical analyses, the ATTD of DM, GE, AEE, and NDF, and the DE and ME were calculated for each diet using the direct procedure (Adeola, 2001). The DE and ME in corn were calculated by dividing the DE and ME in the basal diet by the inclusion rate of corn in the diet (i.e., 97%). The contribution of DE and ME from corn to the DE and ME in the diets containing DDGS was then subtracted from the DE and ME of each DDGS-containing diet, and the DE and ME of each source of DDGS were calculated by difference (Adeola, 2001). Likewise, the ATTD of GE, AEE, and NDF in each source of DDGS was also calculated using the difference procedure (Adeola, 2001).

Exp. 2: Amino Acid Digestibility

In Exp. 2, the ileal digestibility of CP and AA was determined in seven sources of low-oil DDGS (i.e., sources A, B, C, D, E, G, and H). Eight diets were formulated (Tables 5 and 6). Seven diets each contained one source of DDGS as the sole source of AA, and an N-free diet was used to determine basal endogenous losses of CP and AA. Vitamins and minerals were included in all diets to meet or exceed current requirement estimates (NRC, 2012). All diets also contained 0.40% chromic oxide. Pigs were fed at a level of three times the maintenance energy requirement (i.e., 197 kcal ME per kg$^{0.60}$; NRC, 2012). The daily allotment of feed was divided into two equal meals and provided at 0800 and 1600 h, and water was available at all times.

Twenty-four barrows that had a T-cannula installed in the distal ileum were used. Pigs were placed in 1.2 × 1.5 m pens with fully slatted tribar floors. Pigs had an initial body weight of 63.4 ± 3.4 kg and were allotted to a two-period incomplete Latin square design with eight diets and three replicate pigs in each period. There was, therefore, six replicate observations per diet. Each experimental period lasted 7 d. The initial 5 d of each period was considered an adaptation period, but ileal digesta samples were collected on days 6 and 7 for 8 h using standard procedures (Stein et al., 1998). In short, the cannulas were opened and a 225-mL plastic bag was attached to the cannula barrel using a cable tie, and digesta flowing into the bag were collected. Bags were removed whenever they were full, or every 30 min, and replaced with a new. All samples were stored at −20 °C as soon as they were collected.

At the conclusion of the experiment, ileal digesta samples were thawed, mixed, and subsampled. Digesta samples were lyophilized and finely ground. Amino acids in DDGS, diet, and digesta samples were analyzed on a Hitachi Amino Acid Analyzer, Model No. L8800. (Hitachi High Technologies America, Inc; Pleasanton, CA) using ninhydrin for postcolumn derivatization and norleucine as the

internal standard. Prior to analysis, samples were hydrolyzed with 6*N* HCl for 24 h at 110 °C (method 982.30 E(a); AOAC Int., 2007). Methionine and Cys were determined as Met sulfone and cysteic acid after cold performic acid oxidation overnight before hydrolysis (method 982.30 E(b); AOAC Int., 2007). Tryptophan was determined after NaOH hydrolysis for 22 h at 110 °C (method 982.30 E(c); AOAC Int., 2007). Diet and ileal digesta samples were also analyzed for Cr (Method 990.08; AOAC Int., 2007). All samples were also analyzed for DM and CP as explained for Exp. 1.

The AID of CP and AA was calculated in the seven diets containing DDGS (Stein et al., 2007). The basal endogenous losses of CP and AA were calculated from pigs fed the N-free diet as previously described (Stein et al., 2007), and these values were used to correct values for AID of CP and AA to calculate values for SID of CP and AA.

Data Analyses

Data from both experiments were analyzed as a randomized complete block design with the pig as the experimental unit. Homogeneity of the variances was confirmed using the UNIVARIATE procedure in SAS (SAS Institute Inc., Cary, NC). The mixed procedure in SAS was used to conduct an analysis of variance, and diet or ingredient was the fixed effect, and block and replicate within block were the random effects. Least squares means were calculated using the LS means procedure, and means were separated using the PDIFF statement with Tukey's adjustment. In Exp. 1, values for DE and ME and ATTD of energy and nutrients in corn were compared with values for the eight sources of DDGS using a CONTRAST statement. In Exp. 2, means for concentration and digestibility of CP and AA were calculated for each source of DDGS. Results were considered significant at $P < 0.05$ and considered a trend at $P \leq 0.10$.

RESULTS AND DISCUSSION

Nutrient Composition and Physical Characteristics of Low-Oil Distillers DDGS

The DM in all sources of DDGS was greater than 82.0%. When all values were adjusted to 88% DM, the GE in the eight sources of DDGS ranged from 4,455 to 4,963 kcal/kg, and the NDF and ADF ranged from 27.15% to 36.29% and from 10.84% to 16.33%, respectively (Table 1). The concentration of total dietary fiber in all sources of DDGS ranged from 36.20% to 41.94%, and insoluble dietary fiber concentrations were much greater than concentrations of soluble dietary fiber for all sources. Concentrations of GE, ADF, NDF, and TDF have been suggested to be the components with the greatest influence on DE and ME in DDGS (Urriola et al., 2014). The mean CP of the eight sources of low-oil DDGS (adjusted to 88% DM basis) was 28.72% (Table 1), and this value is within the range of CP values for conventional DDGS reported by Fastinger and Mahan (2006), Stein et al. (2006), and NRC (2012). The AEE values for the eight DDGS sources ranged from 7.33% to 9.71%, which indicates that for all sources of DDGS, fat had been removed from the solubles via centrifugation (NRC, 2012). The concentration of Lys in the DDGS samples used in this experiment was between 0.98% and 1.05%, which is greater than most previously published data for low-oil DDGS (NRC, 2012; Curry et al., 2014, 2016). This also resulted in a greater average Lys:CP ratio (3.48%) compared with DDGS samples produced in the past (Kerr et al., 2008; Stein and Shurson, 2009; Kim et al., 2012a). The average glucose and fructose concentration in the eight sources of DDGS was 0.59% and 0.21%, respectively. Some DDGS did not contain any maltose, sucrose, stachyose, and raffinose. The fructo-oligosaccharides in the eight sources of DDGS ranged from 0.15% to 0.24%. The average starch concentration in the eight sources of DDGS was 4.98%, indicating that most of the starch from corn was removed during ethanol production.

Due to fermentation and starch loss, the mineral composition of DDGS is usually greater than in corn (NRC, 2012; Table 2). There were relatively large variations among DDGS sources in concentrations of Ca and phytate bound P with a small variation in total P concentrations. No phytate was detected in DDGS sources A, B, and D, which indicates that producers of these sources used phytase to liberate the bound P and, therefore, may have increased the digestibility of P (Almeida et al., 2013b). The concentration of Ca was less than 0.10% in all sources of DDGS except source C, which contained 0.34%. It is likely that the high concentration of Ca in source C is a result of addition of limestone, which is sometimes added as a flow agent (Ganesan et al., 2008). The average concentrations of Na and S and most microminerals in the eight DDGS sources used in the present study were more than three times greater than in corn. There were relatively large variations among DDGS sources in concentrations of S and most of the microminerals,

Table 1. Chemical composition and physical analysis of corn and eight sources of distillers dried grains with solubles[1]

		Source of distillers dried grains with solubles										
Item, %	Corn	A	B	C	D	E	G	H	I	Mean	SD	CV[6],%
Dry matter	88.66	82.45	85.60	82.27	83.42	86.40	86.32	90.67	88.55	85.71	2.96	3.5
Gross energy, kcal/kg	3,798	4,963	4,798	4,858	4,824	4,613	4,645	4,462	4,455	4,702	188	4.0
Crude protein	7.37	29.40	28.60	29.55	28.93	28.42	29.82	27.87	27.14	28.72	0.90	3.2
AEE[2]	3.84	9.71	9.40	8.01	9.18	8.33	7.33	7.71	7.84	8.44	0.88	10.4
Ash	1.38	7.57	5.91	6.81	6.85	5.88	6.78	6.70	6.44	6.62	0.55	8.3
Carbohydrates												
Glucose	0.36	0.34	0.65	0.26	1.27	0.54	0.55	0.87	0.26	0.59	0.34	58.2
Fructose	0.26	0.09	0.14	0.11	0.44	0.18	0.27	0.24	0.19	0.21	0.11	54.3
Maltose	0.61	0.09	0.07	ND[3]	0.17	ND	ND	ND	ND	—	—	—
Sucrose	1.24	ND	ND	ND	ND	ND	ND	ND	ND	—	—	—
Stachyose	ND	ND	ND	ND	ND	ND	ND	ND	ND	—	—	—
Raffinose	0.19	ND	ND	ND	ND	ND	ND	ND	ND	—	—	—
FOS[2]	0.10	0.15	0.22	0.20	0.22	0.24	0.18	0.19	0.18	0.20	0.03	14.1
Starch	59.93	3.43	5.19	2.73	5.81	3.87	4.93	6.07	7.83	4.98	1.64	32.8
NDF[4]	7.38	36.29	33.89	34.10	31.64	27.90	27.15	28.75	28.59	31.04	3.41	11.0
ADF[4]	2.75	16.33	14.51	12.28	14.69	16.20	11.87	11.39	10.84	13.51	2.19	16.2
SDF[5]	1.87	0.33	3.83	3.63	2.89	3.12	2.52	1.35	2.03	2.46	1.18	48.1
IDF[5]	11.30	39.31	37.11	38.31	36.52	33.68	33.67	34.93	35.23	36.10	2.08	5.8
TDF[5]	13.17	39.64	40.95	41.94	39.41	36.80	36.20	36.28	37.26	38.56	2.22	5.8
Color measurement												
*L**	88.61	64.07	68.18	69.70	66.21	57.61	65.18	64.83	66.10	65.24	3.59	5.5
*a**	1.41	6.62	8.31	6.55	8.87	7.77	10.13	9.79	9.32	8.42	1.36	16.2
*b**	22.33	18.36	23.24	20.17	19.90	11.39	23.35	23.15	23.48	20.38	4.13	20.3
Bulk density, g/L	—	454	471	463	529	470	504	521	508	490	29	5.9
Particle size, µm	—	931	890	656	796	642	322	382	321	617	250	40.5
Indispensable AA, %												
Arg	—	1.24	1.21	1.28	1.24	1.24	1.27	1.15	1.22	1.23	0.04	3.2
His	—	0.72	0.74	0.74	0.76	0.72	0.77	0.71	0.76	0.74	0.02	3.1
Ile	—	1.10	1.12	1.11	1.12	1.03	1.09	1.04	1.12	1.09	0.04	3.4
Leu	—	2.98	3.22	3.08	3.20	2.88	3.20	2.87	2.99	3.05	0.14	4.7
Lys	—	1.02	0.98	1.05	1.00	0.98	0.99	1.01	1.00	1.00	0.02	2.4
Met	—	0.52	0.53	0.53	0.47	0.52	0.53	0.50	0.51	0.52	0.02	3.9
Phe	—	1.26	1.34	1.29	1.35	1.24	1.34	1.22	1.27	1.29	0.05	3.7
Thr	—	1.11	1.09	1.12	1.09	1.03	1.14	1.04	1.00	1.08	0.05	4.6
Trp	—	0.20	0.21	0.21	0.20	0.19	0.19	0.17	0.19	0.20	0.01	6.1
Val	—	1.50	1.50	1.53	1.49	1.41	1.46	1.40	1.41	1.46	0.05	3.5
Total	—	11.65	11.94	11.96	11.92	11.24	11.99	11.12	11.48	11.66	0.35	3.0
Dispensable AA, %												
Ala	—	1.81	1.96	1.91	1.84	1.78	1.98	1.86	1.90	1.88	0.07	3.7
Asp	—	1.77	1.81	1.81	1.79	1.74	1.81	1.76	1.81	1.79	0.03	1.6
Cys	—	0.49	0.51	0.50	0.53	0.56	0.54	0.50	0.59	0.53	0.03	6.1
Glu	—	3.28	3.97	3.59	3.81	3.87	3.89	3.95	4.07	3.80	0.26	6.7
Gly	—	1.15	1.12	1.16	1.11	1.13	1.13	1.07	1.10	1.12	0.03	2.6
Ser	—	1.20	1.25	1.25	1.21	1.13	1.33	1.15	1.07	1.20	0.08	6.6
Tyr	—	0.93	0.96	0.91	0.96	0.88	1.02	0.86	0.94	0.93	0.05	5.4
Total	—	10.63	11.59	11.13	11.25	11.09	11.70	11.16	11.49	11.26	0.34	3.0
All AA, %	—	22.29	23.52	23.09	23.17	22.34	23.69	22.28	22.97	22.92	0.56	2.4

[1]All values except dry matter were adjusted to 88% dry matter basis.

[2]AEE = acid hydrolyzed ether extract; FOS = fructo-oligosaccharides.

[3]ND = not detectable.

[4]NDF = neutral detergent fiber; ADF = acid detergent fiber.

[5]SDF = soluble dietary fiber; IDF = insoluble dietary fiber; TDF = total dietary fiber.

[6]CV = SD/mean × 100.

Table 2. Mineral composition of eight sources of distillers dried grains with solubles[1]

		Source of distillers dried grains with solubles										
Item	Corn	A	B	C	D	E	G	H	I	Mean	SD	CV[5],%
Macromineral, %												
Ca	0.01	0.02	0.02	0.34	0.04	0.03	0.09	0.05	0.06	0.08	0.11	131.1
P	0.25	0.92	0.91	0.91	0.90	0.99	1.03	0.91	0.90	0.93	0.05	5.2
Phytate-P[2]	—	ND[4]	ND	0.36	ND	0.23	0.32	0.28	0.33	0.19	0.16	85.2
Non-phytate P[3]	—	0.92	0.91	0.55	0.90	0.76	0.71	0.62	0.57	0.74	0.15	20.8
Mg	0.09	0.28	0.29	0.30	0.31	0.29	0.36	0.29	0.31	0.30	0.03	8.5
K	0.36	1.14	1.08	1.10	1.11	1.25	1.27	1.15	1.17	1.16	0.07	6.1
Na	0.02	0.23	0.14	0.16	0.22	0.27	0.25	0.25	0.22	0.22	0.05	22.0
S	0.09	0.40	0.47	0.61	0.68	1.25	0.81	0.87	0.89	0.75	0.27	36.2
Cl	0.07	0.15	0.13	0.15	0.17	0.13	0.16	0.18	0.17	0.16	0.02	12.5
Micromineral, ppm												
Cu	5.80	7.75	6.06	161.51	22.58	7.51	4.81	6.32	5.92	27.81	54.33	195.4
Fe	20.94	73.96	58.70	132.63	72.16	77.20	73.10	67.36	70.56	78.21	22.68	29.0
Mn	8.09	14.41	11.82	456.73	18.67	17.11	12.95	16.79	13.22	70.21	156.19	222.5
Se	0.05	0.42	0.27	7.82	0.58	0.27	0.34	0.28	0.21	1.27	2.65	207.7
Zn	22.83	66.81	54.69	280.24	69.42	69.67	64.84	64.64	64.29	91.83	76.27	83.1

[1]All values were adjusted to 88% dry matter basis.

[2]Phytate P was calculated as 28.2% of phytate (Tran and Sauvant, 2004).

[3]Non-phytate P was calculated as the difference between total P and phytate-P.

[4]ND = not detectable.

[5]CV = SD/mean × 100.

which indicates that differences in processing probably affect the concentrations of these minerals. The concentration of Na in the eight DDGS sources ranged from 0.14% to 0.27%, which indicates that the use of Na (mainly as a cleaning agent) varies among plants (Rosentrater, 2012). The concentrations of S in most sources were greater than three times the concentration in corn, which indicates use of sulfuric acid to stabilize pH during fermentation and also to reduce lipid oxidation (Liu and Han, 2011; Song et al., 2013). Previously, variability in S from 0.33% to 1.04% among 35 sources of DDGS with an average of 0.65% was reported (Kim et al., 2012b), and Kerr et al. (2008) reported an average of 0.69% S in 19 sources of DDGS. The current sources of DDGS contained between 0.40% and 1.25% S with an average of 0.75%, indicating that the use of sulfuric acid has probably increased over time (Tables 3–6).

The physical properties that are usually analyzed in DDGS include color, bulk density, and particle size. Color of DDGS may vary due to differences in storage, handling, and drying conditions at the ethanol plants (Rosentrater, 2012), or differences in particle size. For color parameters, L^* (0 dark, 100 lighter) values of the eight DDGS sources range from 57.61 to 69.70, a^* values range from 6.55 to 10.13, and b^* values range from 11.39 to 23.48 (Table 1). L^* values of the DDGS sources used in this experiment were greater compared with previous data (Rosentrater, 2006). Color has been associated with the nutritional quality and can be related to the AA profile of a feed ingredient (Rosentrater, 2012). There may be a relationship

Table 3. Ingredient composition of experimental diets[1] (as-fed basis), Exp. 1

Item, %	Basal	DDGS
Corn	97.00	47.40
Distillers dried grains with solubles	—	50.00
Ground limestone	0.80	1.30
Dicalcium phosphate	1.50	0.60
Sodium chloride	0.40	0.40
Vitamin–mineral premix[2]	0.30	0.30

[1]A total of eight diets containing distillers dried grains with solubles were formulated using eight different sources of distillers dried grains with solubles.

[2]Provided the following quantities of vitamins and micro minerals per kilogram of complete diet: vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 as cholecalciferol, 2,208 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamin mononitrate, 0.24 mg; riboflavin, 6.59 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, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper sulfate and copper chloride; Fe, 126 mg as ferrous sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese sulfate; Se, 0.3 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc sulfate.

Table 4. Analyzed nutrient composition of experimental diets containing eight different sources of distillers dried grains with solubles[1], Exp. 1

		Source of distillers dried grains with solubles							
Item, %	Basal	A	B	C	D	E	G	H	I
Dry matter	90.34	89.17	89.00	88.20	88.85	88.18	88.17	88.12	89.25
Gross energy, kcal/kg	3,685	4,089	4,059	4,073	4,077	4,044	4,047	4,032	4,004
Crude protein	7.57	19.17	18.42	17.80	19.62	19.27	19.33	18.42	18.64
AEE[2]	3.65	5.98	6.08	5.98	6.02	6.39	5.50	5.23	5.19
Ash	3.56	5.72	5.36	6.10	5.83	6.14	6.37	6.60	5.98
Neutral detergent fiber	9.90	22.9	21.7	21.6	20.8	19.6	18.9	19.9	20.5
Acid detergent fiber	3.36	9.30	8.70	8.04	8.71	9.62	6.41	7.10	6.88

[1]All values except dry matter were adjusted to 88% dry matter basis.

[2]AEE = acid hydrolyzed ether extract.

Table 5. Ingredient composition of experimental diets[1] (as-fed basis), Exp. 2

Item	DDGS	N-free
Distillers dried grains with solubles	50.00	—
Soybean oil	2.00	4.00
Ground limestone	1.00	0.3
Dicalcium phosphate	0.50	1.75
Sucrose	10.00	20.00
Cornstarch	35.40	68.35
Solka floc[2]	—	4.00
Magnesium oxide	—	0.10
Potassium carbonate	—	0.40
Sodium chloride	0.40	0.40
Chromic oxide	0.40	0.40
Vitamin–mineral premix[3]	0.30	0.30

[1]A total of seven diets containing distillers dried grains with solubles were formulated using seven different sources of distillers dried grains with solubles.

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

[3]Provided the following quantities of vitamins and microminerals per kilogram of complete diet: vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 as cholecalciferol, 2,208 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamin mononitrate, 0.24 mg; riboflavin, 6.59 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, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper sulfate and copper chloride; Fe, 126 mg as ferrous sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese sulfate; Se, 0.3 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc sulfate.

between DDGS color and Lys concentration with the lightest colored DDGS sources having the greatest concentration of Lys (Cromwell et al., 1993). The lighter color of the DDGS used in the current experiment compared with previous data indicates that the sources of DDGS used in this experiment were less heat damaged during processing compared with DDGS sources produced in the past (González-Vega et al., 2011; Almeida et al., 2013a). Bulk density is associated with particle size and shape of a particle and allows calculation of the storage capacity in containers and bins. Values for bulk density for the eight DDGS sources ranged from 454 to 529 g/L and these values are in agreement with previous data (Curry et al., 2016). The particle size of all DDGS sources ranged from 321 to 931 μm, which is in agreement with data for unground DDGS (Liu, 2008; Yañez et al., 2011; Liu et al., 2012), and indicates that ethanol plants have different strategies for grinding of the corn used in ethanol production. The particle size is, however, important because energy and nutrient digestibility in DDGS may be affected by particle size (Liu, 2008; Yañez et al., 2011; Liu et al., 2012; Woyengo et al., 2014).

Exp. 1: Digestibility of Energy, Acid Hydrolyzed Ether Extract, and Neutral Detergent Fiber

Diet analyses indicated that the intended concentrations of GE, AEE, and NDF were present in all diets (Table 4). Pigs remained healthy during the experiment, and very little feed refusals were observed. Feed intake did not differ among experimental diets, which is probably a result of the restricted feeding program that was used (Table 7). The ATTD of DM and GE in the basal diet was greater ($P < 0.05$) than in all DDGS diets. The ATTD of AEE in the diet containing DDGS source E was greater ($P < 0.05$) than in the DDGS A diet. The ATTD of NDF also was different ($P < 0.05$) among experimental diets. The DE in the basal diet was greater ($P < 0.05$) than in the diet containing DDGS source E. The ME in the basal diet also was greater ($P < 0.05$) than in all DDGS diets except the diet containing DDGS source D.

Table 6. Analyzed nutrient composition of experimental diets containing seven different sources of distillers dried grains with solubles[1], Exp. 2

		Source of distillers dried grains with solubles						
Item	N-free	A	B	C	D	E	G	H
CP, %	0.21	13.29	12.15	13.04	13.66	13.83	13.66	13.23
DM, %	91.25	90.75	90.11	89.25	90.32	90.8	90.66	91.67
Indispensable AA, %								
Arg	0.00	0.63	0.63	0.53	0.58	0.59	0.57	0.60
His	0.00	0.38	0.39	0.32	0.37	0.34	0.37	0.37
Ile	0.01	0.58	0.59	0.47	0.54	0.48	0.54	0.55
Leu	0.02	1.64	1.71	1.33	1.53	1.35	1.51	1.53
Lys	0.02	0.53	0.52	0.45	0.50	0.47	0.50	0.53
Met	0.00	0.28	0.28	0.23	0.23	0.24	0.25	0.25
Phe	0.01	0.70	0.72	0.57	0.65	0.60	0.64	0.66
Thr	0.01	0.58	0.58	0.48	0.54	0.49	0.54	0.51
Trp	0.02	0.14	0.13	0.12	0.12	0.12	0.12	0.12
Val	0.01	0.80	0.80	0.67	0.72	0.67	0.73	0.74
Dispensable AA, %								
Ala	0.01	1.02	1.06	0.85	0.91	0.85	0.96	0.99
Asp	0.01	0.99	1.00	0.81	0.91	0.86	0.91	0.89
Cys	0.00	0.26	0.28	0.22	0.25	0.25	0.26	0.25
Glu	0.03	2.14	2.33	1.79	2.08	2.01	2.10	2.18
Gly	0.01	0.60	0.60	0.50	0.55	0.54	0.55	0.56
Ser	0.01	0.64	0.64	0.51	0.57	0.53	0.59	0.58
Tyr	0.01	0.48	0.48	0.38	0.44	0.41	0.44	0.46
All AA, %	0.44	13.60	14.02	11.31	12.71	12.04	12.85	13.08

[1]All values except dry matter were adjusted to 88% dry matter basis.

Table 7. Apparent total tract digestibility (ATTD) of dry matter (DM), gross energy (GE), acid hydrolyzed ether extract (AEE), and neutral detergent fiber (NDF) and digestible energy (DE) and metabolizable energy (ME) in experimental diets fed to pigs[1] (as-fed basis), Exp. 1

		Source of distillers dried grains with solubles									
Item	Basal	A	B	C	D	E	G	H	I	SEM	*P* value
Intake											
Feed intake, g/d	788	817	833	809	811	878	856	813	851	58	0.273
GE, Mcal/d	2.98^{b}	3.38^{ab}	3.42^{ab}	3.30^{ab}	3.34^{ab}	3.56^{a}	3.47^{ab}	3.28^{ab}	3.45^{ab}	0.24	0.041
AEE, g/d	29^{d}	49^{abc}	51^{ab}	48^{bc}	49^{abc}	56^{a}	47^{bc}	43^{c}	45^{bc}	3	<0.001
NDF, g/d	80.1^{c}	190^{a}	183^{ab}	175^{ab}	171^{ab}	172^{ab}	162^{b}	162^{b}	177^{ab}	12	<0.001
Fecal excretion											
Dry feces output, g/d	72^{b}	151^{a}	143^{a}	136^{a}	134^{a}	166^{a}	146^{a}	143^{a}	160^{a}	17	<0.001
GE, kcal/d	331^{b}	744^{a}	690^{a}	642^{a}	638^{a}	768^{a}	668^{a}	647^{a}	728^{a}	74	<0.001
AEE, g/d	10^{c}	19^{a}	16^{ab}	16^{ab}	15^{ab}	15^{ab}	15^{ab}	13^{bc}	15^{ab}	2	<0.001
NDF, g/d	31^{b}	75^{a}	73^{a}	67^{a}	63^{a}	77^{a}	73^{a}	71^{a}	78^{a}	6	<0.001
ATTD, %											
DM	91.0^{a}	81.5^{b}	83.0^{b}	83.5^{b}	83.7^{b}	81.2^{b}	82.9^{b}	82.6^{b}	81.4^{b}	1.0	<0.001
GE	89.0^{a}	78.1^{b}	80.0^{b}	80.9^{b}	81.1^{b}	78.5^{b}	80.7^{b}	80.5^{b}	79.2^{b}	1.0	<0.001
AEE	66.7^{ab}	61.9^{b}	69.4^{ab}	66.4^{ab}	69.9^{ab}	73.4^{a}	68.6^{ab}	69.4^{ab}	67.3^{ab}	2.5	0.014
NDF	61.4^{ab}	60.7^{ab}	60.4^{ab}	62.4^{a}	63.0^{a}	55.3^{b}	55.0^{b}	56.6^{b}	56.2^{b}	1.7	0.003
DE in diet, kcal/kg	3,364^{a}	3,236^{ab}	3,284^{ab}	3,303^{ab}	3,342^{ab}	3,182^{b}	3,274^{ab}	3,248^{ab}	3,215^{ab}	42	0.009
Urine output, kg/d	2.42^{b}	2.72^{ab}	3.42^{ab}	4.04^{ab}	2.96^{ab}	5.58^{a}	3.17^{ab}	2.62^{ab}	2.89^{ab}	0.76	0.046
Urinary GE output, kcal/d	55^{b}	131^{a}	148^{a}	138^{a}	114^{a}	163^{a}	142^{a}	119^{a}	132^{a}	13	<0.001
ME in diet, kcal/kg	3,295^{a}	3,076^{bc}	3,109^{bc}	3,132^{bc}	3,196^{ab}	2,997^{c}	3,107^{bc}	3,100^{bc}	3,059^{bc}	38	<0.001

[a–e]Within a row means without a common superscript differ ($P < 0.05$).

[1]Each least squares mean for all treatments represents 8 observations respectively except for distillers dried grains with soluble D diet ($n = 7$).

Table 8. Energy values and acid hydrolyzed ether extract (AEE) and neutral detergent fiber (NDF) digestibility in corn and eight sources of distillers dried grains with solubles (DDGS)[1], Exp. 1

		Source of DDGS[2]										*P* value[3]	
Item, %	Corn	A	B	C	D	E	G	H	I	Mean	SEM	DDGS	Corn vs. DDGS
Energy values, kcal/kg[4]													
DE	3,379	3,142	3,243	3,309	3,363	3,069	3,254	3,203	3,098	3,210	84	0.076	0.022
ME	3,309	2,894^{ab}	2,963^{ab}	3,038^{ab}	3,142^{a}	2,769^{b}	2,988^{ab}	2,976^{ab}	2,857^{ab}	2,953	76	0.027	<0.001
ATTD, %[5]													
GE	90.6	68.4	70.3	73.0	74.3	67.9	71.6	69.7	70.1	70.7	1.8	0.102	<0.001
AEE	66.7	60.1^{b}	70.4^{ab}	66.3^{ab}	71.2^{ab}	76.3^{a}	69.6^{ab}	70.6^{ab}	67.5^{ab}	69.0	3.1	0.008	0.402
NDF	61.4	65.0^{ab}	62.0^{ab}	65.6^{ab}	68.0^{a}	57.0^{b}	55.3^{b}	55.6^{b}	59.9^{ab}	61.1	2.3	0.001	0.891

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

[1]Each least squares mean for each ingredient represents eight observations except for distillers dried grains with solubles D ($n = 7$).

[2]Least squares means were separated within 8 sources of distillers dried grains with solubles with alpha level of 0.05.

[3]DDGS = testing a model that includes a source of distillers dried grains with solubles as an independent variable; corn vs. DDGS = contrasting the means energy and digestibility values in corn and distillers dried grains with solubles.

[4]All values for DE and ME were adjusted to 88% dry matter basis. DE = digestible energy; ME = metabolizable energy.

[5]ATTD = apparent total tract digestibility.

The DE and ME of corn that were calculated in this experiment were close to expected values and in good agreement with previous data (Table 8; NRC, 2012). The DE did not differ among the eight sources of DDGS and the same was true for ME values with the exception that DDGS source E contained less ($P < 0.05$) ME than DDGS source D. The ATTD of GE also did not differ among the eight sources of DDGS, but DE, ME, and ATTD of GE in corn were greater ($P < 0.05$) than in the eight sources of DDGS. However, the ATTD of AEE and NDF in corn and the eight sources of DDGS were not different. The ATTD of AEE in DDGS source E was greater ($P < 0.05$) than in DDGS source A. The ATTD of NDF in DDGS source D was greater ($P < 0.05$) than in DDGS sources E, G, and H.

The DE and ME in the DDGS used in this study were less than reported by NRC (2012) for low-oil DDGS. However, values obtained in this experiment are in agreement with values reported for low-oil DDGS that had similar fat contents as the samples used in this study (Kerr et al., 2013; Gutierrez et al., 2014). However, the samples used in this experiment had greater DE and ME than the average for 20 sources of DDGS that contained 7.37% AEE on average (88% DM basis; Curry et al., 2016). The DDGS samples used by Curry et al. (2016) had reduced GE and reduced AEE compared with the eight sources of DDGS used in this experiment, and although it has been suggested that ether extract does not impact the DE and ME of DDGS (Urriola et al., 2014), it is possible that concentrations of AEE may affect DE and ME. The ATTD of AEE in corn and DDGS were greater than in previous studies (Kim et al., 2013; Wang et al., 2017), which further support the hypothesis that AEE may affect energy utilization in DDGS. The differences in ATTD of AEE among studies may be a result of differences in the quality and condition of corn and DDGS used, but the concentration of AEE in the diets used in this experiment was greater compared with some other experiments, which may also have contributed to the greater ATTD of AEE that was observed. The ATTD of NDF in the eight sources of DDGS were less than the values reported by Stein and Shurson (2009) and Gutierrez et al. (2014), but in agreement with the values reported by Urriola et al. (2010) and Kerr et al. (2013). The observation that the ATTD of NDF in the DDGS was not different from the ATTD of NDF in corn indicates that the NDF fraction is probably not changed during fermentation. Corn fiber contains mainly arabinoxylans and cellulose and is largely insoluble (Jaworski et al., 2015), which is probably the reason these fibers are not fermented in the ethanol plant.

Exp. 2: Amino Acid Digestibility

Diet analyses indicated that the intended concentration of CP and AA were present in all diets (Table 6). There were no differences between pigs fed DDGS A and B in AID and SID of AA (Tables 9 and 10). The AID and SID of Lys, Met, and Trp did not differ among DDGS sources A, B, and E,

Table 9. Apparent ileal digestibility (AID) of crude protein (CP) and amino acids (AA) in distillers dried grains with solubles[1], Exp. 2

	Source of distillers dried grains with solubles									
Item, %	A	B	C	D	E	G	H	Mean	SEM	*P* value
CP	66.5	66.1	66.9	62.0	66.5	69.4	65.8	66.2	1.5	0.117
Indispensable AA										
Arg	80.0^{ab}	82.5^{a}	78.0^{b}	72.8^{c}	80.5^{ab}	78.8^{b}	78.0^{b}	78.7	1.6	<0.001
His	76.0^{ab}	77.5^{a}	70.2^{cd}	67.6^{d}	72.4^{bc}	73.6^{abc}	72.8^{bc}	72.1	1.4	<0.001
Ile	74.6^{ab}	77.4^{a}	69.6^{cd}	67.5^{d}	71.5^{bc}	72.6^{bc}	71.5^{bc}	72.1	1.3	<0.001
Leu	83.8^{ab}	85.7^{a}	80.8^{c}	78.1^{d}	77.6^{d}	83.7^{ab}	83.0^{ab}	81.8	0.9	<0.001
Lys	61.9^{ab}	65.5^{a}	56.3^{cd}	53.1^{d}	62.2^{ab}	58.1^{bc}	58.5^{bc}	59.4	1.7	<0.001
Met	81.1^{ab}	83.5^{a}	77.2^{c}	73.8^{d}	81.8^{ab}	80.2^{b}	79.9^{bc}	79.7	1.0	<0.001
Phe	79.0^{ab}	81.7^{a}	75.2^{cd}	73.1^{d}	76.9^{bc}	78.5^{b}	78.1^{bc}	77.5	1.1	<0.001
Thr	67.3^{a}	70.1^{a}	61.1^{bc}	58.6^{bc}	62.3^{b}	62.4^{b}	58.0^{c}	62.8	1.4	<0.001
Trp	74.4^{a}	74.1^{a}	68.5^{b}	67.2^{b}	70.6^{ab}	67.0^{b}	67.9^{b}	69.9	2.5	0.015
Val	73.3^{ab}	76.2^{a}	69.0^{cd}	66.1^{d}	69.1^{cd}	70.9^{bc}	69.4^{c}	70.6	1.1	<0.001
Total	76.5^{ab}	79.1^{a}	72.3^{cd}	69.5^{d}	73.2^{c}	74.6^{bc}	73.7^{bc}	74.1	1.0	<0.001
Dispensable AA										
Ala	77.5^{ab}	80.2^{a}	73.4^{c}	70.1^{c}	73.9^{bc}	79.0^{a}	78.3^{a}	76.1	1.2	<0.001
Asp	67.0^{ab}	70.3^{a}	59.4^{cd}	56.1^{d}	61.5^{c}	63.1^{bc}	61.6^{c}	62.7	1.7	<0.001
Cys	68.2^{ab}	70.1^{a}	57.1^{c}	56.4^{c}	61.7^{bc}	64.7^{ab}	61.8^{bc}	62.8	2.3	<0.001
Glu	79.8^{a}	82.5^{a}	75.5^{b}	74.3^{b}	75.6^{b}	79.9^{a}	79.8^{a}	78.2	1.4	0.002
Gly	55.2	56.5	42.9	43.5	47.9	52.5	49.3	49.7	4.9	0.185
Ser	74.9^{ab}	78.0^{a}	69.7^{cd}	66.8^{d}	67.8^{cd}	71.7^{bc}	68.1^{cd}	71.0	1.5	<0.001
Tyr	80.9^{ab}	82.1^{a}	76.1^{c}	75.6^{c}	78.0^{bc}	79.1^{b}	79.3^{ab}	78.7	1.0	<0.001
Total	74.0^{ab}	76.8^{a}	68.0^{de}	66.9^{e}	69.1^{cde}	72.9^{abc}	72.0^{bcd}	71.4	1.6	0.001
All AA	75.3^{ab}	77.9^{a}	70.2^{cd}	67.5^{d}	71.1^{cd}	73.8^{bc}	72.8^{bc}	72.7	1.3	<0.001

$^{a-e}$Within a row means without a common superscript differ ($P < 0.05$).

[1]Each least squares mean for each treatment represents six observations, respectively.

but the AID and SID of most indispensable and dispensable AA except Gly were greater ($P < 0.05$) in DDGS source B than in DDGS sources C, D, E, G, and H.

The AID and SID values for AA except Lys in the DDGS sources used in this experiment are in agreement with reported values for conventional and low-oil DDGS (NRC, 2012; Curry et al., 2014; Stein et al., 2016). The greater AID and SID of Lys in the DDGS sources used in this study compared with previous data are most likely a result of less heat damage in the current samples because Lys is usually the first AA to have reduced digestibility if samples are heat damaged (Pahm et al., 2008; Almeida et al., 2013a; Zeng et al., 2017). The observation that the Lys:CP ratio was also greater in the current samples than in samples used in previous experiments supports the hypothesis that samples used in this experiment were less heat damaged than samples used previously. The combined outcome of these effects was a greater concentration of digestible Lys in DDGS samples used in this experiment than observed previously. Generally, improvements in the Lys concentration and Lys:CP ratio of DDGS have been observed over the past years (Figures 1 and 2). The mean Lys concentration of DDGS from 2002 to 2006, 2008 to 2013, and 2014 to 2016 increased from approximately 0.78% to 0.93% and 0.99%, respectively, which is the reason for the improvement in the Lys:CP ratio that has been observed over these years because CP in DDGS did not increase during this time. This indicates that the fuel ethanol industry continues to reduce heat damage and improve the nutritional value of DDGS by implementing improved technologies (i.e., use of more effective enzymes, better fractionation, and improved drying systems) that assist in reducing heat damage in the DDGS.

The differences in the AID and SID of AA among DDGS sources observed in this experiment indicate that there is some variability in AA digestibility among DDGS suppliers, which is consistent with previous observations (Stein et al., 2006; Pahm et al., 2008; Kim et al., 2012a; Zeng et al., 2017). These differences may be a result of differences in

Table 10. Standardized ileal digestibility (SID) of crude protein (CP) and amino acids (AA) in distillers dried grains with solubles[1,2], Exp. 2

	Source of distillers dried grains with solubles									
Item, %	A	B	C	D	E	G	H	Mean	SEM	*P* value
CP	80.4	81.3	81.0	75.5	79.8	82.9	79.7	80.1	1.5	0.089
Indispensable AA										
Arg	88.1^{ab}	90.7^{a}	87.6^{ab}	81.5^{c}	89.1^{ab}	87.7^{ab}	86.4^{b}	87.3	1.6	<0.001
His	81.2^{ab}	82.6^{a}	76.4^{cd}	74.4^{d}	78.3^{bcd}	78.9^{abc}	78.0^{bcd}	78.5	1.4	0.007
Ile	81.2^{ab}	84.0^{a}	77.7^{cd}	74.6^{d}	79.4^{bc}	79.7^{bc}	78.5^{bc}	79.3	1.3	<0.001
Leu	87.4^{ab}	89.2^{a}	85.2^{b}	81.9^{c}	81.9^{c}	87.6^{ab}	86.9^{ab}	85.7	0.9	<0.001
Lys	69.7^{abc}	73.5^{a}	65.4^{cd}	61.4^{d}	70.9^{ab}	66.4^{bc}	66.4^{bc}	67.7	1.7	<0.001
Met	84.0^{ab}	86.4^{a}	80.8^{c}	77.2^{d}	85.2^{ab}	83.4^{bc}	83.1^{bc}	82.9	1.0	<0.001
Phe	84.3^{ab}	86.8^{a}	81.6^{bc}	78.8^{c}	83.1^{b}	84.3^{ab}	83.6^{b}	83.2	1.1	<0.001
Thr	79.1^{ab}	81.9^{a}	75.3^{bcd}	71.4^{d}	76.1^{bc}	74.9^{cd}	71.5^{d}	75.8	1.4	<0.001
Trp	79.8^{a}	79.9^{a}	74.7^{ab}	73.5^{b}	76.9^{ab}	73.2^{b}	74.2^{b}	76.0	2.5	0.038
Val	79.6^{ab}	82.4^{a}	76.5^{bc}	73.1^{d}	76.6^{bc}	77.8^{bc}	76.2^{cd}	77.5	1.1	<0.001
Total	82.6^{ab}	85.1^{a}	79.6^{b}	76.1^{c}	80.3^{b}	81.2^{b}	80.2^{b}	80.7	1.0	<0.001
Dispensable AA										
Ala	83.3^{abc}	85.8^{a}	80.4^{cd}	78.4^{d}	80.9^{bcd}	85.2^{a}	84.3^{ab}	82.6	1.2	0.001
Asp	75.9^{ab}	79.1^{a}	70.3^{cd}	67.0^{d}	71.6^{bcd}	72.7^{bc}	71.4^{bcd}	72.6	1.7	0.001
Cys	78.2^{ab}	79.4^{a}	69.2^{cd}	66.8^{d}	72.2^{bcd}	74.7^{abc}	72.4^{bcd}	73.3	2.3	0.005
Glu	84.3^{ab}	86.7^{a}	80.8^{bc}	77.7^{c}	80.4^{bc}	84.5^{ab}	84.3^{ab}	84.1	1.4	0.002
Gly	80.1	81.6	72.6	70.9	75.5	79.5	76.1	76.6	4.9	0.539
Ser	83.6^{ab}	86.6^{a}	80.6^{bc}	76.5^{d}	78.3^{cd}	81.1^{bc}	77.8^{cd}	80.6	1.5	<0.001
Tyr	86.8^{ab}	88.0^{a}	83.4^{cd}	82.0^{d}	84.9^{bcd}	85.6^{abc}	85.4^{abc}	85.2	1.0	0.005
Total	89.0^{ab}	91.1^{a}	86.1^{bc}	81.5^{c}	85.9^{bc}	88.7^{ab}	87.5^{ab}	87.1	1.6	0.008
All AA	85.7^{ab}	88.1^{a}	82.8^{b}	78.8^{c}	83.1^{b}	85.0^{ab}	83.8^{b}	83.9	1.3	0.001

$^{a–d}$Within a row means without a common superscript differ ($P < 0.05$).

[1]Each least squares mean for each ingredient represents six observations, respectively.

[2]Values for SID were calculated by correcting the values for apparent ileal digestibility for basal ileal endogenous losses. Basal ileal endogenous losses were determined (g/kg of DMI) as CP, 20.93; Arg, 0.58; His, 0.22; Ile, 0.43; Leu, 0.67; Lys, 0.47; Met, 0.09; Phe, 0.42; Thr, 0.78; Trp, 0.08; Val, 0.57; Ala, 0.68; Asp, 1.00; Cys, 0.30; Glu, 1.10; Gly, 1.70; Ser, 0.63; and Tyr, 0.32.

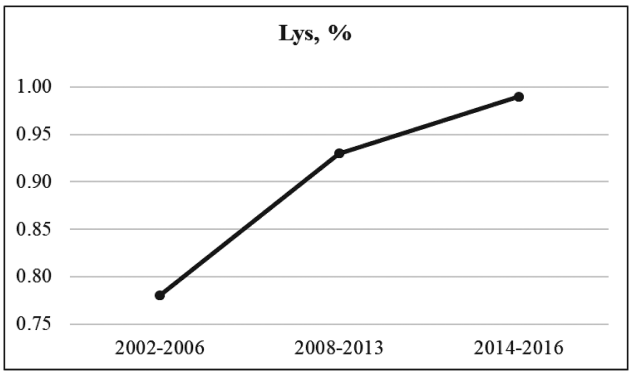

Figure 1. Lysine concentration (%) of distillers dried grains with solubles from 2002 to 2016 (Spiehs et al., 2002; Fastinger and Mahan, 2006; Stein et al., 2006; Pahm et al., 2008; Stein and Shurson, 2009; Urriola et al., 2009; Han and Liu, 2010; Kerr et al., 2013; Curry et al., 2014, 2016).

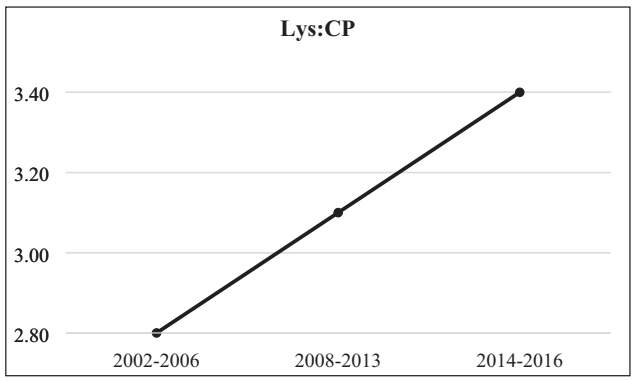

Figure 2. Lysine:crude protein of distillers dried grains with solubles from 2002 to 2016 (Spiehs et al., 2002; Fastinger and Mahan, 2006; Stein et al., 2006; Pahm et al., 2008; Stein and Shurson, 2009; Urriola et al., 2009; Han and Liu, 2010; Kerr et al., 2013; Curry et al., 2014, 2016).

processing, method of fat extraction, and the quality of corn used (Mathew et al., 1999; Urriola et al., 2014). Differences in SID values among suppliers of wheat DDGS, wheat middlings, and rice coproducts have also been reported (Nyachoti et al., 2005; Cozannet et al., 2010; Casas et al., 2015; Casas and Stein, 2017). Thus, it appears that some variability in SID values is common for grain coproducts and not something that is specific to corn DDGS.

In conclusion, values for ME in low-oil DDGS obtained in this experiment are within the range of previous values reported for low-oil DDGS. Values for SID of AA except Lys observed in the seven low-oil sources of DDGS were in agreement with values published for conventional DDGS and do not indicate that removal of oil reduces AA digestibility. The increased concentration and SID of Lys observed in this experiment compared with previously reported values indicate that the ethanol industry continues to reduce heat damage in DDGS, which is also reflected in a greater Lys:CP ratio. Some variability in the nutritional value among sources of DDGS used in this work was observed, which is consistent with what has been reported for other cereal coproducts.

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