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Non Ruminant Nutrition

NON RUMINANT NUTRITION

A new source of high-protein distillers dried grains with solubles (DDGS) has greater digestibility of amino acids and energy, but less digestibility of phosphorus, than de-oiled DDGS when fed to growing pigs

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Abstract

Three experiments were conducted to test the hypothesis that standardized ileal digestibility (**SID**) of amino acids (**AA**), concentration of metabolizable (**ME**), and standardized total tract digestibility (**STTD**) of P in a new source of distillers dried grains with solubles (**DDGS**; ProCap DDGS) are greater than in conventional de-oiled DDGS. In experiment 1, nine barrows (initial BW: 67.2 ± 6.4 kg) with a T-cannula in the distal ileum were allotted to a triplicated 3 × 3 Latin square design with three diets and three periods for a total of nine replicate pigs per diet. Two diets included ProCap DDGS or de-oiled DDGS as the sole source of crude protein (**CP**) and AA. An N-free diet was used to determine the basal endogenous losses of CP and AA. Ileal digesta were collected on days 5 and 6 of each period after 4 d of adaptation to diets. Results from experiment 1 indicated that ProCap DDGS contained more CP and AA compared with de-oiled DDGS. The SID of all AA in ProCap DDGS was greater ($P < 0.001$) compared with de-oiled DDGS with the exception that the SID of Pro was not different between the two sources of DDGS. In experiment 2, 24 growing barrows (initial BW: 32.7 ± 3.1 kg) were housed individually in metabolism crates and used in a randomized complete block design and fed a corn-based diet or two diets containing corn and each source of DDGS with eight replicate pigs per diet. Fecal and urine samples were collected for 4 d after 7 d of adaptation. Results from experiment 2 indicated that concentration of ME in ProCap DDGS was greater ($P < 0.05$) compared with corn or de-oiled DDGS. In experiment 3, 32 growing barrows (initial BW: 20.2 ± 0.9 kg) were placed in metabolism crates and allotted to four diets with eight pigs per diet using a 2 × 2 factorial treatment arrangement. The de-oiled DDGS and ProCap DDGS were both included in a diet without microbial phytase and a diet with microbial phytase (500 units/kg diet). Pigs were adapted to the diets for 5 d and fecal samples were collected for 4 d. Results from experiment 3 indicated that inclusion of phytase in the diet containing ProCap DDGS increased ($P < 0.05$) the STTD of P, but addition of phytase to the de-oiled DDGS diet did not increase STTD of P (interaction, $P < 0.001$), but the STTD of P was greater ($P < 0.05$) in de-oiled DDGS compared with ProCap DDGS. In conclusion, ProCap DDGS has greater SID of AA and contains more ME, but has reduced STTD of P compared with conventional de-oiled DDGS.

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

Abbreviations

AID	apparent ileal digestibility
ATTD	apparent total tract digestibility
DDGS	distillers dried grains with solubles
SID	standardized ileal digestibility
STTD	standardized total tract digestibility

Introduction

Distillers dried grains with solubles (**DDGS**) is a co-product from dry-grind ethanol production (Cromwell et al., 1993). Ethanol production has increased over the last 20 yr, which in turn has led to an increase in the production of DDGS, and the quantity of DDGS used in swine diets has also increased (Mumm et al., 2014). Therefore, the nutritional values of DDGS as an energy, protein, and P source in diets for pigs have been reported (Stein and Shurson, 2009; Espinosa and Stein, 2018; Espinosa et al., 2019). The quality and nutrient content of DDGS may differ among sources and origins and new technologies allow for the production of DDGS with different chemical composition as well as different nutritional value (Espinosa and Stein, 2018; Yang et al., 2019). Recently, a new source of DDGS (ProCap DDGS; Marquis Energy, Hennepin, IL) was developed by isolating high-protein and low-fiber fractions from the solubles and drying these fractions separately. This new source of DDGS has greater concentrations of crude protein (**CP**) and fat, but contains less fiber, compared with conventional de-oiled DDGS, which may affect digestibility of nutrients and concentration of energy in ProCap DDGS compared with de-oiled DDGS. There are, however, no data for the digestibility of energy and nutrients in this new source of DDGS. Therefore, the objective of this research was to test the hypothesis that standardized ileal digestibility (**SID**) of amino acids (**AA**), apparent total tract digestibility (**ATTD**) of gross energy (**GE**), concentrations of digestible energy (**DE**) and metabolizable (**ME**), and standardized total tract digestibility (**STTD**) of P in ProCap DDGS are greater in the ProCap DDGS than in conventional de-oiled DDGS when fed to growing pigs.

Materials and Methods

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocols for three experiments. Pigs that were used in the three experiments were the offspring of Line 359 boars and Camborough females (Pig Improvement Company, Hendersonville, TN). The two sources of DDGS (i.e., ProCap DDGS and de-oiled DDGS) that were used in the three experiments were obtained from the same batch of corn grain (Table 1). Both sources of DDGS were produced by Marquis Energy, Hennepin, IL.

Animals, housing, diets, feeding, and sample collection

Experiment 1. AA digestibility

Nine growing pigs (initial BW: 67.2 ± 6.4 kg) that had a T-cannula installed in the distal ileum were used. Pigs were placed in 1.2 × 1.5 m pens with fully slatted tri-bar floors. Pigs were allotted to a triplicated 3 × 3 Latin square design with three diets and three 6-d periods. There were three pigs per diet in each period for a total of nine observations per treatment.

Each source of DDGS was included in one diet as the sole source of AA (Tables 2 and 3). A nitrogen-free diet was used to determine the basal endogenous losses of AA. Vitamins and minerals were included in all diets to meet or exceed current requirement estimates (NRC, 2012). All diets also contained 0.40% chromic oxide as an indigestible marker. A sample of each diet was collected at the time of diet mixing.

Pigs were fed their respective diets at three times the maintenance requirement for ME (i.e., 197 kcal ME per kg $BW^{0.60}$; NRC, 2012) and water was available at all times. Pig weights were recorded at the beginning of each period and at the conclusion of the experiment. Each experimental period lasted 6 d. The initial 4 d of each period was considered an adaptation period. Ileal digesta were collected on days 5 and 6 for 9 h using standard procedures (Stein et al., 1998). Pigs were fed experimental diets at 0700 hours and ileal digesta samples were collected from 0700 to 1600 hours. Cannulas were opened at the beginning of collection and a 225-mL plastic bag was attached to the cannula barrel using a cable tie. Digesta flowing into the bag were collected and bags were replaced whenever they were full or at least once every 30 min. All samples were stored at –20 °C after collection. At the conclusion of the experiment, ileal digesta samples were

Table 1. Nutrient composition of conventional de-oiled DDGS and ProCap DDGS[1]

Item, %	De-oiled DDGS	ProCap DDGS
DM	87.42	94.59
GE, kcal/kg	4,471	5,100
Acid-hydrolyzed ether extract	4.14	9.49
Ash	5.11	7.38
Total dietary fiber	37.75	22.79
Soluble dietary fiber	1.21	1.02
Insoluble dietary fiber	36.54	21.77
Calcium	0.04	0.04
Phosphorus	1.01	0.77
Phytic acid	< 0.14	2.12
Phytate P[2]	< 0.04	0.17
Nonphytate P[3]	0.97 to 1.01	1.52
Phytase, unit/kg	1,200	<70
CP	31.14	48.09
Lys:CP	3.31	3.93
Indispensable AA		
Arg	1.35	2.47
His	0.78	1.40
Ile	1.13	2.03
Leu	3.24	5.57
Lys	1.03	1.89
Met	0.54	1.09
Phe	1.33	2.51
Thr	1.09	1.89
Trp	0.20	0.49
Val	1.46	2.84
Dispensable AA		
Ala	2.00	3.41
Asp	1.94	3.38
Cys	0.57	1.00
Glu	4.32	7.52
Gly	1.17	2.06
Pro	2.21	3.52
Ser	1.29	2.20
Tyr	0.97	1.90

[1]All values except DM were adjusted to 88% DM.
[2]Phytate P was calculated by multiplying the analyzed phytic acid by 0.282 (Tran and Sauvant, 2004).
[3]Nonphytate P was calculated as the difference between total P and phytate P.

Table 2. Ingredient composition of experimental diets containing de-oiled DDGS and ProCap DDGS, as-fed basis (experiment 1)

Ingredient, %	De-oiled DDGS	ProCap DDGS	N-free
De-oiled DDGS	55.00	—	—
ProCap DDGS	—	32.00	—
Soybean oil	2.00	3.00	4.00
Calcium carbonate	1.00	0.75	0.30
Dicalcium phosphate	0.35	0.85	1.75
Sucrose	10.00	10.00	20.00
Cornstarch	30.70	52.45	68.50
Solka floc[1]	—	—	4.00
Magnesium oxide	—	—	0.10
Potassium carbonate	—	—	0.40
Sodium chloride	0.40	0.40	0.40
Chromic oxide	0.40	0.40	0.40
Vitamin–mineral premix[2]	0.15	0.15	0.15

[1]Fiber Sales and Development Corp., Urbana, OH.
[2]The vitamin–micromineral premix provided the following quantities of vitamins and micro minerals per kilogram of complete diet: vitamin A as retinyl acetate, 11,150 IU; vitamin D_3 as cholecalciferol, 2,210 IU; vitamin E as selenium yeast, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.42 mg; thiamin as thiamine mononitrate, 1.10 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 1.00 mg; vitamin B_{12}, 0.03 mg; $_D$-pantothenic acid as $_D$-calcium pantothenate, 23.6 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 125 mg as iron sulfate; I, 1.26mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese hydroxychloride; Se, 0.30 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc hydroxychloride.

thawed, mixed within animal and diet, and a subsample was collected for analysis.

Experiment 2. Digestibility of GE and concentrations of DE and ME

Twenty-four barrows (initial BW: 32.7 ± 3.1 kg) were allotted to three diets and eight replicate pigs per diet with individual pig BW being the blocking factor using a randomized complete block design. Pigs were housed individually in metabolism crates that were equipped with a self-feeder, a nipple waterer, and a slatted floor. A screen and a urine pan were placed under the slatted floor for the total, but separate, collection of urine and fecal samples.

A basal diet containing corn (particle size 366 µm) as the sole source of energy and two diets containing corn and each source of DDGS were formulated—thus, a total of three diets were used (Table 4). Vitamins and minerals were included in all diets to meet or exceed current requirement estimates (NRC, 2012). Pigs were limit fed at 3.2 times the ME requirement for maintenance, which was provided each day in two equal meals at 0800 and 1600 hours. The concentration of ME in the three diets was calculated based on the ME in each ingredient (NRC, 2012). Water was available at all times. Feed consumption was recorded daily and pigs were fed experimental diets for 13 d. The initial 7 d were considered the adaptation period to the diet. Fecal samples were collected for 4 d according to standard procedures using the marker-to-marker approach (Adeola, 2001), whereas urine samples were collected for 4 d using a time-based method. Briefly, urine collection started at 0900 hours on day 8 and ceased at 0900 hours on day 12. Urine was collected in urine buckets over a preservative of 50 mL of 3 N HCl. Fecal samples and 20% of the collected urine were stored at –20 °C immediately after collection.

Table 3. Analyzed nutrient compositions of experimental diets containing de-oiled DDGS and ProCap DDGS, as-fed basis (experiment 1)

	Diet		
Item, %	De-oiled DDGS	ProCap DDGS	N-free
ME[1], kcal/kg	3,612	3,781	3,793
DM	90.88	93.15	92.36
CP	15.61	16.73	0.26
Indispensable AA			
Arg	0.67	0.80	0.01
His	0.40	0.47	—
Ile	0.57	0.69	0.01
Leu	1.68	1.89	0.02
Lys	0.53	0.64	0.01
Met	0.29	0.35	0.01
Phe	0.71	0.86	0.01
Thr	0.57	0.64	0.01
Trp	0.14	0.17	<0.02
Val	0.74	0.95	0.01
Dispensable AA			
Ala	1.03	1.16	0.01
Asp	1.04	1.15	0.02
Cys	0.31	0.33	0.01
Glu	2.38	2.58	0.02
Gly	0.61	0.70	0.01
Pro	1.19	1.18	0.04
Ser	0.65	0.72	0.01
Tyr	0.53	0.56	0.01

[1]ME in all diets was calculated (NRC, 2012).

Experiment 3. Digestibility of P and effects of microbial phytase

Thirty-two barrows (initial BW: 20.2 ± 0.9 kg) were allotted to four diets and eight replicate pigs per diet using a randomized complete block design. Individual pig BW was used as the blocking factor. The four diets were arranged in a 2 × 2 factorial with two sources of DDGS (ProCap DDGS and de-oiled DDGS) and two levels of microbial phytase (0 and 500 units/kg diet; Quantum Blue, AB Vista, Marlborough, UK; Table 5). Vitamins and minerals other than P and Ca were included in all diets to meet or exceed the estimated nutrient requirements for growing pigs (NRC, 2012). Housing, feeding, and sample collection were as for experiment 2 with the exception that no urine samples were collected and the adaptation period was 5 d. On day 6 in the morning, the start marker was included in the morning meal, and on day 10, the stop marker was provided with the morning meal. Fecal collections were initiated when the start marker first appeared in the feces, and ceased when the stop marker appeared, which for most pigs was on day 11, but for a few pigs on day 12.

Sample analysis

At the conclusion of experiment 1, ileal digesta samples were lyophilized and finely ground; fecal samples from experiments 2 and 3 were dried in a 55 °C forced air drying oven prior to analysis. It took 7 to 8 d for fecal samples to be dried to <10% moisture. Urine samples from experiment 2 were thawed and mixed within animal and diet, and a sub-sample was lyophilized before analysis using a standard procedure (Kim et al., 2009). Briefly, 10 mL of urine was dripped on a cotton ball that was placed in a plastic bag and the bag with the urine and cotton ball was lyophilized and GE was analyzed in the bag and in empty bags and cotton balls to calculate the GE in the 10 mL of urine.

Table 4. Ingredient and analyzed nutrient compositions of experimental diets containing de-oiled DDGS and ProCap DDGS, as-fed basis (experiment 2)

Item	Corn	De-oiled DDGS	ProCap DDGS
Ingredient, %			
Ground corn	97.45	42.90	70.65
De-oiled DDGS	—	55.00	—
ProCap DDGS	—	—	27.00
Calcium carbonate	0.70	1.30	1.00
Dicalcium phosphate	1.30	0.25	0.80
Sodium chloride	0.40	0.40	0.40
Vitamin–mineral premix[1]	0.15	0.15	0.15
Nutrient composition, %			
DM	87.86	88.19	89.05
GE, kcal/kg	3,761	4,180	4,152
ME[2], kcal/kg	3,310	3,310	3,310
CP	6.57	19.26	19.88

[1]The vitamin–micromineral premix provided the following quantities of vitamins and micro minerals per kilogram of complete diet: vitamin A as retinyl acetate, 11,150 IU; vitamin D_3 as cholecalciferol, 2,210 IU; vitamin E as selenium yeast, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.42 mg; thiamin as thiamine mononitrate, 1.10 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 1.00 mg; vitamin B_{12}, 0.03 mg; $_{D-}$pantothenic acid as $_{D-}$calcium pantothenate, 23.6 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 125 mg as iron sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese hydroxychloride; Se, 0.30 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc hydroxychloride.
[2]ME in all diets was calculated (NRC, 2012).

Dry matter in ingredient, diet, freeze dried ileal digesta, and oven-dried fecal samples was measured using a drying oven for 2 h at 135 °C (method 930.15; AOAC Int., 2007). Ash in corn and the two sources of DDGS and diet samples from experiment 3 was also analyzed (method 942.05; AOAC Int., 2007). CP in ingredient, diet from experiments 1 and 2, and ileal digesta samples was calculated as N × 6.25 and N was measured using the combustion procedure (method 990.03; AOAC Int., 2007) on a LECO FP628 (LECO Corp., Saint Joseph, MI). The GE in ingredient, diet, fecal, and urine samples from experiment 2 was measured using an isoperibol bomb calorimeter (Model 6400, Parr Instruments, Moline, IL). Acid-hydrolyzed ether extract in both sources of DDGS was analyzed by acid hydrolysis using 3 N HCl (Ankom^{HCl}, Ankom Technology, Macedon, NY) followed by crude fat extraction using petroleum ether (Ankom^{XT15}, Ankom Technology, Macedon, NY). Insoluble and soluble dietary fiber in the two sources of DDGS were analyzed according to the method 991.43 (AOAC Int., 2007) using the Ankom^{TDF} Dietary Fiber Analyzer (Ankom Technology, Macedon, NY). Phytic acid in the two sources of DDGS was also analyzed (Ellis et al., 1977). Amino acids in ingredient and in diet and ileal digesta samples from experiment 1 were analyzed on a Hitachi Amino Acid Analyzer (Model No. L8800; Hitachi High Technologies America, Inc., Pleasanton, CA) using ninhydrin for postcolumn derivatization and norleucine as the internal standard. Prior to analysis, samples were hydrolyzed with 6 N HCl for 24 h at 110 °C [method 982.30 E(a); AOAC Int., 2007]. Methionine and Cys were determined as Met sulfone and cysteic acid after cold performic acid oxidation overnight before hydrolysis [method 982.30 E(b); AOAC Int., 2007]. Tryptophan was determined after NaOH hydrolysis for 22 h at 110 °C [method 982.30 E(c);

Table 5. Ingredient and analyzed nutrient compositions of experimental diets containing de-oiled DDGS and ProCap DDGS, as-fed basis (experiment 3)

Item	De-oiled DDGS		ProCap DDGS	
Phytase, unit/kg	0	500	0	500
Ingredient, %				
De-oiled DDGS	45.00	45.00	—	—
ProCap DDGS	—	—	45.00	45.00
Phytase concentrate[1]	—	0.01	—	0.01
Cornstarch	40.55	40.54	40.55	40.54
Soybean oil	3.00	3.00	3.00	3.00
Sucrose	10.00	10.00	10.00	10.00
Calcium carbonate	0.90	0.90	0.90	0.90
Sodium chloride	0.40	0.40	0.40	0.40
Vitamin–mineral premix[2]	0.15	0.15	0.15	0.15
Nutrient composition, %				
ME[3], kcal/kg	3,730	3,730	3,730	3,730
DM	91.3	91.2	93.5	93.6
Ash	3.4	3.5	3.2	3.2
P	0.40	0.38	0.33	0.35
Ca	0.36	0.34	0.36	0.36
Phytase, unit/kg	500	600	<70	310

[1]Phytase concentrate was added to provide 500 units of phytase (Quantum Blue, AB Vista, Marlborough, UK) per kilogram of diet.
[2]The vitamin–mineral premix provided the following quantities of vitamins and micro minerals per kilogram of complete diet: vitamin A as retinyl acetate, 11,150 IU; vitamin D_3 as cholecalciferol, 2,210 IU; vitamin E as selenium yeast, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.42 mg; thiamin as thiamine mononitrate, 1.10 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 1.00 mg; vitamin B_{12}, 0.03 mg; $_{D-}$pantothenic acid as $_{D-}$calcium pantothenate, 23.6 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 125 mg as iron sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese hydroxychloride; Se, 0.30 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc hydroxychloride.
[3]ME in all diets was calculated (NRC, 2012).

AOAC Int., 2007]. Chromium in diet and ileal digesta samples from experiment 1 was analyzed using Inductive Coupled Plasma Atomic Emission Spectrometric method (method 990.08; AOAC Int., 2007). Calcium and P in the two sources of DDGS and in diet and fecal samples from experiment 3 were analyzed by inductively coupled plasma spectroscopy (AOAC Int., 2007; method 985.01 A, B, and C) after wet ash sample preparation [AOAC Int., 2007; method 975.03 B(b)]. Phytase activity in the two sources of DDGS and in diet samples from experiment 3 was also measured (Phytex Method, Version 1; Eurofins, Des Moines, IA).

Calculations and statistical analysis

Experiment 1. AA digestibility

Apparent ileal digestibility (**AID**) and SID of CP and AA were calculated using the analyzed CP, AA, and Cr concentrations in the diets (Stein et al., 2007). The basal endogenous losses of CP and AA were calculated from pigs fed the N-free diet as previously described (Stein et al., 2007).

Data were analyzed using the PROC MIXED procedure (SAS Inst. Inc., Cary, NC). The model included diet as the fixed effect and square, period, and animal as the random effects. Mean values were calculated using the LSMeans statement. Pig was the experimental unit and results were considered significant at $P \leq 0.05$ and considered a tendency at $P \leq 0.10$.

Experiment 2. Digestibility of GE and concentrations of DE and ME

The ATTD of GE and DM was calculated for each diet, and the DE and ME in each diet were calculated as well (NRC, 2012). The DE and ME in corn were calculated by dividing the DE and ME of the basal diet by the inclusion rate of corn in that diet. The contribution of DE and ME from corn to the DE and ME in the diets containing both corn and one of the two sources of DDGS were subtracted from the DE and ME of each diet, and the DE and ME in each source of DDGS were calculated by difference (Adeola, 2001). The ATTD of GE in each source of DDGS was calculated using the same procedure.

Data were analyzed using the PROC MIXED in SAS (SAS Institute Inc., Cary, NC). Diet or ingredient was the fixed effect and block was the random effect. Least squares means were calculated and separated using the PDIFF statement with Tukey's adjustment. Pig was the experimental unit. Results were considered significant at $P \leq 0.05$ and considered a tendency at $P \leq 0.10$.

Experiment 3. Digestibility of P and effects of microbial phytase

The ATTD of P and Ca in each diet was calculated (NRC, 2012) and the ATTD of P in the diets also represented the ATTD of P in each source of DDGS because DDGS was the only source of P in the diets. Values for ATTD of P were calculated based on calculated P in the diets. By correcting these values for the basal endogenous losses of P (i.e., 190 mg per kg DM intake; NRC, 2012), the STTD of P in each source of DDGS without and with phytase was calculated.

Data were analyzed using the PROC MIXED in SAS (SAS Institute Inc., Cary, NC). Source of DDGS, phytase, and the interaction between DDGS and phytase were the fixed effects and block was the random effect. Least squares means were calculated and separated using the PDIFF statement with Tukey's adjustment. Pig was the experimental unit. Results were considered significant at $P \leq 0.05$ and considered a tendency at $P \leq 0.10$.

Results

Pigs remained healthy during the three experiments and very few feed refusals were observed. Results from experiment 1 indicated that the AID and SID of all AA in ProCap DDGS were greater ($P < 0.001$) than in de-oiled DDGS with the exception that the AID and SID of Pro were not different between the two sources of DDGS (Table 6).

Daily GE intake in experiment 2 was not different between pigs fed the two DDGS-containing diets, but greater ($P < 0.05$) than for pigs fed the corn diet (Table 7). Fecal excretion of GE was greater ($P < 0.05$) from pigs fed the de-oiled DDGS diet than from pigs fed the ProCap DDGS diet, but pigs fed the corn diet had the least ($P < 0.05$) fecal excretion of GE. Excretion of GE in urine was not different between pigs fed the two diets containing corn and each source of DDGS, but pigs fed the corn diet had the least ($P < 0.05$) urine excretion of GE. The ATTD of GE for the ProCap DDGS diet was greater ($P < 0.05$) than for the de-oiled DDGS diet, but not different compared with the corn diet. The concentration of DE in the ProCap DDGS diet was greater ($P < 0.05$) than in the corn diet and in the de-oiled DDGS diet. Diets containing ProCap DDGS contained the greatest ($P < 0.05$) ME followed by the corn diet and the de-oiled DDGS diet. Concentrations of DE and ME in ProCap DDGS were greater ($P < 0.05$) compared with corn or de-oiled DDGS.

Feed intake in experiment 3 was greater ($P < 0.05$) for pigs fed the diet containing ProCap DDGS compared with pigs fed the diets containing de-oiled DDGS (Table 8). There was no difference in P intake among diets, but P excretion in feces was greater ($P < 0.05$) from pigs fed the ProCap DDGS diet that was not supplemented with phytase compared with the other three diets. There was an interaction ($P < 0.05$) between diet and phytase for the ATTD and STTD of P because the inclusion of phytase in the diet containing ProCap DDGS increased ($P < 0.05$) the ATTD and STTD of P, but addition of phytase to the de-oiled DDGS diet did not increase the ATTD or STTD of P. Regardless of phytase, the ATTD of P and STTD of P were greater ($P < 0.05$) in de-oiled DDGS than in ProCap DDGS. There was also an interaction ($P < 0.05$) between diet and phytase for the ATTD of Ca because inclusion of phytase in the diet containing ProCap DDGS increased ($P < 0.05$) the ATTD of Ca, but phytase addition to the de-oiled DDGS diet did not change ATTD of Ca. Regardless of phytase, the ATTD of Ca was greater ($P < 0.05$) in the diet containing de-oiled DDGS than in the diet containing ProCap DDGS.

Discussion

Nutrient composition

The fact that the concentration of acid-hydrolyzed ether extract was ~4% in the de-oiled DDGS indicated that the oil removal from the solubles was very efficient and this DDGS used can therefore be considered a de-oiled DDGS according to the definition of different sources of DDGS (NRC, 2012). The lower oil in the de-oiled DDGS is likely the reason why this source of DDGS contained more CP and AA and less GE compared with low-oil DDGS used in previous studies, but fiber concentrations were in agreement with previous values (NRC, 2012; She et al., 2015; Li et al., 2017). Concentrations of CP and AA in the ProCap DDGS used in this work were greater, but GE was within the range of values (4,825 to 4,986 kcal/kg) observed in recent experiments using high-protein DDGS (Adeola and Ragland, 2016; Rho et al., 2017;

Table 6. AID and SID of CP and AA in de-oiled DDGS and ProCap DDGS[1,2], experiment 1

	AID				SID			
Item, %	De-oiled DDGS	ProCap DDGS	SEM	P-value	De-oiled DDGS	ProCap DDGS	SEM	P-value
CP	63.8	77.7	2.0	<0.001	70.7	84.4	2.0	<0.001
Indispensable AA								
Arg	72.8	86.7	2.3	<0.001	79.1	92.0	2.3	<0.001
His	70.0	85.8	1.6	<0.001	72.6	88.1	1.6	<0.001
Ile	70.2	84.4	1.3	<0.001	73.6	87.3	1.3	<0.001
Leu	80.7	88.1	1.0	<0.001	82.6	89.8	1.0	<0.001
Lys	55.7	81.0	1.8	<0.001	60.2	84.8	1.8	<0.001
Met	78.2	87.7	0.9	<0.001	80.1	89.4	0.9	<0.001
Phe	77.1	87.2	0.9	<0.001	79.7	89.4	0.9	<0.001
Thr	61.3	77.7	1.7	<0.001	66.7	82.6	1.7	<0.001
Trp	72.0	86.4	1.3	<0.001	76.4	90.2	1.3	<0.001
Val	66.1	81.8	1.5	<0.001	70.5	85.3	1.5	<0.001
Total	72.0	85.0	1.3	<0.001	75.5	88.0	1.3	<0.001
Dispensable AA								
Ala	73.3	82.0	1.7	<0.001	77.3	85.7	1.7	<0.001
Asp	60.9	77.6	1.6	<0.001	65.4	81.7	1.6	<0.001
Cys	65.2	80.4	1.6	<0.001	68.8	83.9	1.6	<0.001
Glu	77.4	87.1	1.4	<0.001	79.7	89.3	1.4	<0.001
Gly	39.9	58.7	5.0	<0.001	58.7	75.5	5.0	<0.001
Pro	38.4	38.2	10.8	0.958	71.6	72.5	10.8	0.850
Ser	69.0	82.2	1.8	<0.001	73.5	86.3	1.8	<0.001
Tyr	79.1	87.5	0.8	<0.001	81.9	90.3	0.8	<0.001
Total	64.6	75.2	2.9	<0.001	73.8	83.8	2.9	<0.001
Total AA	67.9	79.8	2.1	<0.001	74.5	85.8	2.1	<0.001

[1]Each least squares mean for experimental diets from growing pigs represents nine observations, respectively.
[2]Values for SID were calculated by correcting the values for AID for the basal ileal endogenous losses. The basal ileal endogenous losses were determined (g/kg DMI) as CP, 11.91; Arg, 0.46; His, 0.12; Ile, 0.21; Leu, 0.34; Lys, 0.26; Met, 0.06; Phe, 0.20; Thr, 0.34; Trp, 0.07; Val, 0.36; Ala, 0.45; Asp, 0.51; Cys, 0.12; Glu, 0.62; Gly, 1.26; Pro, 4.35; Ser, 0.32; and Tyr, 0.17.

Table 7. ATTD of GE and concentrations of DE and ME in diets and corn, de-oiled DDGS, and ProCap DDGS, experiment 2[1]

Item	Corn	De-oiled DDGS	ProCap DDGS	SEM	P-value
Diets					
Intake					
Feed, g/d in DM basis	1,085[b]	1,168[ab]	1,283[a]	61	0.015
GE, kcal/d	4,645[b]	5,535[a]	5,979[a]	281	<0.001
Fecal excretion					
Dry feces output, g/d	92.8[c]	241.5[a]	135.1[b]	17.6	<0.001
GE, kcal/d	454[c]	1,222[a]	673[b]	92	<0.001
Urinary excretion					
Urine output, g/d	926[b]	1,707[b]	1,719[b]	236	0.006
GE, kcal/d	76[b]	174[a]	163[a]	20	<0.001
ATTD of GE, %	90.1[a]	77.9[b]	88.8[a]	1.2	<0.001
Energy in diets, kcal/kg					
DE	3,389[b]	3,258[b]	3,686[a]	49.3	<0.001
ME	3,327[b]	3,128[c]	3,572[a]	55.1	<0.001
Energy in feed ingredients, kcal/kg					
As-fed basis					
DE	3,477[b]	3,211[b]	4,560[a]	88	<0.001
ME	3,414[b]	3,025[c]	4,306[a]	100	<0.001
DM basis					
DE	3,980[b]	3,667[c]	4,945[a]	100	<0.001
ME	3,908[b]	3,454[c]	4,669[a]	113	<0.001

[1]Each least squares mean for experimental diets represents eight observations, respectively, with the exception that the corn diet only had seven observations.
[a–c]Within a row, means without a common superscript differ ($P < 0.05$).

Espinosa and Stein, 2018). As expected, concentrations of CP, acid-hydrolyzed ether extract, and GE were greater and insoluble dietary fiber concentration was less in ProCap DDGS compared with de-oiled DDGS. The ProCap DDGS is different from de-oiled DDGS because the solids that form the ProCap DDGS are collected from thin stillage after the removal of wet

Table 8. ATTD and STTD of P in de-oiled DDGS and ProCap DDGS and ATTD of Ca in diets fed to growing pigs[1], experiment 3

	De-oiled DDGS		ProCap DDGS			P-value		
Item	0	500	0	500	SEM	DDGS	Phytase	Interaction
Feed intake, g/d in DM basis	637	656	828	827	42	<0.001	0.829	0.810
Dry feces output, g/d	89.7	103.5	58.5	60.1	6.0	<0.001	0.212	0.315
P digestibility								
P intake, g/d	2.8	2.9	2.9	2.9	0.2	0.673	0.813	0.793
P in feces, %	0.7[c]	0.7[c]	2.3[a]	1.5[b]	0.1	<0.001	<0.001	<0.001
P output, g/d	0.6[b]	0.8[b]	1.5[a]	0.9[b]	0.1	<0.001	0.019	<0.001
ATTD of P, %	76.8[a]	73.9[a]	50.7[b]	68.5[a]	2.3	<0.001	0.003	<0.001
Basal endogenous loss[2], mg/d	484	499	588	629	45	0.014	0.542	0.774
STTD of P[3], %	81.1[a]	78.2[a]	56.0[b]	73.8[a]	2.3	<0.001	0.003	<0.001
Ca digestibility								
Ca intake, g/d	2.5	2.6	3.2	3.2	0.2	<0.001	0.827	0.802
Ca in feces, %	0.4[c]	0.5[c]	1.7[a]	0.9[b]	0.1	<0.001	<0.001	<0.001
Ca output, g/d	0.4[b]	0.5[b]	1.1[a]	0.6[b]	0.1	<0.001	0.034	<0.001
ATTD of Ca, %	83.4[a]	79.9[a]	66.4[b]	81.8[a]	2.3	0.003	0.015	<0.001

[1]Each least squares mean for experimental diets represents eight observations, respectively.
[2]The basal endogenous loss of P expressed as milligram per day was calculated by multiplying the basal endogenous loss (mg/kg DMI) by the daily DM feed intake (kg/d) of each diet.
[3]Values for the STTD of P were calculated by correcting values for the ATTD of P with the basal endogenous loss (i.e., 190 mg/kg DMI; NRC, 2012).
[a–c]Within a row, means without a common superscript differ ($P < 0.05$).

distillers grain. The solids removed from thin stillage are then concentrated to produce the ProCap DDGS, which contains ~48% CP instead of approximately 30% in conventional de-oiled DDGS (88% DM basis).

The concentration of acid-hydrolyzed ether extract in the ProCap DDGS used in this experiment (9.49%) is greater than observed for high-protein DDGS used in previous studies (range = 2.8% to 8.9%; Widmer et al., 2007; Kim et al., 2009; Jacela et al., 2010; Almeida and Stein, 2012; Rho et al., 2017; Espinosa and Stein, 2018; Son et al., 2019). This increased concentration of acid-hydrolyzed ether extract in the ProCap DDGS is likely the reason why the ProCap DDGS contained more GE compared with the de-oiled DDGS.

AA digestibility

Concentrations of CP and Lys in the de-oiled DDGS were greater compared with previous values (NRC, 2012; She et al., 2015; Li et al., 2017), which is likely due to the reduced acid-hydrolyzed ether extract because all other nutrients are concentrated if acid-hydrolyzed ether extract is reduced. However, the SID of AA in the de-oiled DDGS was in agreement with previous values (NRC, 2012). The Lys to CP ratio in the de-oiled DDGS was 3.31%, indicating that this source of DDGS was not heat damaged (Espinosa et al., 2019). The Lys:CP ratio in DDGS has gradually increased in DDGS over the last 15 yr, which is likely due to improvements in processing technology including use of more effective enzymes, better fractionation, and improved drying systems (Espinosa et al., 2019). The Maillard reaction is a chemical reaction between NH_3 in AA and reducing sugars that takes place in the presence of moisture and heat (Maillard, 1912). Lysine is usually the AA that is most susceptible to heat damage because Lys has an amino group in the side chain (the epsilon amino group), but the fact that the de-oiled DDGS used in this experiment had a Lys to CP ratio that is in line with recent reports indicates that there was minimal heat damage during processing to produce this DDGS. The Lys:CP ratio in corn grain is 3.03% (NRC, 2012) and the observation that the Lys:CP ratio in the DDGS used in this experiment is greater than in corn grain further indicates that Lys had not been destroyed during drying.

The ProCap DDGS also contained more Lys relative to CP and had greater SID of CP and AA than the de-oiled DDGS and other high-protein DDGS used in previous studies (Rho et al., 2017; Espinosa and Stein, 2018). The greater values for SID of AA and the Lys to CP ratio confirm that there likely was very little heat damage of ProCap DDGS. It is also possible that differences in fat and fiber concentrations in the two sources of DDGS resulted in differences in the SID of CP and AA because greater fat concentration can reduce passage rate by increasing transit time, which may allow more dietary AA to be digested and absorbed (Li and Sauer, 1994; Kil and Stein, 2011). The ProCap DDGS contained less fiber compared with the de-oiled DDGS, which may also result in greater values for the SID of CP and AA because dietary fiber increases the specific endogenous losses of AA, and thus reduces SID of AA (Schulze et al., 1994). The very high SID values for AA in ProCap DDGS indicates that this source of DDGS is of very high quality and may be used as a source of digestible AA in diets fed to pigs.

Energy digestibility and energy concentrations

Concentrations of DE and ME in corn used in this study were in agreement with values previously reported (NRC, 2012), which gives confidence that values for DE and ME in the two sources of DDGS are accurate. Low-oil DDGS has previously been reported to contain 3,117 to 3,836 kcal/kg DE and 2,844 to 3,633 kcal/kg ME, whereas high-protein DDGS has been reported to contain 3,826 to 4,627 kcal/kg DE and 3,698 to 4,303 kcal/kg ME (Kim et al., 2009; NRC, 2012; Curry et al., 2016; Li et al., 2017; Rho et al., 2017; Espinosa and Stein, 2018). The de-oiled DDGS and ProCap DDGS had DE and ME that were within these ranges. Concentrations of DE and dietary fiber in feed ingredients are negatively correlated, whereas a positive correlation exists between DE and CP (NRC, 2012; Gutierrez et al., 2014). Therefore, it is likely that the lower concentration of dietary fiber in ProCap DDGS

and the greater concentration of CP and acid-hydrolyzed ether extract, resulted in the greater DE and ME in ProCap compared with de-oiled DDGS. This observation is also in agreement with previous data for high-protein DDGS (Rho et al., 2017; Espinosa and Stein, 2018). The observation that ProCap DDGS has very high concentration of ME compared with corn and the de-oiled DDGS indicates that ProCap DDGS is a well-digested energy source in diets fed to pigs.

Phosphorus digestibility and effects of phytase

The reason feed intake was greater for pigs fed ProCap DDGS compared with de-oiled DDGS is that there was more feed refusal from pigs fed the de-oiled DDGS. The difference in Ca intake is also a result of this difference in feed intake.

The ATTD and STTD of P in the de-oiled DDGS were in agreement with previous data (Almeida and Stein, 2012; Baker et al., 2013; Rojas et al., 2013; She et al., 2015). However, there are no previous data for the ATTD or STTD of P in ProCap DDGS. Most Ca in all diets originated from calcium carbonate and the ATTD of Ca in the diets, therefore, represents the ATTD of Ca in calcium carbonate. Values obtained in this experiment were within the range reported for ATTD of Ca in calcium carbonate (González-Vega et al., 2015; Lee et al., 2019).

The observation that the use of microbial phytase increased the STTD of P and the ATTD of Ca in the diet containing ProCap DDGS indicates that there were enough substrate (i.e., phytate) for microbial phytase in ProCap DDGS and that phytate from ProCap DDGS bound Ca from calcium carbonate by forming a Ca-phytate complex in the intestinal tract. Therefore, when microbial phytase was added, this Ca was released and the ATTD increased. This interaction among phytate, P, and Ca has been demonstrated in previous studies (Almeida and Stein, 2012; González-Vega et al., 2015; Lee et al., 2019). However, no effects of microbial phytase were observed on the STTD of P and the ATTD of Ca in the diet containing de-oiled DDGS, which is likely a result of the very low concentration of phytate in the de-oiled DDGS. The low phytate in the de-oiled DDGS indicates that most of the P in the de-oiled DDGS is not bound to phytate, and therefore, there is no Ca-phytate complex formed in the intestinal tract of pigs. In the production of the de-oiled DDGS, phytase was used in the fermentation process, which likely is the reason for the low phytate concentration in de-oiled DDGS was produced. Therefore, Ca and P digestibility in the DDGS used in this experiment was greater than observed in previous experiments (Almeida and Stein, 2012; Rojas et al., 2013; She et al., 2015). This also explains why the de-oiled DDGS had greater P digestibility compared with ProCap DDGS used in this experiment. The observation that ProCap DDGS contained much more phytate than de-oiled DDGS also indicates that most phytate is collected in the solubles used to produce ProCap DDGS and thus ProCap DDGS has greater phytate concentration compared with corn or the conventional de-oiled DDGS.

Conclusion

The new source of DDGS, ProCap DDGS, contains more CP, GE, and acid-hydrolyzed ether extract and less dietary fiber and P compared with conventional de-oiled DDGS. Values for the SID of AA and concentrations of DE and ME were greater in ProCap DDGS than in de-oiled DDGS. The STTD of P was less in ProCap DDGS than in de-oiled DDGS due to the presence of phytate, but there was no difference in the STTD of P if microbial phytase is used.

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Conflict of interest statement

The authors declare no real or perceived conflicts of interest.

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