Effects of high-protein distillers dried grains on growth performance of nursery pigs

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ABSTRACT: A total of 300 pigs (DNA 400 × 200, Columbus, NE), initially 11.1 kg, were used in a study to evaluate the effects of increasing amounts of high-protein distillers dried grains (HP DDG) on growth performance and to estimate its energy value relative to corn. Pigs were weaned, placed in pens with five pigs each, and fed a common diet for 21 d after weaning. Then, pens were assigned to treatments in a randomized complete block design. There were 5 treatments with 12 replicates per treatment. Treatments consisted of 0, 10, 20, 30, or 40% HP DDG, formulated by changing only the amounts of corn and feed-grade amino acids. Pigs were weighed weekly for 21 d to evaluate average daily gain (ADG), average daily feed intake (ADFI), and gain-to-feed ratio (G:F). Caloric efficiency was obtained by multiplying ADFI by kcal of net energy (NE) per kg of diet and dividing by ADG. The NE values for corn and soybean meal were obtained from NRC (2012), and initial estimates for HP DDG NE were derived from the Noblet et al. (1994) equation. The energy of HP DDG was estimated based on caloric efficiency relative to the diet without HP DDG. Pigs fed diets with increasing HP DDG had a linear decrease ($P < 0.01$) in ADG, ADFI, and final body weight. There was a tendency for a quadratic response ($P = 0.051$) in G:F, with the greatest G:F observed for pigs fed diets with 40% HP DDG. There was a linear reduction ($P < 0.05$) in caloric efficiency with increasing amounts of HP DDG, indicating the initial NE estimate of HP DDG was underestimated. The use of caloric efficiency to estimate the energy value of HP DDG presents several limitations. This approach assumes that the NE values of corn and soybean meal are accurate and does not take into account possible changes in body composition, which can influence the G:F response as leaner pigs are more efficient. In conclusion, increasing HP DDG in the diet linearly decreased ADG and ADFI. Using caloric efficiency to estimate energy content relative to corn, the HP DDG used in this study was estimated to be 97.3% of the energy value of corn. Direct or indirect calorimetry is needed to confirm this value.

Key words: caloric efficiency, growth, high-protein distillers dried grains, swine

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INTRODUCTION

Distillers dried grains with solubles (DDGS) is a co-product of the ethanol industry widely

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used in swine diets. Recently, new processing techniques have been developed to remove non-fermentable components before fermentation (Sekhon et al., 2015) resulting in a high-protein DDG (HP DDG) with approximately 40% crude protein. The HP DDG generated has a different chemical composition and nutritive value than DDGS for swine diets. Therefore, it is important to characterize the nutrient profile of HP DDG and its effects on growth performance. Recently, Rho et al. (2017) determined the standardized ileal digestibility (SID) of amino acids (AA) and digestible energy (DE) content of HP DDG and observed similar AA digestibility coefficients, but approximately 25% greater DE than conventional DDGS. However, growth performance was not evaluated in that study and it is not clear if the greater DE content translates to improved growth performance.

Feeding increasing amounts of an ingredient and using the differences in caloric efficiency to estimate the energy content of the test ingredient relative to a known ingredient, usually corn, has been reported by others and sometimes termed productive energy (Boyd et al., 2010, 2011; Graham et al., 2014; Gonçalves et al., 2016; Estrada et al., 2017). This method is a more practical approach than determining net energy (NE) using direct or indirect calorimetry. Energy estimation from caloric efficiency calculations are done using growth assays under field conditions. Therefore, this method may be more predictive of growth performance than systems based on digestible or metabolizable energy (Cemin et al., 2020). The use of the method presented in the current study to estimate the energy value of HP DDG presents several limitations. This approach assumes that the NE values of corn and soybean meal are accurate and does not take into account possible changes in body composition, which can influence the G:F response as leaner pigs are more efficient (Campbell and Taverner, 1988).

The objective of this study was to determine differences in growth performance of pigs fed increasing amounts of HP DDG in order to estimate its energy content relative to corn.

MATERIALS AND METHODS

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment. The experiment was conducted at the Kansas State University Swine Segregated Early Weaning Facility in Manhattan, KS.

Animals and Diets

Samples of corn, soybean meal, and HP DDG (ICM, Inc., Kolwich, KS) were submitted to the Agricultural Experimental Station Chemical Laboratories (University of Missouri-Columbia, Columbia, MO) for total AA content analysis (method 982.30; AOAC International, 2006) prior to diet formulation (Table 1). The total AA values for corn and soybean meal were multiplied by NRC (2012) SID coefficients and the values for HP DDG were multiplied by Rho et al. (2017) SID coefficients and used in diet formulation. Corn, soybean meal, and HP DDG were also analyzed (Ward Laboratories, Inc., Kearney, NE) for dry matter (DM) (method 935.29; AOAC International, 1990), crude protein (CP) (method 990.03; AOAC International, 1990), acid detergent fiber (ADF) (Ankom, 1998), neutral detergent fiber (NDF) (Ankom, 1998), ether extract (EE) (Ankom, 2004), starch (Xiong et al., 1990), and ash (method 942.05; AOAC International, 1990). A sample of HP DDG was analyzed (North Dakota State University Veterinary Diagnostic Laboratory, Fargo, ND) for mycotoxin concentrations through extraction in acetonitrile and water followed by chromatography/mass spectrometry/mass spectrometry (LC/MS/MS) detection (Table 2).

A total of 300 barrows (DNA 400 × 200, Columbus, NE; initially 11.1 kg) were used in a 21-d growth trial. Pigs were weaned at approximately 21 d of age, placed in pens of five pigs each based on initial body weight (BW), and fed common diets for 21 d. On d 21, which was considered d 0 of the trial, pens of pigs were allotted to one of five treatments in a randomized complete block design with BW as the blocking factor. There were 12 replicates per treatment. Treatments consisted of corn–soybean meal diets with increasing amounts of HP DDG at 0, 10, 20, 30, or 40% of the diet. The addition of HP DDG was made at the expense of corn and feed-grade AA while the amount of soybean meal in the diet was held constant (Table 3). Diets were not balanced for NE content. Each pen (1.2 × 1.2 m) was equipped with a 4-hole, dry self-feeder and a cup waterer to provide ad libitum access to feed and water. Pigs were weighed and feed disappearance was measured weekly to determine average daily gain (ADG), average daily feed intake (ADFI), and gain-to-feed ratio (G:F).

Caloric efficiency was obtained by multiplying ADFI by kcal of NE per kg of diet and dividing by

Table 1. Chemical analysis of corn, soybean meal, and high-protein distillers dried grains (HP DDG; as-fed basis)[1]

Item, %	Corn	Soybean meal	HP DDG
Dry matter	87.1	89.8	91.4
Crude protein	7.4	47.3	39.0
Ether extract	2.7	1.3	8.4
Ash	1.2	5.9	3.1
Neutral detergent fiber	5.8	11.1	36.0
Acid detergent fiber	1.8	9.5	21.3
Starch	59.0	1.2	2.3
Amino acids			
Alanine	0.56	2.01	2.79
Arginine	0.37	3.38	1.64
Aspartic acid	0.53	5.27	2.52
Cysteine	0.19	0.70	0.83
Glutamic acid	1.39	8.48	6.26
Glycine	0.31	2.00	1.54
Histidine	0.22	1.20	1.06
Isoleucine	0.28	2.27	1.67
Leucine	0.88	3.58	4.93
Lysine	0.27	3.01	1.22
Methionine	0.18	0.66	0.83
Phenylalanine	0.38	2.38	2.08
Proline	0.67	2.37	3.21
Serine	0.34	2.01	1.63
Threonine	0.28	1.81	1.47
Tryptophan	0.06	0.63	0.32
Tyrosine	0.23	1.72	1.56
Valine	0.38	2.32	2.05

[1] A sample of each ingredient was obtained, homogenized, and submitted to Ward Laboratories, Inc. (Kearney, NE) for proximate analysis and to the Agricultural Experimental Station Chemical Laboratories (University of Missouri-Columbia, Columbia, MO) for amino acid analysis prior to diet formulation.

Table 2. Mycotoxins analysis of high-protein distillers dried grains (HP DDG)[1]

Mycotoxins	Practical quantitation limit, µg/kg	HP DDG, µg/kg
Aflatoxin B1	20	<20
Aflatoxin B2	20	<20
Aflatoxin G1	20	<20
Aflatoxin G2	20	<20
Deoxynivalenol	200	560
Fumonisin B1	200	<200
Fumonisin B2	200	<200
HT-2 toxin	200	<200
Ochratoxin A	20	<20
T-2 toxin	20	<20
Sterigmatocystin	20	<20
Zearalenone	100	<100

[1] A representative samples of HP DDG were collected, homogenized, and submitted to North Dakota State University Veterinary Diagnostic Laboratory (Fargo, ND) for analysis.

ADG. The NE value for HP DDG was estimated using proximate analysis values by three different methods:

a) Equation 1: DE was estimated from Noblet and Perez (1993) equation as DE, kcal/kg = 4,168 – (9.1 × ash) + (1.9 × CP) + (3.9 × EE) – (3.6 × NDF). This DE value was then used in the Noblet et al. (1994) equation to estimate NE as NE, kcal/kg = (0.700 × DE) + (1.61 × EE) + (0.48 × starch) – (0.91 × CP) – (0.87 × ADF), where all components are expressed as g/kg of DM;
b) Equation 2: DE was estimated from Anderson et al. (2012) equation as DE, kcal/kg = –2,161 + (1.39 × gross energy) – (20.7 × NDF) – (49.3 × EE), where gross energy is expressed as kcal/kg DM and other components are expressed as percentages. This DE value was then used in the Noblet et al. (1994) equation to determine NE;
c) Equation 3: DE value was obtained from Rho et al. (2017; 4,555 kcal/kg DM) and this was used in the Noblet et al. (1994) equation to determine NE.

The equations resulted in energy values on a DM basis, which were then multiplied by the

Table 3. Diet composition (as-fed basis)

	HP DDG[1], %				
Item	0	10	20	30	40
Ingredient, %					
Corn	68.6	59.3	49.7	40.0	30.3
Soybean meal, 47% crude protein	26.5	26.5	26.5	26.5	26.5
HP DDG	—	10.0	20.0	30.0	40.0
Calcium carbonate	0.98	1.05	1.13	1.18	1.25
Monocalcium phosphate, 21.5% P	1.60	1.35	1.15	0.95	0.75
Sodium chloride	0.50	0.50	0.50	0.50	0.50
L-Lysine HCl	0.58	0.51	0.45	0.39	0.33
DL-Methionine	0.22	0.12	0.01	—	—
L-Threonine	0.30	0.21	0.13	0.06	—
L-Tryptophan	0.06	0.05	0.03	0.01	—
L-Valine	0.17	0.04	—	—	—
L-Isoleucine	0.10	—		—	—
L-Histidine	0.06	—	—	—	—
Vitamin premix[2]	0.25	0.25	0.25	0.25	0.25
Trace mineral premix[3]	0.15	0.15	0.15	0.15	0.15
Total	100.0	100.0	100.0	100.0	100.0
Calculated analysis					
SID[4] amino acids, %					
Lysine	1.30	1.30	1.30	1.30	1.30
Isoleucine:lysine	61	61	69	77	85
Leucine:lysine	105	131	157	184	210
Methionine:lysine	37	33	29	33	37
Methionine & cystine:lysine	57	57	57	64	72
Threonine:lysine	65	65	65	65	67
Tryptophan:lysine	19	19	19	19	20
Valine:lysine	70	70	77	86	96
Histidine:lysine	36	36	41	45	50
Net energy[5], kcal/kg	2,437	2,360	2,285	2,212	2,138
Crude protein, %	19.5	22.2	25.1	28.1	31.0
Neutral detergent fiber, %	8.4	11.2	13.9	16.6	19.3
Calcium, %	0.82	0.82	0.82	0.82	0.82
STTD P[6], %	0.45	0.45	0.45	0.45	0.45
Analyzed values, %					
Dry matter	89.0	89.4	89.8	90.0	90.3
Crude protein	19.0	21.7	24.4	27.2	30.1
Neutral detergent fiber	5.2	7.2	10.5	15.4	17.4
Calcium	1.07	0.85	0.93	0.96	0.94
Phosphorus	0.65	0.56	0.57	0.57	0.57

[1] HP DDG, high-protein distillers dried grains.

[2] Provided per kg of diet: 4,134 IU vitamin A; 1,653 IU vitamin D; 44 IU vitamin E; 3 mg vitamin K; 0.03 mg vitamin B12; 50 mg niacin; 28 mg pantothenic acid; 8 mg riboflavin.

[3] Provided per kg of diet: 110 mg Zn from Zn sulfate; 110 mg Fe from iron sulfate; 33 mg Mn from manganese oxide; 17 mg Cu from copper sulfate; 0.30 mg I from calcium iodate; 0.30 mg Se from sodium selenite.

[4] SID, standardized ileal digestible.

[5] Initial net energy estimates were obtained using NRC (2012) values for corn and soybean meal. For HP DDG, digestible energy value was first derived using Noblet and Perez et al. (1993) equation: DE, kcal/kg = 4,168 – (9.1 × ash) + (1.9 × crude protein) + (3.9 × ether extract) – (3.6 × NDF) and net energy value was then derived from Noblet et al. (1994) equation: NE, kcal/kg = (0.700 × digestible energy) + (1.61 × ether extract) + (0.48 × starch) – (0.91 × crude protein) – (0.87 × acid detergent fiber), where all components are expressed as g/kg of dry matter, using analyzed values for ether extract, starch, crude protein, acid detergent fiber, and neutral detergent fiber.

[6] STTD P, standardized total tract digestible phosphorus.

analyzed DM content of HP DDG and presented on an as-fed basis. Corn calculated NE value using Equation (1) was similar to that presented in the NRC (2012), thus it was assigned NE value obtained from the NRC (2012) as 2,672 kcal/kg.

Chemical Analysis

Representative diet samples were obtained from all feeders of each treatment and stored at –20°C until analysis. Samples were analyzed (Ward Laboratories, Inc., Kearney, NE) for DM (method 935.29; AOAC International, 1990), CP (method 990.03; AOAC International, 1990), calcium (method 985.01; AOAC International, 1990), phosphorus (method 985.01; AOAC International, 1990), and NDF (Ankom, 1998).

Statistical Analysis

Data were analyzed as a randomized complete block design with block as a random effect and pen as the experimental unit. Polynomial contrasts were constructed to evaluate the linear and quadratic effects of increasing HP DDG on ADG, ADFI, G:F, BW, and caloric efficiency. Data were analyzed using the GLIMMIX procedure of SAS 9.4 (SAS Institute Inc., Cary, NC). Results were considered significant at $P \leq 0.05$ and a tendency at $0.05 < P \leq 0.10$.

RESULTS AND DISCUSSION

Chemical Analysis

The total AA content of HP DDG was similar to that observed by Rho et al. (2017; Table 1). Mycotoxins were under the detectable values except for deoxynivalenol, which was present at 560 µg/kg (Table 2). The U.S. Food and Drug Administration recommends that feed ingredients contain less than 5,000 µg/kg deoxynivalenol and that these ingredients do not exceed 20% of the diet, for a maximum of 1,000 µg/kg deoxynivalenol in complete feed (FDA, 2010). Therefore, the mycotoxin levels in HP DDG used in this study were not deemed to impact pig performance. The analyzed CP, calcium, phosphorus, and NDF of the complete diets were consistent with formulated values (Table 3).

Growth Performance

Pigs fed diets with increasing HP DDG had a linear decrease ($P < 0.01$) in ADG, ADFI, and final BW (Table 4). There was a tendency ($P = 0.051$) for a quadratic response in G:F, with the greatest value observed for pigs fed the diet with 40% HP DDG. The negative impact of HP DDG on ADG resulted in a decrease (linear, $P < 0.01$) in d 21 BW with increasing HP DDG.

In a recent study, Yang et al. (2019) observed that the inclusion of up to 30% HP DDGS to diets for 7–22-kg pigs linearly decreased growth performance, which is in agreement with our findings. For finishing pigs, Kim et al. (2009) were able to completely replace soybean meal with HP DDG in diets for 58–130-kg pigs without compromising growth performance. However, it should be noted that the HP DDG source as well as age and BW range of pigs used in that experiment were not the same as in the current study.

A potential cause for the decreased growth performance observed in the current study is dietary fiber level. The calculated NDF in our diets ranged from 8.4 to 19.3%. Similarly, Yang et al. (2019) reported an NDF range of 6.3–13.5% with increasing HP DDGS from 0 to 30%. There are no specific requirements for fiber in swine diets, and there may be potential benefits from functional properties of insoluble fiber especially in weaned pigs (Molist et al., 2014). However, dietary fiber may have a negative effect on nutrient digestibility (Schulze et al., 1994) and it is possible that the ability to utilize fiber is lower in young pigs compared with older pigs (Le Goff et al., 2003).

Dietary Thr content also could have influenced the results. The NRC (2012) requirement estimate for 11–25-kg pigs is 59% SID Thr:Lys. However, Mathai et al. (2016) observed that the SID Thr:Lys requirement for ADG is approximately 8% greater (71% vs. 66% SID Thr:Lys) in growing pigs fed high fiber diets, which was most likely driven by greater mucin production and endogenous Thr losses. Therefore, although diets in the current study were well above the NRC (2012) recommendations with 65–67% SID Thr:Lys, Thr could have been limiting in diets with high levels of HP DDG according to Mathai et al. (2016).

Diets formulated with high levels of corn by-products, such as HP DDG, can result in a branched-chain AA (BCAA) imbalance due to the increased Leu content relative to Val and Ile (NRC, 2012). The BCAA are structurally similar and share the first steps of their catabolism. Therefore, excess of one BCAA, particularly Leu, may result in increased degradation of all three BCAA (Harper et al., 1984). The BCAA requirements for nursery pigs have been recently reported as 102–108% SID Leu:Lys (Gloaguen et al., 2013; Wessels et al., 2016), 52% SID Ile:Lys (Soumeh et al., 2014; Clark et al., 2017a), and 63–74% SID Val:Lys (Clark et al., 2017b). However, Val and Ile requirements seem to depend on the dietary Leu level. Htoo et al.

Table 4. Effects of high-protein distillers dried grains (HP DDG) on nursery pig performance[1,2]

	HP DDG, %						Probability, $P <$	
Item[3]	0	10	20	30	40	SEM	Linear	Quadratic
BW, kg								
d 0	11.1	11.1	11.1	11.1	11.1	0.18	0.985	0.814
d 21	22.3	22.6	21.4	21.2	21.4	0.39	0.001	0.366
d 0 to 21								
ADG, g	536	550	493	483	490	12.2	0.001	0.385
ADFI, g	830	855	778	755	746	18.2	0.001	0.715
G:F, g/kg	645	644	634	640	657	7.1	0.365	0.051
CE, kcal/kg gain (Equation (1))[4]	3,782	3,669	3,607	3,463	3,258	38.3	0.001	0.068
CE, kcal/kg gain (Equation (2))[5]	3,782	3,709	3,687	3,584	3,415	39.2	0.001	0.067
CE, kcal/kg gain (Equation (3))[6]	3,782	3,764	3,798	3,747	3,626	40.6	0.014	0.062

[1] A total of 300 pigs were used in a 21-d study with 5 pigs per pen and 12 replicates per treatment.

[2] Diets contained 2,498, 2,414, 2,330, 2,249, and 2,165 kcal/kg calculated net energy, respectively. Net energy values for corn and soybean meal were obtained from NRC (2012) and for HP DDG, digestible energy value was first derived using Noblet and Perez et al. (1993) equation: DE = 4,168 – (9.1 × ash) + (1.9 × crude protein) + (3.9 × ether extract) – (3.6 × NDF) and net energy value was then derived from Noblet et al. (1994) equation: NE = (0.700 × digestible energy) + (1.61 × ether extract) + (0.48 × starch) – (0.91 × crude protein) – (0.87 × acid detergent fiber), using analyzed values for ether extract, starch, crude protein, acid detergent fiber, and neutral detergent fiber.

[3] BW, body weight; ADG, average daily gain; ADFI, average daily feed intake; G:F, gain-to-feed ratio; CE, caloric efficiency.

[4] For CE (Equation (1)), digestible energy value for HP DDG was first derived using Noblet and Perez et al. (1993) equation: DE, kcal/kg = 4,168 – (9.1 × ash) + (1.9 × crude protein) + (3.9 × ether extract) – (3.6 × NDF) and net energy value was then derived from Noblet et al. (1994) equation: NE, kcal kg = (0.700 × digestible energy) + (1.61 × ether extract) + (0.48 × starch) – (0.91 × crude protein) – (0.87 × acid detergent fiber), where all components are expressed as g/kg of dry matter, using analyzed values for ether extract, starch, crude protein, acid detergent fiber, and neutral detergent fiber.

[5] For CE (Equation (2)), digestible energy value for HP DDG was first derived using values were obtained using Anderson et al. (2012) equation: DE, kcal/kg = –2,161 + (1.39 × gross energy) – (20.7 × neutral detergent fiber) – (49.3 × ether extract), where gross energy is expressed as kcal/kg and others are expressed as percentages, and net energy value was then derived from Noblet et al. (1994) equation: NE, kcal/kg = (0.700 × digestible energy) + (1.61 × ether extract) + (0.48 × starch) – (0.91 × crude protein) – (0.87 × acid detergent fiber), where all components are expresses as g/kg of dry matter, using analyzed values for gross energy, ether extract, starch, crude protein, acid detergent fiber, and neutral detergent fiber.

[6] For CE (Equation (3)), digestible energy value for HP DDG was first obtained from Rho et al. (2017; 4,555 kcal/kg of dry matter) and net energy value was then derived from Noblet et al. (1994) equation: NE, kcal/kg = (0.700 × digestible energy) + (1.61 × ether extract) + (0.48 × starch) – (0.91 × crude protein) – (0.87 × acid detergent fiber), where all components are expressed as g/kg of dry matter, using analyzed values for ether extract, starch, crude protein, and acid detergent fiber.

(2017) observed that 8–25-kg pigs fed diets with 110 or 160% SID Leu:Lys have a different SID Ile:Lys requirement of 54 or 58%, respectively. The diets in the current study ranged from 105 to 210% SID Leu:Lys, 61 to 85% SID Ile:Lys, and 70 to 96% SID Val:Lys. It is important to note that while Leu levels were excessive in diets with high amounts of HP DDG, the other BCAA were also well above the estimated requirement. Cemin et al. (2019) determined that the negative effects of high levels of Leu can be counteracted by concomitant increases in Ile, Val, or Trp. Millet et al. (2015) observed that 10–45-kg pigs fed diets with increased Leu concentrations (192% SID Leu:Lys) had decreased growth performance, but the addition of Val effectively counteracted the negative effects of excessive Leu. Thus, it could be hypothesized that the high Leu levels in our diets were at least partially compensated by the concomitant increase in Ile and Val.

Energy Estimation

Using the DE value (3,298 kcal/kg) estimated by Equation (1) resulted in a NE estimate of 1,914 kcal/kg for HP DDG. The DE value (3,663 kcal/kg) from Equation (2) resulted in a slightly greater estimate of 2,170 kcal/kg NE. Using the DE energy value (4,162 kcal/kg) from Rho et al. (2017) in Equation (3) resulted in the greatest NE estimate of 2,519 kcal/kg. The NE for soybean meal and corn used in diet formulation were obtained from the NRC (2012), thus these values were used to estimate the energy value of HP DDG.

The use of the method presented in the current study to estimate the energy value of HP DDG presents several limitations. This approach assumes that the NE values of corn and soybean meal are accurate. Also, the current study did not measure body composition changes, which can influence the G:F response as leaner pigs are more efficient (Campbell and Taverner, 1988).

All equations resulted in similar responses in caloric efficiency, with a decrease (linear, $P \leq 0.014$; quadratic, $P \leq 0.062$) in caloric efficiency as HP DDG increased. This result suggests that in order to obtain a caloric efficiency similar to the corn-soybean meal diet, the energy value of HP DDG would need to be 97.3% of the energy value of corn. If corn NE is assumed to be 2,672 kcal/kg (NRC, 2012), HP DDG would have a NE estimate of 2,600 kcal/kg. In comparison, the initial energy value of HP DDG was estimated as 71.6% of corn NE using Equation (1), 81.2% of corn NE using Equation (2), and 94.3% of corn NE using Equation (3).

Energy is the most expensive component of swine diets. Therefore, it is critical to accurately determine the energy content of feed ingredients and its availability to the animal. This is especially true for novel alternative feedstuffs that are available to the swine industry and can be important cost-effective alternatives to traditional corn-soybean meal-based diets. The NE system has the highest correlation to performance compared with digestible or metabolizable energy systems (Nitikanchana et al., 2015). However, direct measurement of NE is highly specialized and labor intensive. The utilization of caloric efficiency to estimate the energy value of a test ingredient relative to a known ingredient, typically corn, is sometimes termed productive energy (Boyd et al., 2010, 2011; Estrada et al., 2017). This method was developed as a more practical approach to energy estimations of any ingredient (Gonçalves et al., 2016). Under or overestimation of an energy value can be detected if pigs fed diets with increasing amounts of the test ingredient present differences in caloric efficiency (De Jong et al., 2014). In the current study, caloric efficiency linearly decreased with increasing HP DDG, indicating that the initial energy value of HP DDG was underestimated. The closest energy estimate was obtained using actual DE values determined by Rho et al. (2017) in combination with the Noblet et al. (1994) equation. Using the DE value estimated by Noblet and Perez (1993) equation in the Noblet et al. (1994) equation or the DE equation of Anderson et al. (2012) coupled with the Noblet et al. (1994) equation underestimated HP DDG energy, which may be driven by the equations too severely penalizing HP DDG due to its high CP and fiber concentrations.

In conclusion, feeding diets with increasing HP DDG resulted in a linear decrease ADG and ADFI. The caloric efficiency indicates that the initial HP DDG energy value was underestimated and that using this method the energy value of HP DDG in this study was estimated to be approximately 97% of the energy value of corn. Direct or indirect calorimetry is needed to confirm this value.

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