The effects of low-, medium-, and high-oil distillers dried grains with solubles on growth performance, nutrient digestibility, and fat quality in finishing pigs[1,2]

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ABSTRACT: A total of 1,480 pigs were used in 3 experiments to determine the effects of corn distillers dried grains with solubles (DDGS) varying in oil content on growth performance, carcass traits, and nutrient digestibility in finishing pigs. In Exp. 1, 1,198 pigs (PIC Line 337 × 1050; initially 46.1 kg) were allotted to a corn–soybean meal–based diet or diets with 20 or 40% of a 5.4% oil DDGS (29.5% CP, 8.9% ADF, and 21.8% NDF; as-fed basis) or a 9.6% oil DDGS (29.6% CP, 15.3% ADF, and 28.6% NDF; as-fed basis). From d 0 to 82, ADG was unaffected by DDGS source or level. However, increasing 5.4% oil DDGS decreased (linear, $P < 0.01$) G:F, whereas G:F did not change among pigs fed 9.6% oil DDGS (DDGS source × level interaction; $P < 0.01$). Regardless of DDGS source, carcass yield and HCW decreased (linear, $P < 0.04$) with increasing DDGS. Increasing DDGS increased jowl iodine value (IV), but the magnitude was greater in pigs fed the 9.6% oil DDGS compared with those fed 5.4% oil DDGS (DDGS source × level interaction; $P < 0.01$). In Exp. 2, 270 pigs (PIC Line 327 × 1050; initially 46.5 kg) were allotted a corn–soybean meal–based diet or diets with 20 or 40% of a 9.4% oil DDGS (29.4% CP, 19.6% ADF, and 34.5% NDF; as-fed basis) or a 12.1% oil DDGS (28.5% CP, 17.6% ADF, and 31.4% NDF; as-fed basis). From d 0 to 75, ADG increased and then decreased for pigs fed 9.4% oil DDGS but was unchanged for pigs fed 12.1% oil DDGS (quadratic interaction, $P < 0.02$). Increasing DDGS increased (linear, $P < 0.01$) jowl IV and tended (linear, $P < 0.07$) to increase G:F. Regardless of source, HCW and carcass yield decreased (linear, $P < 0.05$) as DDGS increased. In Exp. 3, nutrient digestibility of the 4 DDGS sources was determined using pigs fed either a corn-based basal diet (96.6% corn and 3.4% vitamins and minerals) or a DDGS diet with 50% basal diet and 50% DDGS. On an as-fed basis, corn contained 3,871 and 3,515 kcal/kg GE and DE, respectively. The 5.4, 9.6, 9.4, and 12.1% oil DDGS contained 4,347, 4,648, 4,723, and 4,904 kcal/kg (as-fed basis) GE and 3,417, 3,690, 3,838, and 3,734 kcal/kg DE, respectively (as-fed basis). Stepwise regression indicated that the oil (ether extract) content was the only significant variable to explain differences in energy content. The equations generated to predict DE and NE as a function of oil content on an as-fed basis were DE (kcal/kg) = 62.347 × ether extract (%) + 3,058.13 ($n = 5$, adjusted $R^2 = 0.41$) and NE (kcal/kg) = 115.011 × ether extract (%) + 1,501.01 ($n = 5$, adjusted $R^2 = 0.86$).

Key words: corn, distillers dried grains with solubles, digestibility, finishing pigs, growth, iodine value

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INTRODUCTION

Distillers dried grains with solubles (**DDGS**) are a byproduct of the ethanol industry and commonly used to replace portions of corn and soybean meal in swine diets. Traditional DDGS with approximately 10% oil have a relatively similar energy value to that of corn (Stein, 2007). In a review of over 20 papers, Stein and Shurson (2009) concluded that growth performance will not change when feeding DDGS up to 30% of the

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diet; however, carcass characteristics such as carcass yield and jowl iodine value (**IV**) are adversely affected with feeding DDGS, due to the high fiber and unsaturated fatty acid content of DDGS, respectively.

As the value of corn oil has risen, many ethanol plants have implemented oil extraction procedures that recover a greater portion of the corn oil, resulting in DDGS that vary in oil content from approximately 4 to 12% (CEPA, 2011). Because the feeding value of DDGS may be largely based on its energy content, changing the oil content of DDGS may affect growth performance. As a result, NRC (2012) nutrient values for DDGS are based on oil content and are categorized as low (>4% oil), medium (between 6 and 9% oil), or high oil (>10%; NRC, 2012).

Research suggests that variables such as GE, ash, oil (ether extract), ADF, and total dietary fiber are significant in estimating energy values of corn coproducts (Pedersen et al., 2007; Anderson et al., 2012). However, relatively little data is available comparing the feeding value of DDGS containing less than 8% oil.

Therefore, the objectives of these studies were to evaluate the effects of DDGS with varied oil content on finishing pig growth performance, carcass characteristics, and carcass fat quality and to determine the DE content and nutrient digestibility relationships between DDGS sources.

MATERIALS AND METHODS

General

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in these experiments.

Experiment 1 was conducted in a commercial research finishing barn in southwestern Minnesota. The barn was naturally ventilated and double-curtain sided. Pens had completely slatted flooring and deep pits for manure storage. Each pen (5.5 by 3.0 m) was equipped with a 4-hole stainless steel dry self-feeder (Thorp Equipment, Thorp, WI) and a cup waterer providing ad libitum access to feed and water.

Experiment 2 was conducted at the K-State Swine Teaching and Research Center in Manhattan, KS. The facility was a totally enclosed, environmentally regulated, mechanically ventilated barn containing 36 pens (2.4 by 3.1 m). The pens had adjustable gates facing the alleyway, allowing for 0.93 m^2/pig. Each pen was equipped with a cup waterer and a single-sided, dry self-feeder (Farmweld, Teutopolis, IL) with 2 eating spaces located in the fence line. Pens were located over a completely slatted concrete floor with a 1.2-m pit underneath for manure storage. Facilities in both Exp. 1 and 2 were equipped with a computerized feeding system (FeedPro; Feedlogic Corp., Willmar, MN) that delivered and recorded daily feed additions and diets as specified. The equipment provided pigs with ad libitum access to feed and water.

In Exp. 3, pigs were housed in a totally enclosed, environmentally controlled, mechanically ventilated facility containing 12 stainless steel metabolism cages (1.5 by 0.6 m). Each cage was equipped with a feeder as well as a nipple waterer to allow ad libitum access to water and had metal mesh flooring that allowed for total collection of feces.

Animals and Diets

Samples of DDGS from Exp. 1 were taken on delivery of every new batch, whereas DDGS from Exp. 2 were from a single batch of either 9.4 or 12.1% oil DDGS. Corn samples were obtained at the time of diet manufacture for Exp. 1, 2, and 3. These DDGS and corn samples were combined and homogenized and subsamples were taken and analyzed for DM (method 934.01; Horwitz and Latimer, 2006), CP (method 990.03; Horwitz and Latimer, 2006), crude fiber (method 978.10; Horwitz and Latimer, 2006), NDF, and ADF (Van Soest, 1963), and ether extract (method 920.39 A; AOAC, 2007) at a commercial laboratory (Ward Laboratories, Inc., Kearney, NE; Table 1). The AA profile was analyzed at the University of Missouri-Columbia Agricultural Experiment Station Chemical Laboratory (Columbia, MO; Horwitz and Latimer, 2006; Table 1). Fatty acid analyses were conducted on the various DDGS samples at the Kansas State University Analytical Lab (Manhattan, KS; Table 2; Sukhija and Palmquist, 1988).

Samples of every DDGS delivery were collected and a composite sample was used to measure bulk density (Seedburo Model 8800; Seedburo Equipment, Chicago, IL; Table 3). Bulk density of a material represents the weight per unit of volume (g per L). Lastly, particle size was measured on all DDGS sources used (ASABE, 2008; Table 3).

Experiment 1. A total of 1,198 pigs (PIC Line 337 × 1050; Hendersonville, TN; initially 46.1 kg BW) were used in an 82-d growth study to determine the effects of 5.4 or 9.6% oil corn DDGS in finishing diets on growth performance, carcass characteristics, and carcass fat quality. There were 26 or 27 pigs per pen and pens of pigs were randomly allotted to 1 of 5 treatment groups with average pig BW balanced across treatments to provide 9 replications per treatment. All diets were fed in meal form, with treatments delivered over 3 phases (46 to 71, 71 to 105, and 105 to 129 kg; Tables 4, 5, and 6). Pigs were allotted to a corn–soybean meal–based control diet or the control diet with 20 or 40% of the 5.4% oil DDGS source or 9.6% oil DDGS source. Diets were balanced across treatments by phase for standardized ileal digestible (**SID**) Lys and available P but not for energy. At the time of diet formulation, the 2012 NRC publication was

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

	Exp. 1	Exp. 2	Exp. 3	Exp. 1		Exp. 2	
Item, %	Corn	Corn	Corn	5.4% oil DDGS[2]	9.6% oil DDGS	9.4% oil DDGS	12.1% oil DDGS
DM	88.51	89.53	88.03	92.38	91.97	93.17	93.20
CP	8.24	7.96	8.80	29.53	29.63	29.40	28.53
Crude fiber	1.51	1.92	1.82	7.93	11.02	11.25	12.07
ADF	2.93	3.23	2.25	8.90	15.25	19.57	17.57
NDF	5.75	6.77	7.46	21.75	28.58	34.50	31.38
Ash	1.21	1.58	1.49	4.90	3.94	4.65	4.61
Ether extract	3.09	2.50	2.21	5.42	9.58	9.37	12.13
AA, %							
Arg	–	–	–	1.31	1.30	1.38	1.27
Cys	–	–	–	0.57	0.54	0.54	0.46
His	–	–	–	0.79	0.77	0.78	0.69
Ile	–	–	–	1.09	1.13	1.16	1.02
Leu	–	–	–	3.27	3.39	3.42	3.06
Lys	–	–	–	1.03	1.12	1.00	0.90
Met	–	–	–	0.58	0.58	0.54	0.49
Thr	–	–	–	1.10	1.09	1.10	1.02
Trp	–	–	–	0.19	0.22	0.22	0.21
Val	–	–	–	1.40	1.46	1.50	1.34

[1]Values represent the mean of 3 samples analyzed in duplicate.

[2]DDGS = dried distillers grains with solubles.

not available; therefore, total AA and SID coefficients in DDGS from Stein (2007) were used in diet formulation.

On d 61, the 3 heaviest pigs from each pen (determined visually) were weighed and sold in accordance with the farm's normal marketing procedure. Their weight gain was included in the ADG, ADFI, and G:F calculations, but they were not used in carcass data collection. Near the conclusion of the experiment, all remaining pigs were tattooed according to pen number and dietary treatment to allow for carcass data collection and data retrieval by pen. On d 82, 2 medium-weight barrows were selected from each pen and transported approximately 1.5 h to a commercial packing plant (Sioux-Preme Packing Co., Sioux Center, IA) where they were harvested and jowl, backfat, and belly fat samples were collected and analyzed for their fatty acid content. Jowl samples were collected from the distal end of the carcass and belly fat samples were taken along the proximal end of the teat line. Backfat samples were taken midline at the 10th rib, with care taken to sample all 3 layers. Fatty acid analysis was conducted in the University of Nebraska Department of Nutrition and Health Sciences Analytical Lab (Lincoln, NE; Supelco SP-2330, Sigma Aldrich, St Louis, MO). In brief, ground fat (50 µg) was weighed into screw-cap tubes with Teflon-lined caps. Fat (50 µg) was combined with 3 mL of methanolic-HCl and 2 mL of internal standard (2 mg/mL of methyl heptadecanoic acid [C17:0] in benzene) and subsequently heated in a water bath for 120 min at 70°C for transmethylation. Upon cooling, 2 mL of benzene and 3 mL of K_2CO_3 were added, which allowed the methyl esters to be extracted and transferred to a vial for subsequent quantification of the methylated fatty acids by gas chromatography for fatty acid analysis. Injection port and detector temperatures were 250°C with a flow rate of 1 mL/min helium and a split ratio of 100:1. Oven temperature began at 140°C and increased at 2°C/min to 200°C and then at 4°C/min to 245°C and was held for 17 min.

On d 82, the remaining pigs were transported approximately 1 h to a different commercial packing plant (JBS Swift and Company, Worthington, MN) for data collection. Hot carcass weight was measured immediately after evisceration, and carcass yield was calculated as HCW divided by live weight at the plant. Fat depth and loin depth were measured with an optical probe (Fat-O-Meater; SFK Technology A/S, Herlev, Denmark) inserted between the third and fourth last rib (counting from the ham end of the carcass) at a distance approximately 7 cm from the dorsal midline. Fat-free lean index was calculated according to National Pork Producers Council (NPCC, 1991) procedures.

Experiment 2. A total of 270 pigs (PIC Line 327 × 1050; Hendersonville, TN; initially 46.5 kg BW) were used in a 75-d growth study to determine the effects of 9.4 or 12.1% oil corn DDGS in finishing diets on pig growth performance and carcass characteristics. There were 8 pigs per pen and 7 replications per treatment. All diets were fed in meal form and treatments were fed over 3 phases (47 to 73, 73 to 100, and 100 to 122 kg; Tables 4, 5, and 6). Pigs were allotted to a corn–soybean meal–based control diet or the control diet with 20 or 40% of a 9.4% oil DDGS source or a 12.1% oil DDGS source. In this study, NRC (2012) nutrient values for DDGS with greater than 10% oil were used to formulate both DDGS

Table 2. Fatty acid analysis of low- and high-oil distillers dried grains with solubles (DDGS; as-fed basis)

	Exp. 1		Exp. 2	
Item	5.4% oil DDGS	9.6% oil DDGS	9.4% oil DDGS	12.1% oil DDGS
Ether extract, %	5.40	9.6	9.4	12.1
Fatty acids, %				
Myristic (14:0)	0.08	0.08	0.07	0.06
Palmitic (16:0)	14.87	14.65	14.11	13.88
Palmitoleic (16:1)	0.14	0.13	0.13	0.13
Margaric acid (17:0)	0.08	0.08	0.08	0.08
Stearic (18:0)	2.33	2.15	2.01	1.98
Elaidic (18:1*t*9)	0.08	0.07	0.07	0.07
Oleic (18:1*n*9)	26.14	26.57	26.01	25.46
Vaccenic (18:1*n*7)	0.00	0.00	0.00	0.00
Linoleic (18:2)	50.43	52.47	53.85	54.96
Linolenic (ω18:3)	1.54	1.62	1.50	1.44
Arachidic (20:0)	0.41	0.44	0.41	0.38
(20:1*n*9)	0.42	0.44	0.41	0.36
Docosanoic (22:0)	0.23	0.24	0.22	0.22
Erucic (22:1*n*9)	0.04	0.00	0.02	0.00
Lignoceric (24:0)	0.37	0.32	0.33	0.30
Other fatty acids	2.80	0.70	0.74	0.64
Total SFA,[1] %	18.29	17.88	17.15	16.82
Total MUFA,[2] %	41.09	41.29	40.19	39.41
Total PUFA,[3] %	51.97	54.09	55.35	56.4
UFA:SFA ratio[4]	5.09	5.33	5.57	5.70
PUFA:SFA ratio[5]	2.84	3.03	3.23	3.35
Iodine value,[6] %	114.4	118.5	120.1	121.3

[1]Total saturated fatty acids = ([C8:0] + [C10:0] + [C12:0] + [C14:0] + [C16:0] + [C17:0] + [C18:0] +[C20:0] + [C22:0] + [C24:0]); brackets indicate concentration.

[2]Total monounsaturated fatty acids = ([C14:1] + [C16:1] + [C18:1 *cis*-9] + [C18:1*n*-7] + [C20:1] + [C24:1]); brackets indicate concentration.

[3]Total polyunsaturated fatty acids = ([C18:2*n*-6] + [C18:3*n*-3] + [C18:3*n*-6] + [C20:2] + [C20:4*n*-6]); brackets indicate concentration.

[4]Unsaturated fatty acids (UFA):SFA = (total MUFA + total PUFA)/total SFA.

[5]PUFA:SFA = total PUFA/total SFA.

[6]Calculated as iodine value = [C16:1] × 0.95 + [C18:1] × 0.86 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C22:1] × 0.723; brackets indicate concentration.

sources. Diets were formulated above the pig's requirement estimate for AA to avoid limiting growth performance. All pigs and feeders were weighed on d 0, 14, 26, 38, 54, and 75 to determine ADG, ADFI, and G:F.

On d 75, all pigs were weighed and transported approximately 2.5 h to a commercial packing plant (Triumph Foods LLC, St. Joseph, MO) for harvest under USDA inspection. Before slaughter, pigs were individually tattooed to allow for individual carcass data collection at the packing plant. Hot carcass weight was measured immediately after evisceration and each carcass was evaluated for carcass yield, backfat depth, loin depth, percentage lean, and jowl IV. Carcass yield was calculated by dividing HCW at the plant by live weight at the farm before transport to the plant. Fat depth and loin depth were measured with an optical probe (Fat-O-Meater; SFK Technology A/S) inserted

Table 3. Bulk densities and particle size of distiller dried grains with solubles (DDGS) sources (as-fed basis)[1]

	Source and DDGS, %			
	Exp. 1		Exp. 2	
Item	5.4% oil DDGS	9.6% oil DDGS	9.4% oil DDGS	12.1% oil DDGS
Bulk density, g/L[2]	588	549	564	517
Particle size, μ	371	562	744	687

[1]Ingredient samples were taken from every delivery (Exp. 1) and were combined so that a composite sample could be evaluated. In Exp. 2, all diets were made from single batches of both DDGS sources; therefore, a representative sample was analyzed.

[2]Bulk densities represent the weight per unit volume. Diet samples were taken from feeders during each phase.

between the third and fourth last rib (counting from the ham end of the carcass) at a distance approximately 7 cm from the dorsal midline. Jowl fat samples were collected and analyzed by near-infrared spectroscopy (Bruker MPA, Breman, Germany) at the plant for IV using the equation of Cocciardi et al. (2009).

Experiment 3. A total of 12 barrows (PIC Line 327 × 1050; Hendersonville, TN; initially 25.6 kg BW) were used in a 6-wk study to determine nutrient digestibility of corn and of the 4 DDGS sources used in Exp. 1 and 2 and a fifth source of medium-oil DDGS used in a different growth study outlined by Graham et al. (2014). The fifth source used contained 7.6% oil, 30.1% CP, 19.53% ADF, and 36.47% NDF (as-fed basis). The 5 DDGS sources plus the control corn basal diets were evaluated using a replicated Latin square design with 6 pigs assigned to each square to achieve 12 replications per diet. The pigs within each replicate square were randomly allotted to treatment within each period using the PROC PLAN procedure of SAS (SAS Inst. Inc., Cary, NC). The sources of DDGS used in the digestibility study were from the same batches as the corresponding growth experiments. Nutrient digestibility of the DDGS source was determined by feeding either a 96.6% corn-based basal diet (96.6% corn and 3.4% vitamins and minerals) or 50% basal diet and 50% DDGS (Table 7); thus, vitamins and minerals in the test diet were fed at half of the levels fed in the corn basal diet.

Pigs were fed the same amount of each diet for the duration of each 7-d period. Feeding level was 2.5 times maintenance requirements and was determined based on pig BW on d 1 of each period. Daily rations were equally divided between 2 meals fed at 0600 and 1800 h. Each period consisted of 5 d of diet adjustment (10 meals) followed by 2 consecutive days of total fecal collection. A 2-d, timed collection method was used and based on procedures where a 2-d period was used for collection for ileal digesta for AA digestibility or fecal grab samples for determining DE (Jacela et al., 2010b, 2011). On the morning of d 6 (meal 11), pigs were allowed approximately 5 min to stand, drink, and defecate before eating. After that

Table 4. Phase 1 diet compositions (as-fed basis)[1]

	Exp. 1			Exp. 2		
	Control	DDGS source,[2] % inclusion		Control	DDGS source,[3] % inclusion	
Item	0	20	40	0	20	40
Ingredient, %						
Corn	76.16	59.37	41.9	74.21	58.05	41.81
Soybean meal (46.5% CP)	21.45	18.50	15.80	22.88	19.25	15.65
5.4 or 9.6% oil DDGS	–	20.00	40.00	–	–	–
9.4 or 12.1% oil DDGS	–	–	–	–	20.00	40.00
Monocalcium P (21% P)	0.43	0.03	–	0.90	0.45	–
Limestone	0.90	1.10	1.38	0.95	1.2	1.45
Salt	0.35	0.35	0.35	0.35	0.35	0.35
Vitamin/trace mineral premix[4]	0.10	0.10	0.10	0.30	0.30	0.30
L-Lys HCl	0.48	0.53	0.58	0.23	0.27	0.31
DL-Met	0.04	–	–	0.02	–	–
L-Thr	0.07	0.01	–	0.03	–	–
Phytase	0.02	0.01	0.01	0.13	0.13	0.13
Total	100.00	100.00	100.00	100.00	100.00	100.00
Calculated analysis						
Standardized ileal digestible (SID) AA, %						
Lys	0.95	0.95	0.95	0.95	0.95	0.95
Ile:Lys	62	68	75	65	70	74
Leu:Lys	139	179	219	150	177	205
Met:Lys	29	30	34	29	32	37
Met and Cys:Lys	55	59	66	57	61	66
Thr:Lys	60	60	65	61	63	69
Trp:Lys	18	18	18	18	18	18
Val:Lys	69	79	89	75	82	90
Total Lys, %	1.07	1.10	1.13	1.06	1.10	1.14
ME, kcal/kg	3,319	3,270	3,204	3,325	3,332	3,341
SID lys/ME, g/Mcal	2.86	2.91	2.96	2.86	2.85	2.84
CP, %	17.0	19.7	22.5	17.2	19.6	22.0
Ca, %	0.48	0.48	0.57	0.63	0.63	0.63
P, %	0.44	0.44	0.53	0.55	0.53	0.51
Available P, %	0.27	0.27	0.37	0.38	0.38	0.38

[1]Phase 1 diets were fed in meal form from d 0 to 27 (Exp. 1) and d 0 to 26 (Exp. 2).

[2]Diets included both 5.4 and 9.6% oil distillers dried grains with solubles (DDGS) sources fed at 20 and 40% of the diet.

[3]Diets included both 9.4 and 12.1% oil DDGS sources fed at 20 and 40% of the diet.

[4]Provided per kilogram of diet: 8,818 IU vitamin A, 1,102 IU vitamin D_3, 35 IU vitamin E, 3.5 mg vitamin K, 6.6 mg riboflavin, 22 mg pantothenic acid, 40 mg niacin, 0.03 mg vitamin B_{12}, 26.5 g Mn from manganese oxide, 110 g Fe from iron sulfate, 110 g Zn from zinc sulfate, 11 g Cu from copper sulfate, 198 mg I from calcium iodate, and 198 mg Se from sodium selenite. Experiment 2 premix provided per kilogram of complete feed: 13,230 IU of vitamin A, 1,654 IU of vitamin D, 53 IU of vitamin E, 5 mg of vitamin K, 0.05mg of vitamin B_{12}, 60 mg of niacin, 33 mg of pantothenic acid, 10 mg of riboflavin, 17 mg of Cu from $CuSO_4 \cdot 5H_2O$, 0.30 mg of I as $C_2H_2(NH_2)_2 \cdot 2HI$, 110 mg of Fe as $FeSO_4H_2O$, 33 mg of Mn as $MnSO_4 \cdot H_2O$, 0.30 mg of Se as Na_2SeO_3, and 110 mg of Zn as $ZnSO_4$.

time, feces were removed and the morning meal was fed. This meal on the morning of d 6 marked the beginning of the timed fecal collection period. On d 8 of period 1, (d 1 of period 2 or meal 15), the same amount of time was given to pigs, allowing them to stand up, drink, and defecate. Before feeding, all feces were collected, marking the end of the timed collection period. On the same morning that collection ended, pigs were weighed and fed a new treatment diet in a random order. Feces were stored in a freezer (–20°C) until further processing and analysis. At the conclusion of a collection period, all feces for each pig were combined, homogenized, and dried in a in a forced-air oven at 50°C. Samples were finely ground and then subsampled for further analysis following the procedures of Jacela et al. (2010b). Gross energy concentrations of the ingredients, diets, and fecal samples were measured via adiabatic bomb calorimetry (Parr Instruments, Moline, IL). Calculations using the indirect method outlined by Adeola (2001) were used to determine energy values. Ingredients, diets, and feces were also analyzed for DM (method 934.01; Horwitz and Latimer, 2006), CP (method 990.03; Horwitz and Latimer, 2006), crude fiber (method 978.10; Horwitz and Latimer, 2006), NDF (Van Soest. 1963), ADF (Van Soest. 1963), and ether extract (method 920.39 A; Horwitz and Latimer, 2006) at a commercial laboratory (Ward Laboratories, Inc., Kearney, NE).

Table 5. Phase 2 diet compositions (as-fed basis)[1]

	Exp. 1			Exp. 2		
	Control	DDGS source,[2] % inclusion		Control	DDGS source,[3] % inclusion	
Item	0	20	40	0	20	40
Ingredient, %						
Corn	79.75	62.80	45.37	79.52	63.27	47.06
Soybean meal (46.5% CP)	18.09	15.26	12.38	17.74	14.16	10.49
5.4 or 9.6% oil DDGS	–	20.00	40.00	–	–	–
9.4 or 12.1% oil DDGS	–	–	–	–	20.00	40.00
Monocalcium P (21% P)	0.40	–	–	0.80	0.35	–
Limestone	0.90	1.10	1.35	0.98	1.25	1.43
Salt	0.35	0.35	0.35	0.35	0.35	0.35
Vitamin/trace mineral premix[4]	0.10	0.10	0.10	0.25	0.25	0.25
L-Lys HCl	0.35	0.38	0.44	0.20	0.24	0.29
DL-Met	0.01	–	–	0.01	–	–
L-Thr	0.03	–	–	0.02	–	–
Phytase	0.02	0.01	0.01	0.13	0.13	0.13
Total	100.00	100.00	100.00	100.00	100.00	100.00
Calculated analysis						
Standardized ileal digestible (SID) AA, %						
Lys	0.80	0.80	0.80	0.80	0.80	0.80
Ile:Lys	66	74	82	67	72	77
Leu:Lys	156	203	250	163	196	228
Met:Lys	29	33	38	29	35	41
Met and Cys:Lys	58	66	75	60	66	73
Thr:Lys	61	65	71	62	66	73
Trp:Lys	18	18	18	18	18	18
Val:Lys	75	87	98	78	87	96
Total Lys, %	0.91	0.94	0.98	0.90	0.94	0.98
ME, kcal/kg	3,321	3,272	3,208	3,330	3,338	3,345
SID Lys:ME, g/Mkcal	2.41	2.45	2.49	2.40	2.40	2.39
CP, %	15.5	18.3	21.1	15.2	17.6	20.0
Ca, %	0.47	0.47	0.55	0.60	0.61	0.60
P, %	0.42	0.42	0.51	0.51	0.49	0.49
Available P, %	0.26	0.26	0.36	0.35	0.35	0.38

[1]Phase 2 diets were fed in meal form from d 27 to 61 (Exp. 1) and d 26 to 54 (Exp. 2).

[2]Diets included both 5.4 and 9.6% oil distillers dried grains with solubles (DDGS) sources fed at 20 and 40% of the diet.

[3]Diets included both 9.4 and 12.1% oil DDGS sources fed at 20 and 40% of the diet.

[4]Provided per kilogram of diet: 8,818 IU vitamin A, 1,102 IU vitamin D_3, 35 IU vitamin E, 3.5 mg vitamin K, 6.6 mg riboflavin, 22 mg pantothenic acid, 40 mg niacin, 0.03 mg vitamin B_{12}, 26.5 g Mn from manganese oxide, 110 g Fe from iron sulfate, 110 g Zn from zinc sulfate, 11 g Cu from copper sulfate, 198 mg I from calcium iodate, and 198 mg Se from sodium selenite. Experiment 2 premix provided per kilogram of complete feed: 11,023 IU of vitamin A, 1,377 IU of vitamin D, 44.1 IU of vitamin E, 4.4 mg of vitamin K, 0.04 mg of vitamin B_{12}, 50.0 mg of niacin, 27.6 mg of pantothenic acid, 8.3 mg of riboflavin, 14 mg of Cu from $CuSO_4 \cdot 5H_2O$, 0.25 mg of I as $C_2H_2(NH_2)_2 \cdot 2HI$, 92 mg of Fe as $FeSO_4H_2O$, 28 mg of Mn as $MnSO_4 \cdot H_2O$, 0.25 mg of Se as Na_2SeO_3, and 92 mg of Zn as $ZnSO_4$.

Statistical Analysis

Data for the growth experiments was analyzed as a completely randomized design with pen as the experimental unit and treatment as a fixed effect; IV analysis in Exp. 1, however, was analyzed using a completely randomized design with the fixed effect of treatment and the random effect of pen. Analysis of variance was used with the MIXED procedure of SAS (SAS Inst. Inc., Cary, NC). Because HCW differed, it was used as a covariate for backfat, loin depth, and percentage lean. For Exp. 1 and 2, contrasts were used to make comparisons between 1) the linear and quadratic interactions of DDGS source × level, 2) corn–soy and 20 and 40% DDGS- containing diets, and 3) linear and quadratic effects of increasing DDGS. In Exp. 3, period, pig, and Latin square were random effects and treatment was a fixed effect. Single degree of freedom contrasts were used to separate means of pigs fed either the corn- or DDGS-based diet in the nutrient balance study. Differences were considered significant at $P \leq 0.05$ and a trend at $P > 0.05$ and $P \leq 0.10$.

The NE of the DDGS sources was calculated based on the actual growth performance from Exp. 1 and 2 and growth data from the 7.6% oil DDGS from Graham et al. (2014). Net energy efficiency (**NEE**) was determined by

Table 6. Phase 3 diet compositions (as-fed basis)[1]

	Exp. 1			Exp. 2		
	Control	DDGS source,[2] % inclusion		Control	DDGS source,[3] % inclusion	
Item	0	20	40	0	20	40
Ingredient, %						
Corn	76.60	59.36	41.99	83.07	66.89	50.55
Soybean meal (46.5% CP)	21.39	18.58	15.66	14.36	10.76	7.20
5.4 or 9.6% oil DDGS	–	20.00	40.00	–	–	–
9.4 or 12.1% oil DDGS	–	–	–	–	20.00	40.00
Monocalcium P (21% P)	0.15	–	–	0.80	0.30	–
Limestone	0.85	1.10	1.38	0.88	1.15	1.30
Salt	0.35	0.35	0.35	0.35	0.35	0.35
Vitamin/trace mineral premix[4]	0.10	0.10	0.10	0.20	0.20	0.20
L-Lys HCl	0.38	0.43	0.48	0.18	0.22	0.27
DL-Met	0.05	–	–	–	–	–
L-Thr	0.08	0.04	–	0.03	–	–
Phytase	0.02	0.01	0.01	0.13	0.13	0.13
Ractopamine HCl, 20 mg/kg[5]	0.03	0.03	0.03	–	–	–
Total	100	100	100	100	100	100
Standardized ileal digestible (SID) AA, %						
Lys	0.90	0.90	0.90	0.70	0.70	0.70
Ile:Lys	65	72	79	68	75	81
Leu:Lys	148	190	231	175	213	250
Met:Lys	32	31	36	31	38	44
Met and Cys:Lys	59	62	70	63	71	79
Thr:Lys	65	67	69	65	69	76
Trp:Lys	18	18	18	18	18	18
Val:Lys	73	83	94	81	92	102
Total Lys, %	1.02	1.05	1.08	0.79	0.83	0.87
ME, kcal/kg	3,327	3,268	3,204	3,336	3,345	3,352
SID Lys:ME, g/Mkcal	2.70	2.75	2.80	2.10	2.09	2.09
CP, %	16.9	19.7	22.4	13.9	16.3	18.8
Ca, %	0.42	0.48	0.57	0.55	0.56	0.55
P, %	0.38	0.44	0.53	0.50	0.47	0.48
Available P, %	0.21	0.26	0.37	0.35	0.34	0.37

[1]Phase 3 diets were fed in meal form from d 61 to 82 (Exp. 1) and d 54 to 75 (Exp. 2).

[2]Diets included both 5.4 and 9.6% oil distillers dried grains with solubles (DDGS) sources fed at 20 and 40% of the diet.

[3]Diets included both 9.4 and 12.1% oil DDGS sources fed at 20 and 40% of the diet.

[4]Provided per kilogram of diet: 8,818 IU vitamin A, 1,102 IU vitamin D_3, 35 IU vitamin E, 3.5 mg vitamin K, 6.6 mg riboflavin, 22 mg pantothenic acid, 40 mg niacin, 0.03 mg vitamin B_{12}, 26.5 g Mn from manganese oxide, 110 g Fe from iron sulfate, 110 g Zn from zinc sulfate, 11 g Cu from copper sulfate, 198 mg I from calcium iodate, and 198 mg Se from sodium selenite. Experiment 2 premix provided per kilogram of complete feed: 8,802 IU of vitamin A, 1,103 IU of vitamin D, 35 IU of vitamin E, 4 mg of vitamin K, 0.03 mg of vitamin B_{12}, 40 mg of niacin, 22 mg of pantothenic acid, 7 mg of riboflavin, 11 mg of Cu from $CuSO_4 \cdot 5H_2O$, 0.20 mg of I as $C_2H_2(NH_2)_2 \cdot 2HI$, 73 mg of Fe as $FeSO_4H_2O$, 22 mg of Mn as $MnSO_4 \cdot H_2O$, 0.20 mg of Se as Na_2SeO_3, and 73 mg of Zn as $ZnSO_4$.

[5]Paylean (Elanco Animal Health, Greenfield, IN); provided 5 mg/kg ractopamine HCL.

calculating the calories of NE intake in kilocalories per kilogram of gain on a phase basis by solving functions to set the NEE of pigs fed each DDGS source equal to that of those fed the corn–soybean meal control diet. This was done with the assumption that the NE content of corn and soybean meal is 2,672 and 2,087 kcal/kg, respectively (as-fed basis; NRC, 2012). Because pigs were fed different diets based on weight range in a phase feeding regimen (2 or 3 phases per experiment), NEE was calculated by growth performance within each dietary phase. Best-fit equations on each phase NEE value as well as averages of 2 or more phases were fitted to the data for each study. The equation with the slope closest to 0 (indicating relatively equal NNE) was selected for each DDGS source, and that dietary NE content was then used to calculate the NE of DDGS according to the percentage of DDGS in that diet.

The DE and NE for the 5 DDGS sources were used to establish the DE and NE prediction equations using a stepwise regression algorithm (Montgomery et al., 2006). The algorithm used backward elimination procedure with revalidation of the model by adding back single terms to determine best-fit parameters. The adjusted R^2 and the Mallows statistic [C(p)] were used to characterize the best fit equation. Explanatory variables

Table 7. Diet composition, Exp. 3 (as-fed basis)[1]

Ingredient, %	Corn basal diet
Corn	96.90
Limestone	2.30
Salt	0.40
Vitamin premix[2]	0.25
Trace mineral premix[3]	0.15

[1]A total of 12 pigs (PIC 327 × 1050; initially 25.6 kg BW) were used in a 6-wk study to provide 12 observations per treatment. The basal diet was blended 50/50 with the 4 distillers dried grains with solubles sources to provide the other experimental diets.

[2]Provided per kilogram of complete feed: 13,230 IU of vitamin A, 1,654 IU of vitamin D, 53 IU of vitamin E, 5 mg of vitamin K, 0.05mg of vitamin B_{12}, 60 mg of niacin, 33 mg of pantothenic acid, and 10 mg of riboflavin.

[3]Provided per kilogram of complete feed: 17 mg of Cu from $CuSO_4 \cdot 5H_2O$, 0.30 mg of I as $C_2H_2(NH_2)_2 \cdot 2HI$, 110 mg of Fe as $FeSO_4H_2O$, 33 mg of Mn as $MnSO_4 \cdot H_2O$, 0.30 mg of Se as Na_2SeO_3, and 110 mg of Zn as $ZnSO_4$.

evaluated included the linear and quadratic terms for oil (ether extract), CP, crude fiber, ADF, NDF, particle size, and bulk density as well as their 2-way interaction terms. The statistical significance for inclusion of terms in the models was determined at a *P*-value of ≤0.15.

RESULTS

Chemical Analysis

Analyzed samples of DDGS were similar in CP concentrations but varied considerably in fiber content ranging from 7.9 to 12% on an as-fed basis (Table 1). Crude fiber, ADF, and NDF generally increased as oil content increased among the 4 DDGS samples.

According to NRC (2012), the Lys concentrations in low-, medium-, and high-oil DDGS are 0.68, 0.90, and 0.77%, respectively. The analysis of AA on the 5.4, 9.6, 9.4, and 12.1% oil DDGS showed that Lys concentrations were 1.03, 1.12, 1.00, and 0.90%, respectively (Table 1). The analyzed values of Lys from the DDGS sources were greater than those used in diet formulation, so diets containing DDGS contained slightly more Lys and other AA than calculated. Therefore, Lys should not have limited pig performance. The remaining analyzed AA were similar in concentration to values listed in the NRC (2012). Fatty acid profiles for DDGS differing in oil content are not reported in the NRC (2012). Our ingredient analysis would suggest that fatty acid profile will differ slightly depending on oil content of the DDGS with total SFA and MUFA decreasing and total PUFA and IV increasing as oil content of the DDGS is increased (Table 2).

Bulk density decreased within each experiment as oil content increased (Table 3). Particle size varied from 371 to 744 μm in the DDGS used in these experiments.

Table 8. Effects of low- vs. high-oil distillers dried grains with solubles (DDGS) on growth performance of finishing pigs (Exp. 1)[1]

	Control[2]	5.4% oil DDGS		9.6% oil DDGS			5.4% oil DDGS		9.6% oil DDGS		5.4 vs.	DDGS level		Source × level	
Item	0	20	40	20	40	SEM	Linear	Quadratic	Linear	Quadratic	9.6% oil	Linear	Quadratic	Linear	Quadratic
d 0 to 82															
ADG, kg	1.03	1.04	1.02	1.03	1.03	0.01	0.29	0.33	0.73	0.84	0.96	0.42	0.62	0.47	0.36
ADFI, kg	2.60	2.69	2.75	2.58	2.64	0.03	0.002	0.69	0.40	0.36	0.002	0.02	0.73	0.02	0.30
G:F	0.398	0.386	0.370	0.398	0.390	0.004	0.001	0.62	0.21	0.37	0.001	0.001	0.36	0.001	0.76
BW, kg															
d 0	46.18	46.15	46.14	46.18	46.15	0.63	0.96	0.99	0.98	0.98	0.97	0.97	0.99	0.99	0.98
d 82	129.60	129.84	128.54	129.40	129.86	1.09	0.50	0.57	0.87	0.80	0.69	0.77	0.83	0.40	0.52

[1]A total of 1,198 pigs (PIC 337 × 1050) were used in an 82-d study. There were 26 to 27 pigs per pen and 9 pens per treatment.

[2]Refers to the control, corn–soybean meal diet.

Experiment 1

Overall (d 0 to 82), ADG was not affected by DDGS source or level, although there was a DDGS source × level interaction ($P < 0.02$; Table 8) for ADFI and G:F. Increasing 5.4% oil DDGS increased ADFI and decreased G:F but there was no change in ADFI or G:F when pigs were fed increasing amounts of 9.6% oil DDGS. No differences in final BW were observed.

Regardless of DDGS source, carcass yield and HCW decreased (linear, $P < 0.04$) with increasing DDGS (Table 9). As DDGS increased, there was a tendency for loin depth to increase (quadratic, $P = 0.05$), especially in pigs fed the 9.6% oil DDGS source. There were DDGS source × level interactions (linear, $P < 0.02$) observed for jowl, belly, and backfat IV. Increasing DDGS increased jowl, belly and backfat IV, but the magnitude of increase was greater in pigs fed the 9.6% oil DDGS compared with those fed the 5.4% oil DDGS.

Experiment 2

Overall (d 0 to 75), ADG increased in pigs fed 20% of the 9.4% oil DDGS but slightly decreased in those fed 40% DDGS relative to control-fed pigs (Table 10). However, ADG did not differ among pigs fed 12.1% oil DDGS (quadratic interaction, $P < 0.02$). Increasing DDGS, regardless of source, tended (linear, $P < 0.06$) to increase G:F. As DDGS increased, ADFI decreased (linear, $P < 0.04$), regardless of source. Final BW followed the same trend as ADG (quadratic interaction, $P < 0.10$) with the pigs fed 40% of the 9.4% oil DDGS having the lowest final BW among all treatments.

Regardless of source, increasing DDGS decreased (linear, $P < 0.04$) carcass yield and HCW (Table 11). There were no significant differences in backfat depth, loin depth, or percentage lean. Increasing DDGS increased (linear, $P < 0.01$) jowl IV but to a greater extent in pigs fed 12.1% oil DDGS than those fed 9.4% oil DDGS (DDGS source × level interaction; linear, $P < 0.001$) for jowl IV.

Experiment 3

Gross energy values observed for the corn and 5.4, 9.6, 9.4, and 12.1% oil DDGS used in the growth portion of this study were 3,871, 4,347, 4,648, 4,723, and 4,904 kcal/kg, respectively (as-fed basis; Table 12). Based on the corresponding GE digestibility coefficients determined for each DDGS source (Table 13), DE values for the corn and 5.4, 9.6, 9.4, and 12.1% oil DDGS were 3,515, 3,417, 3,690, 3,838, and 3,734 kcal/kg, respectively (as-fed basis). Dry matter digestibility was relatively similar among the 4 DDGS sources (Table 13). Crude protein digestibility was highest in the 9.4 and 9.6% oil DDGS. Digestibility of the ether extract in DDGS was

Table 9. Effects of low- vs. high-oil distillers dried grains with solubles (DDGS) on carcass characteristics of finishing pigs (Exp. 1)[1]

	Control[2]	5.4% oil DDGS		9.6% oil DDGS			5.4% oil DDGS		9.6% oil DDGS		5.4 vs. 9.6%	DDGS level		Source × level	
Item	0	20	40	20	40	SEM	Linear	Quadratic	Linear	Quadratic	oil	Linear	Quadratic	Linear	Quadratic
HCW, kg	95.44	94.03	92.92	93.27	93.83	0.81	0.03	0.88	0.16	0.18	0.93	0.04	0.32	0.43	0.35
Carcass yield, %[3]	76.23	75.99	74.92	75.43	75.21	0.46	0.05	0.47	0.13	0.62	0.78	0.05	0.89	0.66	0.34
Backfat depth, mm[4]	15.58	15.65	15.51	15.33	15.67	0.36	0.89	0.81	0.86	0.50	0.82	0.99	0.77	0.75	0.48
Loin depth, mm[4]	71.62	70.18	70.77	70.05	71.14	0.64	0.36	0.18	0.59	0.09	0.84	0.40	0.05	0.67	0.75
FFLI,[4] %	51.26	51.21	51.29	51.38	51.22	0.17	0.88	0.74	0.89	0.49	0.75	0.99	0.81	0.77	0.43
Jowl IV[5]	67.36	70.92	76.68	72.02	78.73	0.96	<0.001	0.32	<0.001	0.27	0.06	0.001	0.17	0.06	0.96
Belly IV[5]	62.10	67.84	73.52	70.88	76.18	0.96	<0.001	0.98	<0.001	0.11	0.002	0.001	0.29	0.03	0.24
Backfat IV[5]	66.48	70.30	75.79	71.74	78.83	0.74	<0.001	0.34	<0.001	0.25	0.001	0.001	0.94	0.001	0.94

[1]A total of 1,198 pigs (PIC 337 × 1050, initially 46.1 kg) were used in an 82-d study. There were 26 or 27 pigs per pen and 9 pens per treatment.

[2]Refers to the control, corn–soybean meal diet.

[3]Percentage yield was calculated by dividing HCW by live weight obtained at the packing plant.

[4]FFLI = fat-free lean index. Adjusted by using HCW as a covariate.

[5]Calculated as iodine value (IV) = [C16:1] × 0.9502 + [C18:1] × 0.8598 + [C18:2] × 1.7315 + [C18:3] × 2.6152 + [C20:1] × 0.7852 + [C20:4] × 3.2008; brackets indicate concentration.

Table 10. Effects of medium- vs. high-oil distillers dried grains with solubles (DDGS) on growth performance of finishing pigs (Exp. 2)[1]

	DDGS source and percent of diet														
	Control[2]	9.4% oil DDGS		12.1% oil DDGS			9.4% oil DDGS		12.1% oil DDGS		9.4 vs. 12.1%	DDGS level		Source × level	
Item	0	20	40	20	40	SEM	Linear	Quadratic	Linear	Quadratic	oil	Linear	Quadratic	Linear	Quadratic
d 0 to 90															
ADG, kg	1.01	1.05	0.98	1.00	1.00	0.02	0.23	0.01	0.79	0.70	0.34	0.40	0.11	0.34	0.02
ADFI, kg	2.85	2.81	2.68	2.75	2.73	0.05	0.04	0.51	0.14	0.63	0.96	0.04	0.90	0.54	0.38
G:F	0.355	0.375	0.366	0.363	0.368	0.005	0.12	0.03	0.08	0.82	0.31	0.06	0.11	0.85	0.13
BW, kg															
d 0	46.4	46.3	46.4	46.3	46.3	1.3	0.99	0.95	0.93	0.97	0.96	0.95	0.95	0.95	0.99
d 26	72.8	73.8	71.4	72.7	71.8	1.4	0.50	0.35	0.62	0.81	0.80	0.50	0.44	0.86	0.58
d 54	100.6	102.1	97.9	99.7	98.9	1.6	0.22	0.15	0.43	0.99	0.66	0.25	0.35	0.66	0.26
Final BW, kg	122.0	125.1	119.9	121.6	121.9	1.7	0.38	0.06	0.96	0.85	0.66	0.59	0.25	0.41	0.10

[1]A total of 270 pigs (PIC 327 × 1050, initially 46.1 kg BW) were used in a 75-d study. There were 8 pigs per pen and 7 pens per treatment.

[2]Refers to the control, corn–soybean meal treatment.

considerably more variable, ranging from approximately 62 to 76%. In general, the digestibility of ether extract increases as the oil content of DDGS increased, with the exception of the 9.6% oil DDGS used in this study. Acid detergent fiber digestibility of the DDGS sources increased as the oil content increased, with the exception of the 9.4% oil DDGS source that was intermediate. Neutral detergent fiber and crude fiber digestibility did not follow this pattern and varied among sources.

Digestible Energy and NE Prediction Equation Estimates

The equations generated to predict DE and NE as a function of oil content on an as-fed basis were DE (kcal/kg) = 62.347 × ether extract (%) + 3,058.13 (n = 5, adjusted R^2 = 0.41) and NE (kcal/kg) = 115.011 × ether extract (%) + 1,501.01 (n = 5, adjusted R^2 = 0.86; Fig. 1). Using the NRC (2012) NE values for corn and soybean meal, the NE values for the DDGS sources were 2,122, 2,605, 2,582, 2,893, and 2,375 for DDGS sources containing 5.4, 9.6, 9.4, 12.1, and 7.6 % (Graham et al., 2014), respectively.

DISCUSSION

Research has shown that corn DDGS can be fed at up to 30% of the diet without adversely affecting growth performance (Stein and Shurson, 2009). This is because >10% oil DDGS has an energy value similar to that of corn (Stein, 2007). As more oil extraction capabilities are implemented in ethanol plants to harvest a greater portion of the corn oil, reduced-oil DDGS are becoming more abundant in the marketplace. One concern is that the new, reduced-oil DDGS might negatively affect pig growth performance, as was the case in recent research by Graham et al. (2014), where pigs fed increasing medium-oil DDGS (7.6% oil) linearly decreased in ADG and G:F.

The 2012 NRC distinguishes between high- (>10% oil), medium- (>6 and <9% oil), and low-oil (<4% oil) DDGS; however, recent research would suggest that NRC (2012) energy values tend to overestimate medium-oil DDGS values. Graham et al. (2014) observed DE and calculated NE values for DDGS containing 7.6% oil that were lower than the NRC (2012) estimates for medium-oil (>6 and <9% oil) DDGS. The lowest oil DDGS that we fed was above the low-oil classification and below the medium-oil classification established by NRC (2012) and in accordance, our observed DE and ME values were between the NRC (2012) estimates for low- and medium-oil DDGS. However, in the present experiment, the 9.4, 9.6, and 12.1% oil DDGS sources had DE and NE that were all above that reported for high-oil (>10% oil) DDGS by NRC (2012).

Table 11. Effects of medium- vs. high-oil distillers dried grains with solubles (DDGS) on carcass characteristics of finishing pigs (Exp. 2)[1]

	DDGS source and percent of diet														
	Control[2]	9.4% oil DDGS		12.1% oil DDGS			9.4% oil DDGS		12.1% oil DDGS		9.4 vs. 12.1% oil	DDGS level		Source × level	
Item	0	20	40	20	40	SEM	Linear	Quadratic	Linear	Quadratic		Linear	Quadratic	Linear	Quadratic
HCW, kg	88.60	89.20	84.66	87.63	86.77	1.11	0.02	0.06	0.24	0.97	0.81	0.04	0.23	0.18	0.14
Carcass yield, %[3]	72.59	71.94	71.02	72.30	71.16	0.18	0.001	0.54	0.001	0.06	0.17	0.001	0.10	0.59	0.31
Backfat depth,[4] mm	18.59	18.27	18.25	19.06	18.09	0.48	0.62	0.79	0.46	0.23	0.52	0.47	0.53	0.81	0.25
Loin depth,[4] mm	61.28	60.05	59.90	60.17	60.38	0.85	0.26	0.60	0.46	0.54	0.73	0.28	0.45	0.70	0.93
FFLI[4,5], %	51.86	51.93	51.98	51.45	52.10	0.24	0.55	0.72	0.90	0.34	0.76	0.68	0.51	0.77	0.86
Jowl fat IV[6]	66.80	73.08	77.47	73.38	80.01	0.42	0.001	0.07	0.001	0.96	0.002	0.001	0.25	0.0001	0.15

[1]A total of 270 pigs (PIC 327 × 1050, initially 46.5 kg BW) were used in this 75-d study. There were 8 pigs per pen and 7 pens per treatment.

[2]Refers to the control, corn–soybean meal treatment.

[3]Percentage yield was calculated by dividing HCW by live weight obtained at the farm before transport to the packing plant.

[4]Adjusted by using HCW as a covariate.

[5]FFLI = fat-free lean index.

[6]Analyzed by near-infrared spectroscopy (Bruker MPA, Breman, Germany) at the plant for iodine value (IV) using the equation of Cocciardi et al. (2009).

In both Exp. 1 and 2, increasing DDGS, regardless of source, decreased carcass yield. The decrease in carcass yield is consistent with other reports and has been confirmed to be related to increases in intestinal and organ weights from feeding higher fiber diets (Agyekum et al., 2012; Asmus et al., 2014; Graham et al., 2014). However, because the diets were not balanced for CP, the high CP of the DDGS diets may also be a contributing factor. The decrease in HCW and carcass yield agrees with findings by Cook et al. (2005), Whitney et al. (2006), and Linneen et al. (2008); however, they observed decreases in backfat and loin depth with increasing DDGS up to 30% inclusion. Based on their findings, we would have expected to see decreases in backfat and loin depth as well, because up to 40% DDGS were fed in the current study, but this was not the case.

Some DDGS source × level interactions for jowl, backfat, and belly IV were observed in both experiments. In these interactions, IV increased as DDGS increased but to a greater extent in DDGS with the higher oil content. This finding is similar to previous observations (Jacela et al., 2010a; Benz et al., 2010; Asmus et al., 2014), where increasing DDGS increased jowl IV. The increase in IV values for the various fat depots is expected based on the linoleic acid and IV product of the DDGS sources (Benz et al., 2011).

Anderson et al. (2012) and Pedersen et al. (2007) created a series of DE and ME prediction equations based on digestibility trials and measured energy values of a wide variety of corn coproducts. These studies were conducted before the widespread implementation of the oil extraction processes used in the ethanol industry today, so most of DDGS sources used contained greater than 10% oil. In fact, only Anderson et al. (2012) had an oil-extracted DDGS source that contained 2.8% ether extract (as-fed basis). While the work of Stein et al. (2005) had previously established that large amounts of variation exist in the energy content of various sources of DDGS, both studies (Anderson et al., 2012, and Pedersen et al., 2007) determined that stepwise regression could be used to determine prediction equations for DE and ME values of DDGS based on the proximate analysis of the sources. Typical variables for the most significant equations included GE, ash, ether extract, starch, and fiber components such as ADF or total dietary fiber. The hypothesis in the current study was that oil content would be highly significant in predicting energy values of DDGS sources varying considerably in oil content.

Stepwise regression was used to define DE and NE prediction equations based on the 4 DDGS sources used in the growth portion of this study and 1 other source of DDGS outlined by Graham et al. (2014). The DDGS source used in Graham et al. (2014) contained 7.6% oil (as-fed basis) and a DE of 3,356 kcal/kg. The DE content

Table 12. Energy values of corn and distillers dried grains with solubles (DDGS) sources and a 7.6% oil DDGS (Graham et al. 2014; as-fed basis)

		Exp. 1		Exp. 2		Graham et al. (2014)
Item, kcal/kg	Corn	5.4% oil DDGS	9.6% oil DDGS	9.4% oil DDGS	12.1% oil DDGS	7.6% oil DDGS
GE	3,871	4,347	4,648	4,723	4,904	4,585
DE	3,515	3,417	3,690	3,838	3,734	3,356
ME[1]	3,455	3,216	3,488	3,638	3,540	3,153
NE[2]	2,671[3]	2,122	2,605	2,582	2,893	2,375

[1]Eq. [1–6] from NRC (2012).

[2]Based on results of Exp. 3 and estimated NE based on regression analysis determined by estimating NE efficiency from the growth studies.

[3]NRC (2012).

of the corn and the 5 DDGS sources was determined using the digestibility data collected in our third experiment with the 12 pigs housed in metabolism crates. The GE and DE values observed for the corn used in this study, 3,871 and 3,515 kcal/kg (as-fed basis), respectively, compared with published values of 3,993 and 3,451 kcal/kg, respectively (NRC, 2012). Initially, the GE of the diet, ingredients, and feces were determined via bomb calorimetry and apparent total tract digestibility of the energy in the diet was determined based on the total feed intake and feces output on a kilocalories per kilogram basis. The GE values observed for the 5.4, 9.6, 9.4, and 12.1% oil DDGS used in the growth portion of this study were 4,347, 4,648, 4,723, and 4,904 kcal/kg, respectively (as-fed basis; Table 12). These compare to values listed in the NRC (2012) for low-, medium-, and high-oil DDGS of 5,098, 4,710, and 4,849 kcal/kg (as-fed basis), respectively. In contrast to GE values from NRC (2012), those observed in the current study increased as oil content in DDGS increased.

Gross energy digestibility coefficients determined in the current study for 5.4, 9.6, 9.4, and 12.1% oil DDGS were 78.6, 79.4, 81.3, and 76.1%, respectively. The calculated GE digestibility coefficients from low-, medium-, and high-oil DDGS in NRC (2012) are 64.6, 76.1, and 74.7%, respectively. Digestibility of GE in the NRC (2012) is lowest for low-oil DDGS, which is not the case in the current study, but GE digestibility of medium-oil DDGS in the NRC (2012) is greater than that of >10% oil DDGS. The same trend is evident in the current study, as the GE digestibility is decreased in the 12.1% oil DDGS source when compared to the 9.4 and 9.6% oil DDGS sources.

Based on the corresponding GE digestibility coefficients calculated for each DDGS source (Table 13), DE values for the 5.4, 9.6, 9.4, and 12.1% oil DDGS were 3,417, 3,690, 3,838, and 3,734 kcal/kg, respectively (as-fed basis). These DE values compare to values listed in the NRC (2012) for low-, medium-, and high-oil DDGS of 3,291, 3,582, and 3,620 kcal/kg (as-fed basis), respectively. In the current study, similar to NRC (2012) values, DE increases as the oil content of DDGS source increases, with the exception of the 12.1% oil DDGS source, which is intermediate.

When formulating diets containing ingredients that may potentially vary in energy content such as DDGS, assigning accurate energy values is essential to establish feeding values. Caloric efficiency can be calculated to determine if the assigned ingredient energy concentration is accurate. This approach can be applied to all energy systems. If the assigned energy value is correct, regardless of the test ingredient inclusion level, a similar caloric efficiency will be calculated among the dietary treatments. If significant differences in caloric efficiencies of diets containing increasing levels of the test ingredient are observed, the energy level for the ingredient was likely underestimated or overestimated in formulation.

Table 13. Comparison of corn and distillers dried grains with solubles (DDGS) source apparent total tract digestibilities[1]

		Exp. 1		Exp. 2	
Item, %	Corn	5.4% oil DDGS	9.6% oil DDGS	9.4% oil DDGS	12.1% oil DDGS
DM	93.3[a]	70.0[b]	73.6[b]	73.3[b]	71.9[b]
GE	91.1[a]	78.6[bc]	79.4[bc]	81.3[b]	76.1[c]
CP	85.5[a]	78.6[b]	86.3[a]	88.4[a]	76.0[b]
Ether extract	21.8[c]	67.0[ab]	61.8[b]	71.2[ab]	75.6[a]
ADF	59.4[c]	62.8[c]	79.3[ab]	74.9[b]	82.2[a]
NDF	59.9[b]	54.8[bc]	72.0[a]	61.5[b]	51.4[c]
CF[2]	47.4[d]	45.3[d]	53.5[c]	72.1[a]	63.4[b]

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

[1]A total of 12 pigs were used to achieve 12 replications per treatment.

[2]CF = crude fiber.

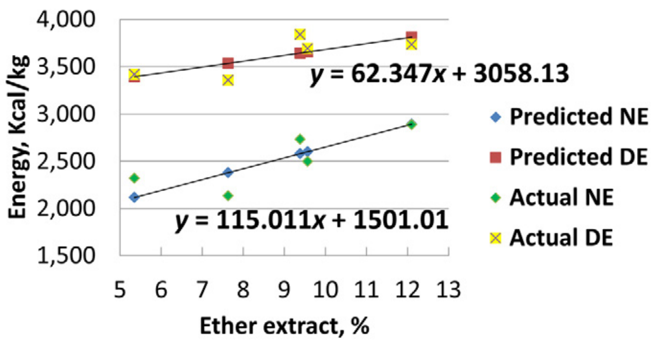

Figure 1. Predicted and measured DE and NE values of distillers dried grains with solubles sources varying in oil content (as-fed basis) using equations created in stepwise regression. DE (n = 5), adjusted R^2 = 0.41; NE (n = 5), adjusted R^2 = 0.86. See online version for figure in color.

National Research Council (NRC, 2012) NE values for corn and soybean meal were used to determine a NEE for the control diets without DDGS. Then, similar NEE was estimated for the diets with increasing DDGS sources. This procedure provided estimated NE values that were then regressed with the various nutrients contained in the DDGS sources resulting in the estimated NE values. Based on the results of the stepwise regression procedure, oil content (ether extract) appeared to be the nutrient best predicting the energy values of the DDGS sources.

Based on results from the growth portion of the current study as well as those of Graham et al. (2014), energy content of DDGS sources should be considered in determining a price relative to corn because of reduced feeding values from the extraction of larger quantities of corn oil from DDGS. The equations generated to predict DE and NE as a function of oil content on an as-fed basis were indicate that changing the oil content 1% in DDGS will result in a DE difference of 62 kcal/kg and NE difference of 115 kcal/kg on an as-fed basis.

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