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Evaluation of ME predictions and the impact of feeding maize distillers dried grains with solubles with variable oil content on growth performance, carcass composition, and pork fat quality of growing-finishing pigs

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ABSTRACT

A total of 432 pigs (initial BW: 25.8 ± 5.1 kg) were used to evaluate growth performance, carcass characteristics, and pork fat quality of growing-finishing pigs fed maize–soybean meal diets containing 40% distillers dried grains with solubles (DDGS) with variable ether extract (EE) content, but similar predicted ME concentration (3232 to 3315 kcal/kg predicted by a commercial service). Pigs were blocked by initial BW, and within blocks, pens were allotted randomly to 1 of 4 dietary treatments (9 pigs/pen, 12 replicates/treatment) in a 4-phase feeding program (26–50 kg, 50–75 kg, 75–100 kg, and 100–120 kg BW). Dietary treatments consisted of: (1) maize–soybean meal (CON); (2) 40% low-oil DDGS (59 g/kg EE; LOW); (3) 40% medium-oil DDGS (99 g/kg EE; MED); and (4) 40% high-oil DDGS (142 g/kg EE; HIGH). Diets contained similar concentrations of standardized ileal digestible amino acids and standardized total tract digestible *P* within each phase. Overall, ADFI of pigs fed CON was greater ($P < 0.05$) than those fed MED and HIGH, resulting in pigs fed CON having greater ($P < 0.05$) overall ADG than pigs fed LOW, MED, and HIGH diets. However, ADFI and ADG did not differ among DDGS treatments, but pigs fed LOW had reduced ($P < 0.05$) G:F compared with the other treatments. Pigs fed CON had greater ($P < 0.05$) HCW, carcass yield, and LM area than those fed the DDGS diets, but there were no differences among DDGS treatments. No treatment differences were observed for backfat depth and percentage of carcass fat-free lean. Back, belly, and jowl fat iodine value of pigs fed LOW and MED were less ($P < 0.01$) than in pigs fed HIGH but greater ($P < 0.01$) than in pigs fed CON. Based on the observed overall G:F responses, dietary ME content of LOW was less than MED, HIGH, and CON diets, indicating a slight overestimation of predicted ME concentration for the low-oil DDGS source using either the commercial service estimates or the Anderson et al. (2012) equations.

Abbreviations: AA, amino acids; ADF, acid detergent fiber; ADFI, average daily feed intake; ADG, agverage daily gain; BF, backfat; BW, body weight; C18:2, linoleic acid; CP, crude protein; DDGS, maize distillers dried grains with solubles; DE, digestible energy; DM, dry matter; EE, ether extract; FFL, carcass fat-free lean; PUFA, polyunsaturated fatty acids; GF, gross energy; G:F, gain to feed; IV, iodine value; LMA, loin muscle area; ME, metabolizable energy; MUFA, monounsaturated fatty acids; NDF, neutral detergent fiber; SFA, saturated fatty acids; SID, standardized ileal digestible; STTD, standardized total tract digestible; TDF, total dietary fiber.

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In conclusion, including 40% DDGS in maize–soybean meal-based diets negatively impacted the growth performance of growing-finishing pigs. However, reduced EE content of DDGS sources did not affect ADG, ADFI, and carcass composition, and led to improvements in pork fat quality. These results suggest that current ME predictions need to be refined for more accurate estimation of ME content for low-oil DDGS sources for swine.

1. Introduction

Maize dried distillers grains with solubles (DDGS) is a widely used alternative feed ingredient in swine diets, with an metabolizable energy (ME) content comparable to maize (Stein and Shurson, 2009). However in recent years, most ethanol plants have been extracting maize oil, thereby producing reduced-oil DDGS. Oil extraction has resulted in large variability in ether extract (EE; 50–120 g/kg) and ME content among DDGS sources (Kerr et al., 2013), which may increase the risk of inaccurate diet formulations. Although the reduction in oil content was expected to reduce ME content of DDGS, Kerr et al. (2013) showed that EE content was a poor predictor of ME content.

Prediction equations (Pedersen et al., 2007; Anderson et al., 2012; Kerr et al., 2013) and a commercial service (ILLUMINATE; Nutriquest, Mason City, IA) have been developed to predict ME content of DDGS sources based on chemical composition. Cross-validation of published equations by Urriola et al. (2014) indicated that using the combination of equations from Anderson et al. (2012): Digestible energy (DE) = −2,161 + (1.39 × gross energy; GE) − (20.7 × neutral detergent fiber; NDF) − (49.3 × EE) and ME = −261 + (1.05 × DE) − (7.89 × crude protein; CP) + (2.47 × NDF) − (4.99 × EE), generated the most accurate and precise ME estimates for DDGS. However, these estimates require validation using growth performance data.

Feeding diets containing a traditional high-oil (>100 g/kg EE) DDGS source reduced belly and pork fat firmness because maize oil contains a high concentration of polyunsaturated fatty acids (PUFA; Stein and Shurson, 2009; Xu et al., 2010a; Davis et al., 2015). Pork fat quality may be improved by feeding DDGS sources with less oil content, but limited data are available to show the magnitude of this improvement. The objectives of this study were to determine the effects of feeding diets containing 40% DDGS with variable oil content on growth performance, carcass traits, and pork fat quality of growing-finishing pigs, and to evaluate the ME predictions for DDGS using the Anderson et al. (2012) equations and ILLUMINATE® estimates.

2. Materials and methods

All experimental procedures in this study were approved by the University of Minnesota Institutional Animal Care and Use Committee (St. Paul, MN).

2.1. Animals and housing

Pigs (416 barrows and 16 gilts) were blocked by initial body weight (BW; 25.8 ± 5.1 kg) and allotted to 12 blocks (4 pens/block; 9 pigs/pen). In blocks 1–4, gender ratio was balanced among pens (8 barrows and 1 gilt), but blocks 5 through 12 were comprised of only barrows. Pigs were housed in an environmentally controlled (20 °C) grower-finisher facility at the University of Minnesota West Central Research and Outreach Center (Morris, MN). Each 1.60 × 4.5 m pen consisted of completely slatted, concrete floors, and was equipped with a nipple waterer and 1 single-sided self-feeder with 4 feeding spaces. Pigs were allowed ad libitum access to feed and water throughout the experiment. Pigs that showed signs of poor health were treated individually with appropriate medication or removed from the experiment.

2.2. Diets and experimental design

ILLUMINATE® (Nutriquest, Mason City, IA) is a proprietary commercial service that uses chemical composition of DDGS sources and prediction equations to estimate DE, ME, net energy (NE), and standardized ileal digestible (SID) amino acid (AA) content of the majority of DDGS sources produced by ethanol plants in the U.S. Results from this ILLUMINATE® service were used to select 3 sources of DDGS with variable oil content, but similar ME concentration, for evaluation in this study. These DDGS sources contained: (1) 58.7 g/kg EE and predicted ME of 3258 kcal/kg for low-oil DDGS (Frontier Ethanol, Gowrie, IA); (2) 98.5 g/kg EE and predicted ME of 3315 kcal/kg for medium-oil DDGS (ADM, Cedar Rapids, IA); and (3) 142.3 g/kg EE and predicted ME of 3232 kcal/kg for high-oil DDGS (Abengoa BioEnergy, Mt. Vernon, IN). All sources of DDGS, maize, and soybean meal were obtained in single lots, and samples were obtained for chemical analyses (Table 1). Results of these analyses were used in diet formulation. Gross energy content of DDGS was determined using bomb calorimetry at the University of Minnesota (Model 1281; Parr Instrument Co., Moline, IL). The estimated ME concentrations for each DDGS source were calculated using the combination of equations from (Anderson et al., 2012): DE = −2,161 + (1.39 × GE) − (20.7 × NDF) − (49.3 × EE) and ME = −261 + (1.05 × DE) − (7.89 × CP) + (2.47 × NDF) − (4.99 × EE). Selection of these equations was based on the results

Table 1
Nutrient composition and physical characteristics of feed ingredients (as-fed basis).

Item, g/kg	Low-oil DDGS[a]	Medium-oil DDGS	High-oil DDGS	Maize	Soybean meal
DM	896.0	896.2	903.4	894.4	896.9
CP	307.1	299.1	285.7	76.0	467.4
Ether extract	58.7	98.5	142.3	47.8	9.8
Ash	45.6	40.3	46.2	12.5	60.7
ADF	81.2	98.8	156.4	22.3	61.0
NDF	283.7	298.0	405.0	98.3	84.4
Total dietary fiber	323.1	330.1	443.7	121.2	120.4
Ca	0.3	0.2	0.2	0.1	4.5
P	8.2	8.0	8.4	2.3	6.1
Starch	73.3	42.1	26.8	638.1	15.0
Essential AA					
Arg	13.0	14.1	13.6	3.7	33.3
His	8.4	8.2	7.9	2.2	12.4
Ile	11.2	11.4	10.8	2.5	21.0
Leu	36.6	36.2	33.7	8.3	35.7
Lys	10.5	10.8	9.9	2.9	30.2
Met	5.8	5.8	6.0	1.6	6.5
Phe	14.6	14.6	13.6	3.4	23.0
Thr	11.4	11.2	10.8	2.7	17.6
Trp	2.4	2.5	2.1	0.7	7.4
Val	15.3	15.8	15.5	3.7	22.9
Non-essential AA					
Ala	21.8	21.2	20.1	5.3	19.7
Asp	19.7	19.3	18.2	5.4	52.7
Cys	5.7	5.2	5.3	1.6	6.6
Glu	45.6	40.7	38.5	12.9	78.0
Gly	11.9	11.6	11.9	3.0	19.1
Hyl	1.1	1.3	1.4	0.2	0.4
Hyp	1.8	2.0	2.3	0.6	0.9
Orn	0.8	0.4	0.4	0.0	0.4
Pro	25.6	22.6	21.4	6.5	23.3
Ser	13.0	12.7	12.0	3.3	19.5
Tau	0.3	0.2	0.2	0.3	0.5
Tyr	10.7	10.8	10.3	2.3	16.0
Particle size, μm	410	350	900	–	–
Bulk density, g/cm^3	0.638	0.631	0.663	–	–
ME[b], kcal/kg	3,258	3,315	3,232	3,395	3,294

[a] Distillers dried grains with solubles (DDGS) containing variable ether extract content but similar predicted ME concentration.
[b] Predicted ME values from a commercial service (ILLUMINATE®; Nutriquest, Mason City, IA) for DDGS sources and recommended ME values from NRC (2012) for maize and soybean meal (dehulled, solvent extracted).

from a cross-validation study conducted by Urriola et al. (2014). Comparison of observed overall gain:feed (G:F) responses among dietary treatments were used to evaluate the ME estimates from ILLUMINATE®, Anderson et al. (2012), and NRC (2012).

Pens of pigs were allotted randomly to 1 of 4 dietary treatments (Tables 2 and 3) in a 4-phase feeding program (25–50 kg, 50–75 kg, 75–100 kg, and 100–120 kg BW for phase 1 to 4, respectively). Phases were switched when average BW of pigs in the pen reached the targeted initial BW ± 2.3 kg of each subsequent phase. Dietary treatments consisted of: (1) maize–soybean meal (CON); (2) CON with 40% low-oil DDGS (LOW); (3) CON with 40% medium-oil DDGS (MED); and (4) CON with 40% high-oil DDGS (HIGH). Diets were not adjusted for dietary ME content, but were formulated to contain similar concentrations of SID AA and standardized total tract digestible (STTD) P within each phase. The coefficients for AA digestibility of DDGS sources were obtained from equations reported by Almeida et al. (2013) based on analyzed AA composition. Energy values and coefficients for SID AA and STTD P of maize and soybean meal were obtained from NRC (2012). All diets met or exceeded the nutrient requirements of growing-finishing pigs from the NRC (2012) model based on growth performance and lean-growth rate of pigs observed in a previous experiment (Song et al., 2013) conducted in the same facilities. During the 2 weeks before the experiment commenced, pigs were double stocked (18 pigs/pen) in one side of the finisher facility and fed a common maize–soybean meal diet until the other side of the facility was prepared for the experiment. As a result, experimental diets were initially offered to pigs at an average BW of 39.3 kg, even though phase 1 diets were formulated for pigs with BW from 25 to 50 kg. Body weight of individual pigs and feed disappearance for each pen were measured every other week to calculate average daily gain (ADG), average daily feed intake (ADFI), and G:F. Feed samples were obtained and frozen (−20 °C) when each batch of feed was mixed, and 4 samples of each treatment (1 sample from each of the 4 phases; 16 samples total) were selected randomly for analysis of nutrient composition.

In the formulation of phase 1 diets, an extra 10 g/kg limestone was mistakenly included at the expense of maize in the LOW diet, which resulted in increased dietary Ca concentration and elevated Ca:P ratio. However, comparison among pigs

Table 2
Phase 1 and 2 diet composition (as-fed basis).

Item	Phase 1 (39–50 kg BW)				Phase 2 (50–75 kg BW)			
	CON[a]	LOW[a]	MED[a]	HIGH[a]	CON	LOW	MED	HIGH
Ingredients, g/kg								
Maize	666.2	470.0	480.0	480.0	722.6	509.4	509.6	508.7
Soybean meal	304.9	85.0	85.0	85.0	252.9	65.0	65.0	65.0
DDGS	–	400.0	400.0	400.0	–	400.0	400.0	400.0
Limestone	11.0	25.8	14.3	14.5	8.9	13.9	14.0	14.0
Monocalcium P (21% P)	10.9	8.5	9.0	8.7	8.9	2.1	2.1	2.1
Salt	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
VTM premix[b]	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
L-Lysine HCl	0.2	4.1	4.3	4.5	0.2	3.0	2.9	3.4
DL-Met	0.2	–	–	–	–	–	–	–
L-Thr	–	–	0.2	0.5	–	–	–	–
L-Trp	–	0.1	0.6	0.4	–	0.1	–	0.3
Total	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0
ME[c], kcal/kg	3,269	3,234	3,248	3,220	3,287	3,296	3,270	3,243
SID Lys[d], g/kg	9.8	9.8	1.01	9.8	8.5	8.5	8.5	8.5
Analyzed composition, g/kg								
DM	871.0	877.1	883.1	883.5	871.1	878.4	878.5	882.6
CP	178.8	200.7	187.6	195.7	181.2	187.0	185.3	185.9
Ether extract	17.1	32.9	44.6	68.0	19.3	36.5	40.9	73.9
Crude fiber	24.2	33.1	36.5	36.5	25.1	35.5	33.2	40.2
ADF	37.5	55.7	60.0	85.5	36.9	54.0	58.2	87.1
NDF	66.4	125.1	137.3	154.2	75.2	138.0	132.2	165.8
Ca	8.9	11.2	7.5	6.3	7.8	6.3	7.1	4.6
P	4.9	6.6	6.3	6.5	4.4	4.9	3.9	5.8
Essential AA, g/kg								
Arg	11.0	9.2	9.5	10.4	11.5	8.7	9.3	9.1
His	4.6	4.9	4.9	5.3	4.7	4.8	4.9	4.9
Ile	7.4	7.4	7.3	8.0	7.8	7.1	7.0	7.1
Leu	15.8	20.4	20.1	21.7	16.3	20.7	20.7	20.4
Lys	9.8	10.6	12.5	11.4	10.3	9.2	9.5	9.1
Met	3.2	3.1	3.0	3.6	2.8	3.3	3.9	3.4
Phe	9.0	9.6	9.4	10.2	9.4	9.4	9.6	9.3
Thr	6.7	7.0	7.4	8.1	6.9	7.2	7.1	7.3
Trp	2.2	1.8	2.2	2.0	2.2	1.7	1.7	1.8
Val	8.1	8.8	8.9	9.6	8.5	8.7	9.0	8.9
Fatty acids, g/kg total lipid								
Linoleic acid	524.0	529.6	527.5	548.2	523.2	525.0	546.6	526.8
SFA[e]	187.6	190.0	184.8	171.3	196.5	181.7	174.0	175.6
MUFA[f]	262.2	262.4	265.0	259.4	250.2	281.5	266.4	280.4
PUFA[g]	553.6	552.9	549.1	566.4	555.7	542.1	562.1	543.1
IV[h]	121.1	120.4	119.8	122.01	120.6	119.6	121.6	119.6

[a] CON = maize–soybean meal control diet; LOW = 40% low-oil distillers dried grains with solubles (DDGS; 59 g/kg ether extract) diet; MED = 40% medium-oil DDGS (99 g/kg ether extract) diet; and HIGH = 40% high-oil DDGS (142 g/kg ether extract) diets.

[b] VTM premix = vitamin-trace mineral premix, which provided the following nutrients per kg of diet: 8,818 IU vitamin A, 1,654 IU vitamin D_3, 33 IU vitamin E, 3.3 mg vitamin K, 5.5 mg riboflavin, 33.1 mg niacin, 22.0 mg pantothenic acid, 0.03 mg vitamin B_{12}, 0.3 mg iodine as ethylenediamine dihydroiodide, 0.3 mg selenium as sodium selenite, 55.1 mg zinc as zinc oxide, 33.1 iron as ferrous sulfate, 5.5 mg manganese as manganous oxide, and 3.9 mg copper as copper sulfate.

[c] Calculated dietary ME based on diet formulation; NRC (2012) recommended ME values were used for maize and soybean meal (dehulled, solvent extracted), and ME estimates from a commercial service (ILLUMINATE®, Nutriquest, Mason City, IA) were used for DDGS sources.

[d] Calculated standardized ileal digestible lysine concentration.

[e] 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.

[f] Total monounsaturated fatty acids = ([C14:1] + [C16:1] + [C18:1 – 9c] + [C18:1 – 11c] + [C20:1] + [C24:1]); brackets indicate concentration.

[g] 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.

[h] Calculated 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 (AOCS, 1998).

fed LOW and other DDGS treatments in phase 1 showed no negative effect of this error in diet formulation on pig growth performance.

2.3. Carcass measurements

Pigs were harvested in 2 groups, with the heavier pigs from blocks 1 through 6 harvested first, followed by pigs from blocks 7 through 12 harvested 8 days later. For each group, when pigs reached market weight, backfat (BF) depth and loin

Table 3
Phase 3 and 4 diet composition (as-fed basis).

Item	Phase 3 (75–100 kg BW)				Phase 4 (100–120 kg BW)			
	CON[a]	LOW[a]	MED[a]	HIGH[a]	CON	LOW	MED	HIGH
Ingredients, g/kg								
Maize	789.5	556.4	556.6	555.3	829.0	563.6	564.4	563.6
Soybean meal	188.9	22.5	22.4	23.0	150.4	16.7	16.0	16.0
DDGS	–	400.0	400.0	400.0	–	400.0	400.0	400.0
Limestone	7.8	12.1	12.2	12.2	7.6	11.7	11.8	11.8
Monocalcium P (21% P)	7.0	–	–	–	6.1	–	–	–
Salt	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
VTM premix[b]	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
L-Lysine HCl	0.3	2.5	2.3	2.8	0.4	1.5	1.3	1.9
L-Trp	–	–	–	0.2	–	–	–	0.2
Total	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0
ME[c], kcal/kg	3,305	3,314	3,288	3,261	3,312	3,314	3,288	3,261
SID Lys[d], g/kg	7.0	7.0	7.0	7.0	6.1	6.1	6.1	6.1
Analyzed composition, g/kg								
DM	870.4	870.7	882.3	877.2	864.9	873.4	879.2	880.6
CP	195.0	172.3	168.9	160.2	136.9	155.9	156.1	159.1
Ether extract	21.0	35.1	47.4	70.2	21.2	32.8	44.9	64.4
Crude fiber	39.0	34.0	36.6	36.8	19.0	31.4	31.7	39.5
ADF	72.5	50.6	60.7	90.7	32.6	43.6	58.5	86.2
NDF	129.0	141.6	142.8	170.7	66.7	133.0	137.0	159.5
Ca	6.4	5.7	5.6	3.9	5.6	6.7	4.2	4.5
P	4.5	4.7	4.5	4.6	4.2	4.1	4.2	4.7
Essential AA, g/kg								
Arg	9.3	7.7	7.6	7.4	7.9	6.8	7.4	7.5
His	4.9	4.5	4.4	4.3	3.5	4.2	4.3	4.1
Ile	7.4	6.5	6.3	6.0	5.5	5.9	6.1	5.8
Leu	20.3	19.9	19.2	18.8	13.2	18.2	19.0	17.5
Lys	9.8	7.7	7.6	6.9	7.1	7.1	6.6	7.0
Met	3.2	3.1	2.8	3.1	2.1	2.7	2.9	2.9
Phe	9.6	8.7	8.4	8.1	7.0	7.9	8.3	7.8
Thr	7.4	6.7	5.8	6.3	4.8	6.1	6.3	5.5
Trp	1.5	1.5	1.3	1.4	1.6	1.3	1.4	1.4
Val	9.0	8.1	7.8	7.8	6.3	7.4	7.6	7.4
Fatty acids, g/kg total lipid								
Linoleic acid	534.5	529.5	537.9	531.6	579.7	522.6	524.9	532.3
SFA[e]	187.7	175.6	173.7	177.0	151.6	180.4	192.7	173.9
MUFA[f]	254.9	277.3	271.8	268.9	249.6	277.7	265.6	275.5
PUFA[g]	555.0	545.6	554.4	550.4	593.7	538.3	546.0	547.6
IV[h]	119.9	119.8	120.8	120.1	125.5	118.5	119.3	119.9

[a] CON = maize–soybean meal control diet; LOW = 40% low-oil distillers dried grains with solubles (DDGS; 59 g/kg ether extract) diet; MED = 40% medium-oil DDGS (99 g/kg ether extract) diet; and HIGH = 40% high-oil DDGS (142 g/kg ether extract) diets.

[b] VTM premix = vitamin-trace mineral premix, which provided the following nutrients per kg of diet: 8,818 IU vitamin A, 1,654 IU vitamin D_3, 33 IU vitamin E, 3.3 mg vitamin K, 5.5 mg riboflavin, 33.1 mg niacin, 22.0 mg pantothenic acid, 0.03 mg vitamin B_{12}, 0.3 mg iodine as ethylenediamine dihydroiodide, 0.3 mg selenium as sodium selenite, 55.1 mg zinc as zinc oxide, 33.1 iron as ferrous sulfate, 5.5 mg manganese as manganous oxide, and 3.9 mg copper as copper sulfate.

[c] Calculated dietary ME based on diet formulation; NRC (2012) recommended ME values were used for maize and soybean meal (dehulled, solvent extracted), and ME estimates from a commercial service (ILLUMINATE®, Nutriquest, Mason City, IA) were used for DDGS sources.

[d] Calculated standardized ileal digestible lysine concentration.

[e] 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.

[f] Total monounsaturated fatty acids = ([C14:1] + [C16:1] + [C18:1 – 9c] + [C18:1 – 11c] + [C20:1] + [C24:1]); brackets indicate concentration.

[g] 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.

[h] Calculated 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 (AOCS, 1998).

muscle area (LMA) were measured between the 10th and 11th ribs using an ALOKA 500 V real-time ultrasound machine (Corometrics Medical Systems, Wallingford, CT) by a certified technician. After ultrasound measurements were obtained, pigs were weighed, tattooed individually, and transported to a commercial abattoir (Hormel Foods; Austin, MN). Hot carcass weight (HCW) was recorded immediately after evisceration and used to calculate carcass yield using the equation: carcass yield, % = HCW/Final BW × 100. Carcasses of 11 pigs were trimmed during USDA inspection, and their HCW data were removed from the dataset. Percentage of carcass fat free lean (FFL) was calculated using the NPPC (2000) equation: FFL,% = {[2.620 + (0.456 × sex of pig) (barrow = 1 and gilt = 2) – (3.358 × 10th rib BF depth, cm) + (0.306 × 10th rib LMA, cm^2) + (0.401 × HCW, kg)]/HCW, kg × 100}.

Table 4
Significance of the effects of dietary treatment and feeding phase on growth performance of growing-finishing pigs.

Source of variation, *P*-value	ADFI	ADG	G:F
Diet	0.017	< 0.01	0.025
Phase	< 0.01	< 0.01	< 0.01
Diet × phase	0.622	0.062	0.061

Samples of BF, belly, and jowl fat ($n = 96$/fat depot) were collected from 2 barrows with a final BW closest to the pen average BW from each pen. Backfat samples were collected from the midline opposite the last rib (included all 3 fat layers), belly fat samples were collected from the midline opposite the last rib on the teat side of the belly, and jowl fat samples were obtained from the anterior tip of the jowl. One jowl fat sample was lost because the carcass was trimmed during USDA inspection. Samples were packaged in Whirlpac bags, stored in a cooler with dry ice, and delivered to the University of Minnesota Swine Nutrition Laboratory within 2 h after collection. All fat samples were frozen with dry ice during transportation to the University of Missouri Agricultural Experiment Station Chemical Laboratory (AESCL; Columbia, MO) for analysis of fatty acid profile.

2.4. Chemical analysis

Five feed ingredient samples (3 sources of DDGS, 1 source of maize, and 1 source of soybean meal) and 16 complete diets were analyzed using AOAC (2006) procedures by AESCL for moisture (Method 934.01), CP (Method 990.03), EE (Method 920.39), crude fiber (Method 978.10), acid detergent fiber (ADF; Method 973.18), NDF (Holst, 1973), total dietary fiber (TDF; Method 985.29), Ca and P (Method 985.01), AA profile (Method 982.30), and starch content (approved methods no. 76-13; AACC, 1995).

Fatty acid composition of BF, belly fat, and jowl fat samples was analyzed (Method 996.06), and iodine value (IV) was calculated using the following equation (AOCS, 1998): $IV = [C16{:}1] \times 0.95 + [C18{:}1] \times 0.86 + [C18{:}2] \times 1.732 + [C18{:}3] \times 2.616 + [C20{:}1] \times 0.785 + [C22{:}1] \times 0.723$, where brackets indicate concentration.

2.5. Statistical analysis

All analyses were conducted using the Proc MIXED procedure (SAS Inst. Inc., Cary, NC) in a randomized complete block design. Pen served as the experimental unit for all data analyses. Growth performance data from each phase were analyzed, and overall ADFI, ADG, and G:F were calculated using a statistical model that included dietary treatment, phase, and dietary treatment × phase interaction as fixed effects, and block as a random effect with repeated measures in phase. For analysis of carcass characteristics, dietary treatment was a fixed effect, block was a random effect, and final BW was used as covariate for BF depth, LMA, and percentage of FFL, if the effect of covariate was significant ($P < 0.05$). The effect of gender in analyses of carcass traits was ignored because of the limited number of gilts ($n = 16$) in the study. Split plot design was used in the analysis of fatty acid profile for pork fat samples, with diet as the whole plot and carcass fat depot as the subplot. The diet × depot interaction was also included in the final statistical analysis. Least-squares means were separated by the PDIFF option when $P < 0.05$, and trends are reported when $0.05 < P < 0.10$.

3. Results

3.1. Growth performance and carcass composition

During the entire feeding period, 8 pigs (1, 2, 2, and 3 pigs from CON, LOW, MED, and HIGH treatments, respectively) were removed from the study due to poor health or death. No diet × phase interaction was observed for ADFI (Table 4). The overall ADFI of pigs fed CON was greater ($P < 0.05$) than MED and HIGH, and tended ($P < 0.10$) to be greater than LOW. However, overall ADFI did not differ among diets formulated with DDGS (Table 5). There was a tendency ($P = 0.06$) for a diet × phase interaction for ADG. In phase 1, pigs fed CON had greater ($P < 0.05$) ADG than pigs fed diets containing DDGS, whereas pigs fed CON had greater ($P < 0.05$) ADG than pigs fed MED and HIGH during phase 2, and LOW and HIGH at the end of phase 3. In phase 4, ADG was not different among dietary treatments. Overall, ADG among pigs fed LOW, MED, and HIGH was not different, but was less ($P < 0.05$) than that of pigs fed CON. There was also a tendency ($P = 0.06$) for a diet × phase interaction for G:F. In phase 1, pigs fed CON had higher ($P < 0.05$) G:F than pigs fed diets containing DDGS. In phase 2 and 3, G:F did not differ among dietary treatments. However, G:F of pigs fed LOW was less ($P < 0.05$) than for pigs fed HIGH, but not for pigs fed CON and MED at the end of phase 4. Overall, pigs fed LOW had slightly reduced ($P < 0.05$) G:F compared with pigs fed CON, MED, and HIGH, but no differences were observed among CON, MED, and HIGH dietary treatments.

As expected, pigs fed CON diets had greater ($P < 0.05$) HCW and carcass yields than pigs fed diets containing 40% DDGS (Table 6). Carcasses of pigs fed CON diets had greater ($P < 0.05$) LMA than carcasses from pigs fed DDGS, but neither BF depth nor percentage of carcass FFL differed in response to dietary treatments.

Table 5
Effects of including 40% distillers dried grains with solubles (DDGS) with variable ether extract (EE) content in the diets offered to growing-finishing pigs on growth performance.

Item		40% DDGS			
	CON[1]	LOW[1]	MED[1]	HIGH[1]	SEM
No. Pens	12	12	12	12	
BW, kg					
Initial[2]	39.24	39.52	38.95	39.58	0.90
Final	122.66[a]	118.65[b]	118.59[b]	119.44[b]	0.90
ADFI, kg/d					
Phase 1	2.06	2.01	1.95	1.98	0.04
Phase 2	2.55[a]	2.48[ab]	2.40[b]	2.43[b]	0.04
Phase 3	3.05[a]	2.93[b]	2.88[b]	2.86[b]	0.04
Phase 4	3.23	3.20	3.21	3.12	0.04
Overall	2.72[a]	2.65[ab]	2.61[b]	2.60[b]	0.03
ADG, kg/d					
Phase 1	0.97[a]	0.87[b]	0.87[b]	0.89[b]	0.02
Phase 2	0.98[a]	0.94[ab]	0.93[b]	0.93[b]	0.02
Phase 3	0.99[a]	0.95[b]	0.95[ab]	0.93[b]	0.02
Phase 4	0.93	0.91	0.95	0.95	0.02
Overall	0.97[a]	0.92[b]	0.92[b]	0.93[b]	0.01
G:F					
Phase 1	0.471[a]	0.436[b]	0.449[b]	0.451[b]	0.006
Phase 2	0.386	0.382	0.386	0.386	0.006
Phase 3	0.326	0.324	0.331	0.326	0.006
Phase 4	0.289[ab]	0.284[b]	0.295[ab]	0.303[a]	0.006
Overall	0.368[a]	0.356[b]	0.365[a]	0.367[a]	0.003

[ab]Means with different superscripts within a row differ ($P < 0.05$).
[1] CON = maize–soybean meal control diet; LOW = low-oil DDGS (59 g/kg EE) diet; MED = medium-oil DDGS (9.9 g/kg EE) diet; and HIGH = high-oil DDGS (14.2 g/kg EE) diet.
[2] Body weight of pigs when feeding experimental diets started.

Table 6
Effects of including 40% distillers dried grains with solubles (DDGS) with variable ether extract (EE) content in the diets offered to growing-finishing pigs on carcass characteristics.

Item		40% DDGS				
	CON[1]	LOW[1]	MED[1]	HIGH[1]	SEM	*P*-value
HCW, kg	90.97[a]	86.69[b]	86.80[b]	87.24[b]	0.88	<0.01
Carcass yield,%	74.2[a]	73.0[b]	72.9[b]	73.0[b]	0.2	<0.01
Backfat depth[2], mm	20.6	19.9	19.2	19.8	0.5	0.288
LM area[2], cm^2	42.06[a]	39.38[b]	39.09[b]	39.37[b]	0.53	<0.01
Fat-free lean[2],%	51.9	51.6	51.9	51.6	0.3	0.858

[ab]Means with different superscripts within a row differ ($P < 0.05$).
[1] CON = maize–soybean meal control diet; LOW = low-oil DDGS (59 g/kg EE) diet; MED = medium-oil DDGS (99 g/kg EE) diet; and HIGH = high-oil DDGS (142 g/kg EE) diets.
[2] Final BW was used as covariate in the statistical analysis.

3.2. Pork fat quality

Regardless of fat depot, fat from CON-fed pigs had the greatest ($P < 0.01$) concentrations of MUFA, and pigs fed LOW and MED diets had greater ($P < 0.01$) MUFA concentrations than pigs fed HIGH diets (Table 7). In addition, MUFA concentration was greater ($P < 0.01$) in belly and jowl fat samples than in BF samples (Table 8).

Dietary treatment × fat depot interactions were observed ($P < 0.01$) for analyses of SFA, linoleic acid (C18:2), PUFA, and IV, which are shown in Figs. 1–4 , respectively. Regardless of fat depot, pigs fed CON had a greater ($P < 0.01$) concentration of SFA than pigs fed diets containing DDGS. The SFA concentrations of BF and belly fat of pigs fed LOW and MED were greater ($P < 0.05$) than that of pigs fed HIGH. However, within jowl fat samples, pigs fed HIGH had lower ($P < 0.05$) concentration of SFA than pigs fed LOW, but was not different compared with pigs fed MED (dietary treatment × fat depot, $P < 0.01$; Fig. 1). For pigs fed CON, SFA concentration in BF was greater ($P < 0.01$) than in belly and jowl fat, and SFA content of belly fat was greater ($P < 0.01$) than in jowl fat. Concentration of SFA in BF or belly fat of pigs fed LOW was not different, but greater ($P < 0.05$) than that of jowl fat. For pigs fed MED, BF contained similar or greater SFA concentration relative to belly or jowl fat, respectively, and no difference was observed between belly and jowl fat. Pigs fed HIGH had similar concentration of SFA among all 3 fat depots.

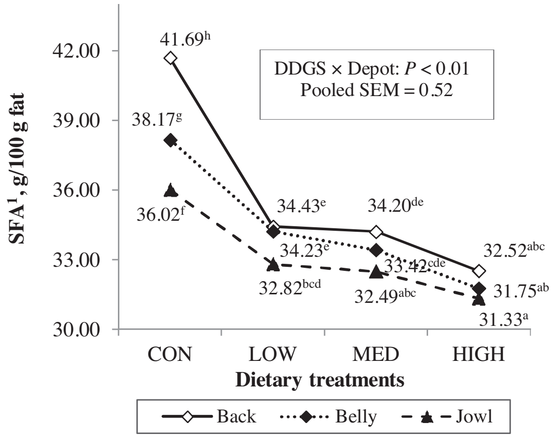

Fig. 1. Effects of dietary dried distillers grains with solubles (DDGS) on SFA concentration of backfat, belly, and jowl fat. Treatments include maize–soybean meal control diet (CON), 40% low-oil DDGS (59 g/kg ether extract; LOW) diet, 40% medium-oil DDGS (99 g/kg ether extract; MED) diet, and 40% high-oil DDGS (142 g/kg ether extract; HIGH) diet. [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. [a–h]Means with different superscripts differ ($P < 0.05$).

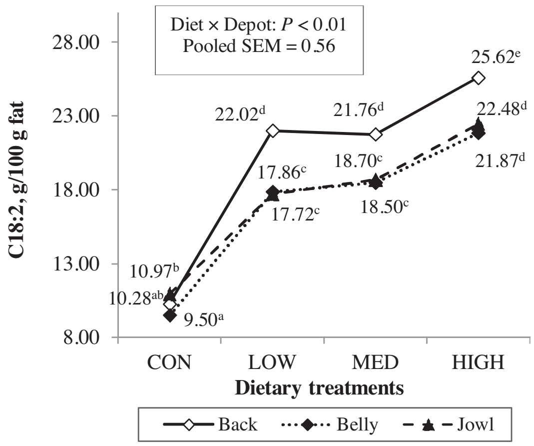

Fig. 2. Effects of dietary dried distillers grains with solubles (DDGS) on linoleic acid (C18:2) concentration of backfat, belly, and jowl fat. Treatments include maize–soybean meal control diet (CON), 40% low-oil DDGS (59 g/kg ether extract; LOW) diet, 40% medium-oil DDGS (99 g/kg ether extract; MED) diet, and 40% high-oil DDGS (142 g/kg ether extract; HIGH) diet. [a–e]Means with different superscripts differ ($P < 0.05$).

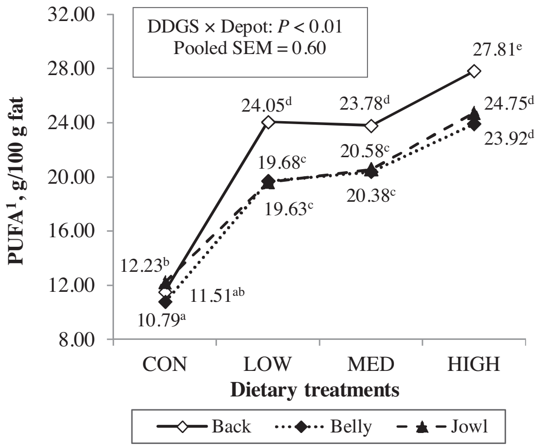

Fig. 3. Effects of dietary dried distillers grains with solubles (DDGS) on PUFA concentration of backfat, belly, and jowl fat. Treatments include maize–soybean meal control diet (CON), 40% low-oil DDGS (59 g/kg ether extract; LOW) diet, 40% medium-oil DDGS (99 g/kg ether extract; MED) diet, and 40% high-oil DDGS (142 g/kg ether extract; HIGH) diet. [1]Total PUFA = ([C18:2n–6] + [C18:3n–3] + [C18:3n-6] + [C20:2] + [C20:4n-6]); brackets indicate concentration. [a–e]Means with different superscripts differ ($P < 0.05$).

Table 7
Effects of including 40% distillers dried grains with solubles (DDGS) with variable ether extract (EE) content in the diets offered to growing-finishing pigs on the fatty acid profile of carcass fat samples (average among backfat, belly, and jowl fat samples).

Item[1]		40% DDGS				
	CON[2]	LOW[2]	MED[2]	HIGH[2]	SEM	P-value
C14:0	1.46[a]	1.29[b]	1.29[b]	1.21[c]	0.03	<0.01
C16:0	24.72[a]	22.05[b]	21.73[b]	20.77[c]	0.21	<0.01
C16:1	2.88[a]	2.26[b]	2.23[b]	1.89[c]	0.09	<0.01
C18:0	11.43[a]	9.45[b]	9.32[b]	8.91[b]	0.20	<0.01
C18:1	40.82[a]	37.53[b]	37.56[b]	35.97[c]	0.32	<0.01
C18:2	10.25[c]	19.20[b]	19.65[b]	23.32[a]	0.45	<0.01
C18:3	0.43[c]	0.56[b]	0.55[b]	0.65[a]	0.03	<0.01
C20:0	0.24	0.24	0.23	0.24	0.01	0.842
C20:1	0.67	0.69	0.69	0.70	0.03	0.939
C20:2	0.49[c]	0.91[b]	0.94[b]	1.06[a]	0.02	<0.01
SFA[3]	38.63[a]	33.83[b]	33.37[b]	31.87[c]	0.37	<0.01
MUFA[4]	48.22[a]	43.59[b]	43.55[b]	41.25[c]	0.42	<0.01
PUFA[5]	11.51[c]	21.12[b]	21.58[b]	25.49[a]	0.48	<0.01
IV[6]	60.03[c]	72.02[b]	72.88[b]	77.42[a]	0.60	<0.01

[a,b,c] Means with different superscripts within a row differ ($P < 0.05$).
[1] Concentrations of fatty acids are expressed as grams of fatty acid/100 g fat. Fatty acids: myristic (C14:0), palmitic (C16:0), palmitoleic (C16:1), stearic (C18:0), oleic (C18:1), linoleic (C18:2), linolenic (C18:3), arachidic (C20:0), gadoleic (C20:1), eicosadienoic (C20:2).
[2] CON = maize–soybean meal control diet; LOW = 40% low-oil DDGS (59 g/kg ether extract) diet; MED = 40% medium-oil DDGS (99 g/kg ether extract) diet; and HIGH = 40% high-oil DDGS (142 g/kg ether extract) diet.
[3] 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.
[4] Total monounsaturated fatty acids = ([C14:1] + [C16:1] + [C18:1 – 9c] + [C18:1 – 11c] + [C20:1] + [C24:1]); brackets indicate concentration.
[5] 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.
[6] Calculated 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 (AOCS, 1998).

Table 8
Effects of anatomical site (fat depot) on the fatty acid profile of carcass fat samples.

Item[1]	Back	Belly	Jowl	SEM	*P*-value
C14:0	1.23[c]	1.43[a]	1.28[b]	0.02	<0.01
C16:0	22.45[a]	22.74[a]	21.76[b]	0.14	<0.01
C16:1	1.78[c]	2.72[a]	2.45[b]	0.06	<0.01
C18:0	10.97[a]	9.20[b]	9.16[b]	0.15	<0.01
C18:1	36.06[c]	38.63[b]	39.21[a]	0.22	<0.01
C18:2	19.92[a]	16.93[b]	17.47[b]	0.28	<0.01
C18:3	0.59[a]	0.56[a]	0.50[b]	0.02	<0.01
C20:0	0.26[a]	0.23[b]	0.22[c]	0.00	<0.01
C20:1	0.70[a]	0.71[a]	0.64[b]	0.02	<0.05
C20:2	0.86[a]	0.79[b]	0.88[a]	0.01	<0.01
SFA[2]	35.71[a]	34.39[b]	33.17[c]	0.26	<0.01
MUFA[3]	41.10[b]	45.56[a]	45.79[a]	0.29	<0.01
PUFA[4]	21.79[a]	18.69[b]	19.30[b]	0.30	<0.01
IV[5]	71.29[a]	69.84[b]	70.64[ab]	0.39	<0.01

[a,b,c] Means with different superscripts within a row differ ($P < 0.05$).
[1] Concentrations of fatty acids are expressed as grams of fatty acid/100 g fat. Fatty acids: myristic (C14:0), palmitic (C16:0), palmitoleic (C16:1), stearic (C18:0), oleic (C18:1), linoleic (C18:2), linolenic (C18:3), arachidic (C20:0), gadoleic (C20:1), eicosadienoic (C20:2).
[2] 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.
[3] Total monounsaturated fatty acids = ([C14:1] + [C16:1] + [C18:1 – 9c] + [C18:1 – 11c] + [C20:1] + [C24:1]); brackets indicate concentration.
[4] 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.
[5] Calculated 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 (AOCS, 1998).

Regardless of fat depot, pigs fed CON had the lowest ($P < 0.01$) concentration of PUFA, and especially linoleic acid (C18:2), whereas C18:2 and total PUFA concentrations in fat depots from pigs fed HIGH was greater ($P < 0.01$) than that of pigs fed LOW and MED diets. In addition, PUFA and C18:2 concentrations in BF samples were greater ($P < 0.01$) compared to jowl and belly fat samples when pigs were fed DDGS. However, when pigs were fed CON diets, jowl fat samples had greater ($P < 0.01$) C18:2 and total PUFA concentrations than belly fat samples, but C18:2 and PUFA content of BF was not different compared with the two other fat depots (dietary treatment × fat depot, $P < 0.01$; Figs. 2 and 3). The results for calculated IV (Fig. 4) followed the same pattern as that for C18:2 and PUFA, except for pigs fed CON where jowl fat had the greatest ($P < 0.05$) IV relative to other depots, and BF IV was lower ($P < 0.01$) than that of belly fat.

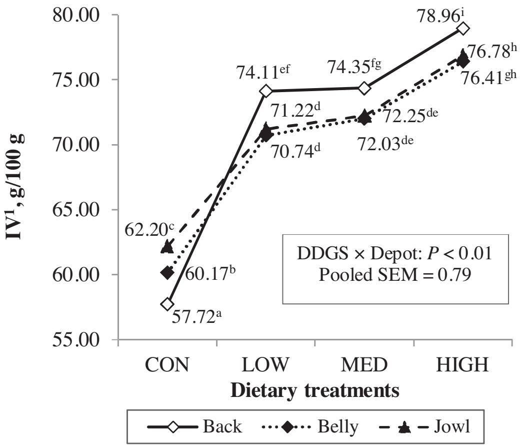

Fig. 4. Effects of dietary dried distillers grains with solubles (DDGS) on iodine value (IV) of backfat, belly, and jowl fat. Treatments include maize–soybean meal control diet (CON), 40% low-oil DDGS (59 g/kg ether extract; LOW) diet, 40% medium-oil DDGS (99 g/kg ether extract; MED) diet, and 40% high-oil DDGS (142 g/kg ether extract; HIGH) diet. [1]Calculated 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 (AOCS, 1998). [a–h]Means with different superscripts differ ($P < 0.05$).

Table 9
Prediction of energy (kcal/kg, as-fed) content for sources of distillers grains with solubles (DDGS) and diets.

Item	Source of estimates	LOW[a]	MED[a]	HIGH[a]	CON[a]
Prediction 1					
DDGS ME	ILLUMINATE®[b]	3258	3315	3232	–
Weighted dietary ME[c]	–	3261	3288	3257	3296
Prediction 2					
DDGS GE	Bomb calorimetry	4607	4703	4940	–
DDGS ME	Anderson et al. (2012)[d]	3349	3286	3215	–
Weighted dietary ME[c]	–	3297	3277	3250	3296
Prediction 3					
DDGS GE	Kerr et al. (2013)[e]	4359	4568	4763	–
DDGS ME	Anderson et al. (2012)	2974	3031	2853	–
Weighted dietary ME[c]	–	3147	3174	3105	3296
Prediction 4					
DDGS ME	NRC (2012)[f]	3396	3434	3434	–
Weighted dietary ME[c]	–	3316	3336	3337	3296

[a] LOW = 40% low-oil DDGS (59 g/kg ether extract) diet; MED = 40% medium-oil DDGS (99 g/kg ether extract) diet; and HIGH = 40% high-oil DDGS (142 g/kg ether extract) diet; CON = maize–soybean meal control diet.
[b] A commercial service provided by Nutriquest (Mason City, IA) that uses chemical composition of DDGS and prediction equations to estimate energy values of the majority of DDGS sources produced by U.S. ethanol plants.
[c] Calculated ME content of diets based on diet formulation; values are presented as the average over 4 phases and weighted for feed disappearance in each phase; NRC (2012) recommended ME values were used for maize and soybean meal (dehulled, solvent extracted).
[d] Refers to $DE = -2{,}161 + (1.39 \times GE) - (20.7 \times NDF) - (49.3 \times EE)$ and $ME = -261 + (1.05 \times DE) - (7.89 \times CP) + (2.47 \times NDF) - (4.99 \times EE)$.
[e] Refers to $GE = 4583 + (50.61 \times EE) - (0.12 \times \text{particle size})$.
[f] Recommended ME of maize DDGS (> 100 g/kg oil) for MED and HIGH, and recommended ME of maize DDGS (>60 and <90 g/kg oil) for LOW.

3.3. Prediction of ME for DDGS

Efficiency of gain (G:F) is a close reflection of dietary energy concentration and therefore, was used as the primary criterion to assess energy estimates of DDGS sources. A detectable difference in overall G:F of 0.01 (SEM = 0.03) was observed in the current study. Predictions from the NRC (2012) growth model suggest that a difference of 80 kcal/kg in dietary ME will alter G:F of pigs by 0.01. Consequently, dietary ME with a variation less than 80 kcal/kg were considered to be similar among the diets fed in this study. This difference in dietary ME content is equivalent to a difference of 200 kcal ME/kg in DDGS because the experimental diets contained 40% DDGS. Therefore, the lower limit of sensitivity for detecting differences in ME concentration in this experiment was 200 kcal/kg.

Using equations from Anderson et al. (2012) and GE inputs determined by bomb calorimetry (prediction 2; Table 9) resulted in similar ME estimates for LOW, MED, and HIGH DDGS sources, and the predicted values were similar to those provided by ILLUMINATE® (prediction 1). Both prediction 1 and 2 resulted in similar dietary ME content between CON and DDGS treatments. Predicted ME values for DDGS based on the combination of $GE = 4583 + (50.61 \times EE) - (0.12 \times \text{particle size}, \mu m)$ from Kerr et al. (2013) and Anderson et al. (2012) equations (prediction 3) were also similar among the 3 sources of DDGS.

However, these estimates were approximately 300 kcal/kg less than the predicted ME content of DDGS using prediction 1 and 2, and consequently, resulted in lower estimated ME content in DDGS diets compared with CON diet. Estimates of ME for DDGS sources from NRC (2012; prediction 4) were similar to those from prediction 1 and 2, and resulted in similar dietary ME among all dietary treatments.

4. Discussion

4.1. Chemical analysis

The high-oil DDGS source used in this study had a maize oil concentration of 14.2%, which was representative of the traditional DDGS sources reviewed by Stein and Shurson (2009) before the U.S. ethanol industry implemented maize oil extraction technologies. In recent years, the majority of ethanol producers in the United States have been partially extracting maize oil prior to manufacturing DDGS, which has resulted in a wide range of EE content (50–120 g/kg; Kerr et al., 2013). The DDGS sources with low- (59 g/kg) and medium-(99 g/kg) oil content used in this study represented the low and high ends of this range. Comparing the nutritional composition (Table 1) of the DDGS sources used in the present study, the concentration of CP and starch increased as EE content declined. Interestingly, high-oil DDGS contained greater concentrations of NDF, ADF, and TDF than low- and medium-oil DDGS, which indicated that fiber content did not increase as expected in the DDGS sources that contained less oil. These observations suggest that with oil extraction, DDGS sources tend to have slightly more CP and starch content, but may not contain a higher fiber concentration than traditional high-oil DDGS sources. It is also important to note that the variation in chemical composition among DDGS sources can also be attributed to the inherent variation in nutrient content of the raw materials used during manufacturing DDGS (Smith et al., 2015).

4.2. Growth performance and carcass composition

Numerous studies have been conducted to evaluate the growth performance of growing-finishing pigs fed diets containing DDGS. In 23 studies reviewed by Stein and Shurson (2009), the majority of studies showed no change in growth performance when up to 30% DDGS was added to growing-finishing pig diets, but 6 studies reported reduced ADFI, and 6 studies showed decreased ADG. Hardman (2013) also reported that overall growth performance was unaffected when 20 and 40% DDGS was included in the diet, but a reduction in ADFI and ADG was observed in pigs fed 60% DDGS compared with those fed maize–soybean meal diets, while G:F was not affected. In the current study, greater overall ADFI was observed for pigs fed CON relative to pigs fed diets containing DDGS, which may be a consequence of a greater fiber concentration in the DDGS diets (134, 137, and 163 g/kg NDF averaged over 4 phases in LOW, MED, and HIGH diets, respectively; Tables 2 and 3) compared with CON (84 g/kg NDF averaged over 4 phases). Diets containing 40% DDGS and elevated NDF content likely increased the gut fill of pigs at lower BW during the early growth phases, which may have resulted in a lower ADFI and ADG of pigs in phases 2 and 3. However, these pigs were able to maintain similar ADFI and ADG with pigs fed CON in the last phase. This observation is in agreement with previous observations (Xu et al., 2010a; Hardman, 2013) that showed a reduction of ADFI and ADG in early feeding phases, but not in late phases, when pigs were fed diets containing 30% or higher inclusion rates of DDGS. The ability of pigs to maintain energy intake from fiber-rich diets appears to be related to the physiological age of the animal and the capacity of the gastrointestinal tract to allow consumption of more feed (Kennelly and Aherne, 1980). According to the observed overall G:F, dietary ME content was similar among CON, MED, and HIGH, but was slightly reduced in LOW. These results suggest that the ME content of the low-oil DDGS source was overestimated in diet formulation. Based on the same overall ADG and ADFI among DDGS treatments, and similar G:F between MED and HIGH, it appears that growth performance of growing-finishing pigs is not affected by variable oil content among sources of DDGS that contain similar predicted ME.

Reduced HCW of pigs fed diets containing DDGS is a result of the reduced ADG and consequently, lower final BW at harvest compared with pigs fed CON. However, reduced LMA was observed for pigs fed DDGS treatments even when final BW was used as a covariate. This observation may have been a result of decreased lysine intake in pigs fed LOW, MED, and HIGH (22.9, 23.6, and 22.4 g/d, respectively) relative to pigs fed CON (25.2 g/d), which may have limited the maximal lean tissue growth potential of pigs fed the DDGS diets. Reduction in carcass yield of pigs fed DDGS diets is consistent with results from previous studies (Linneen et al., 2008; Xu et al., 2010a; Graham et al., 2014) that have also reported decreased carcass yield when 30–45% DDGS was included in growing-finishing diets. Similar to results reported by Xu et al. (2010a), the DDGS sources used in this study contained more than 3 times the dietary NDF content found in maize and soybean meal. Elevated dietary fiber content negatively affects carcass yield by increasing gut fill and intestine and visceral organ weights (Kass et al., 1980; Pond et al., 1988; Agyekum et al., 2012). However, other studies (Widmer et al., 2008; Xu et al., 2010b; Cromwell et al., 2011) have shown that carcass yield was not affected when up to 45% DDGS were added to growing-finishing swine diets.

4.3. Pork fat quality

The dietary treatment × fat depot interactions observed for SFA, C18:2, PUFA, and IV indicated that the magnitude of change in fatty acid content varied among the three anatomical fat depots as the result of feeding different diets (CON vs.

DDGS diets), or the different concentrations of maize oil content in DDGS sources. For SFA, differences among fat depots were more prominent in pigs fed CON compared with the DDGS dietary treatments. Pigs fed DDGS diets consumed more dietary lipid (34.3, 44.5, and 69.1 g/kg EE averaged over all phases in LOW, MED, and HIGH diets, respectively; Tables 2 and 3) than pigs fed CON (19.7 g/kg EE averaged over all phases). Elevated dietary lipid is effective in depressing de novo synthesis of fatty acids, which are generally more saturated, and favors the deposition of fatty acids directly from dietary lipid (Farnworth and Kramer, 1987; Chilliard, 1993). Maize oil present in DDGS contains a high concentration of PUFA (540 g/kg of dietary lipid), but low SFA content (180 g/kg of dietary lipid). Therefore, SFA concentrations in carcass fat depots were markedly reduced in pigs fed DDGS diets, and consequently, differences among fat depots were less prominent compared with pigs fed CON. In contrast, PUFA concentration and IV were greatly increased in fat depots when 40% DDGS was added to diets, which was commonly observed in previous studies (Benz et al., 2010; Jacela et al., 2010; Graham et al., 2014). Among the 3 fat depots, jowl fat has the lowest activity of enzymes for lipogenesis, and fat deposition is more dependent on the composition of dietary lipids (Mourot et al., 1995). Therefore, it was expected that jowl fat would be less saturated and contain greater IV relative to BF and belly fat. However, in the current study, the opposite responses were observed in pigs fed diets containing DDGS, because BF had higher concentrations of linoleic acid, PUFA, and IV compared with belly and jowl fat. The reason for this observation is unclear.

Carcass fat IV was decreased when the oil concentration of DDGS sources was reduced from 142 g/kg to 99 and 59 g/kg. This was mainly due to a decrease in dietary C18:2 intake which was greatest (96.1 g/d averaged over 4 phases) in pigs fed HIGH compared with that from pigs fed MED (62.4 g/d averaged over 4 phases) and LOW (48.3 g/d averaged over 4 phases). Boyd et al. (1997) suggested that the IV threshold of pork fat should be set at 74 to maintain acceptable pork fat quality. In the present study, carcass fat of pigs fed high-oil DDGS had an average IV among depots that exceeded the threshold value of 74, but average carcass fat IV of pigs fed low- and medium-oil DDGS was reduced to an acceptable level (Table 7). However, differences in IV among fat depots should be considered when determining the acceptability of observed IV among diets containing DDGS with different ether extract content.

4.4. Prediction of ME for DDGS

Predicted ME content of DDGS sources was provided by ILLUMINATE® prior to conducting this study. These ME estimates were used as the basis for selecting the 3 sources of DDGS to achieve our goal of obtaining DDGS sources that contained similar ME, but variable EE content. Except for CON, diets were formulated to contain 40% DDGS with similar amounts of maize and soybean meal within phase so that the ME differences among DDGS diets were only related to ME content of the DDGS sources. As a result, calculated dietary ME content was similar (3257–3288 kcal/kg; prediction 1) across DDGS treatments within each phase, and we hypothesized that pigs fed the DDGS diets would have similar overall G:F if ME concentrations of DDGS sources were predicted correctly. The observed overall G:F responses indicated that dietary ME was similar in MED, HIGH, and CON. However, the slight reduction in overall G:F for pigs fed LOW indicated that the low-oil DDGS source may have contained slightly less ME content than other DDGS sources. This was not surprising because all published DE and ME prediction equations evaluated by Urriola et al. (2014) represented very few DDGS samples that contained less than 60 g/kg EE. These results validate the accuracy of ME estimates for medium- and high-oil DDGS from ILLUMINATE® and Anderson et al. (2012) equations (prediction 1 and 2, respectively), but also indicate a slight overestimation of ME content for DDGS containing low oil concentration.

Prediction of ME for DDGS requires an input of the GE content, and is highly dependent on the accuracy of determining the GE concentration (Urriola et al., 2014). Therefore, GE content measured by bomb calorimetry is preferred when using the Anderson et al. (2012) equations compared with using GE prediction equations based on chemical composition (Urriola et al., 2014). However, realizing the difficulties of quickly obtaining actual GE values in commercial feed production operations, equations have also been developed to predict GE concentration of feed ingredients (Ewan, 1989) and DDGS (Anderson et al., 2012; Kerr et al., 2013) based on chemical composition. Unfortunately, Urriola et al. (2014) reported large discrepancies between actual GE measurements and predicted GE values generated by the published GE equations. If these GE prediction equations are used, the equation from Kerr et al. (2013) had the greatest R^2 and least prediction error. Using the combination of the Kerr et al. (2013) GE prediction equation and the Anderson et al. (2012) ME prediction equations (prediction 3) resulted in about 310 kcal/kg less predicted ME content for all 3 DDGS sources compared with estimates from predictions 1 and 2. The lower estimates of ME content in the DDGS sources resulted in about 150 kcal/kg less dietary ME for LOW, MED, and HIGH diets compared with CON diet. These results suggest that ME content for medium- and high-oil DDGS sources will be underestimated using this approach, and laboratory determined GE should be used as the input for the Anderson et al. (2012) equations.

The NRC (2012) categorized sources of maize DDGS into 3 groups based on oil (EE) concentrations: >100 g/kg oil, >60 and <90 g/kg oil, and <40 g/kg oil. The medium-oil (99 g/kg) and high-oil (142 g/kg) DDGS evaluated in the present study fall into the class of DDGS with >100 g/kg oil; whereas, the low-oil (59 g/kg) DDGS is close to the category of DDGS with >60 and <90 g/kg oil. Based on this classification, use of the NRC (2012) estimates for ME content of DDGS (prediction 4) correctly predicted the G:F of pigs fed MED and HIGH based on the comparison to those fed CON. However, using ME values from NRC (2012) based on the current classification of oil concentration, the ME content for DDGS with low oil content would be overestimated.

Energy prediction equations developed in previous studies were either based on data from DDGS with more than 90 g/kg EE (Stein et al., 2006; Pedersen et al., 2007; Stein et al., 2009), or developed for complete diets (Noblet and Perez, 1993). Although Anderson et al. (2012) determined the ME content of a variety of maize co-products with EE content ranging from 1.7 to 121 g/kg, the use of ME estimates from ILLUMINATE® and the robustness of Anderson et al. (2012) ME equations provides acceptable accuracy and precision for estimating ME content of high- and medium-oil DDGS sources, but are not as accurate for estimating ME content of lower oil (<60 g/kg) DDGS sources. In addition, reduced gain efficiency was observed for pigs fed MED and HIGH compared with pigs fed CON in phase 1. This suggests that the ME estimates of medium- and high-oil DDGS for young (<50 kg) pigs were slightly overestimated by ILLUMINATE® and the Anderson et al. (2012) equations. These results are consistent with results from another study (Wu et al., 2016), where DDGS had less energy value in the early growing phase than in finishing phase, which suggested that younger pigs may have less capability to obtain energy from the fiber present in DDGS than older finisher pigs.

5. Conclusions

Growing-finishing pigs fed diets containing 40% DDGS are likely to have slightly depressed feed intake and BW gain relative to pigs fed maize–soybean meal diets, which may be explained by the elevated fiber content in DDGS diets. Among pigs fed DDGS diets, the overall growth performance and carcass characteristics were not affected by the variable oil content of DDGS, as long as their predicted ME contents were similar. Reduction in oil content of DDGS decreased PUFA intake of pigs, and thus, improved pork fat quality by reducing IV of carcass fat depots. Furthermore, the ME content of DDGS with medium and high oil content can be accurately and precisely predicted by ILLUMINATE® or by using the combination of equations from Anderson et al. (2012): $DE = -2{,}161 + (1.39 \times GE) - (20.7 \times NDF) - (49.3 \times EE)$ and $ME = -261 + (1.05 \times DE) - (7.89 \times CP) + (2.47 \times NDF) - (4.99 \times EE)$, with actual GE content measured by bomb calorimetry. Additional chemical composition and ME determinations are needed to refine equations to accurately predict ME content of low-oil (<60 g/kg EE) DDGS sources for swine.

Conflict of interest

All authors declare that we have no actual or potential conflict of interest including any financial, personal, or other relationships that could inappropriately influence, or be perceived to influence this work.

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