RESEARCHREPORT
ANIMAL SCIENCE

Title: Validation of Digestible and Metabolizable Energy Prediction Equations, and Determination of Net Energy of Corn DDGS Sources Varying in Fat and Fiber Content in Growing Pigs, - **NPB #11-136** **revised**

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Industry Summary

Use of alternative feedstuffs in feed formulation is increasingly important with elevated grain prices and the availability of alternative ingredients, largely corn-dried distillers grains with solubles (C-DDGS). Changes are constantly occurring in the corn milling industry with the most recent technology, oil extraction, resulting in C-DDGS with a wider range of energy and nutrient composition. Past research has focused on determining the digestible and metabolizable energy (DE and ME, respectively) concentration of C-DDGS, and generation of prediction equations for DE and ME based upon compositional analysis. However, a further improvement in relating animal growth to dietary energy is to formulate diets on a net energy (NE) basis. While NE is commonly used in Europe, nutritionists in the U.S. have been reluctant to adapt this technology due to lack of information on the NE value of specific ingredients and data supporting its validity in U.S. style feeding programs.

The objectives of the following studies were to: 1—obtain sources of C-DDGS varying in energy and nutrient content and determine DE, ME, and NE and to determine if the composition of these C-DDGS samples could be utilized to develop or refine current DE and ME prediction equations, and to generate a NE prediction equations; 2—to obtain a single source of C-DDGS and using recent data to accurately estimate its NE value, formulate diets with graded levels of C-DDGS, but equal levels of dietary NE and determine the impact on pig performance and carcass dressing percent when fed at a commercial production facility.

The results of the experiments conducted at a university research facility indicate that, although C-DDGS composition can vary and subsequent DE, ME, and NE also varies, a wider range in ingredient composition and DE, ME, and NE values are necessary to generate prediction equations. Data obtained indicated that on average, the C-DDGS contained 3,931, 3,793, and 2,133 kcal of DE, ME, and NE/kg DM, respectively. These DE and ME values are within the ranges reported in the literature; with the NE value reported herein being the first reported for C-DDGS.

Based upon this data and a review of relevant literature, diets in the field study were formulated to contain 0, 10, 20, and 30% C-DDGS, but with equal levels of dietary NE across all levels of C-DDGS. Diets were fed to 3 barns of pigs at the same location, each containing 48 pens and 20 pigs per pen (2,880 pigs total). Overall, there were no differences noted for average daily gain, average daily feed intake or feed efficiency among pigs fed the different C-DDGS levels. In addition, there was no effect of dietary treatment on dressing percent,

suggesting that the estimates of NE, AA, and minerals utilized for feed formulation were relatively accurate. The data presented herein provide valid estimates of the DE, ME, and NE of C-DDGS and support the use of formulating diets on a NE basis, which is especially important in utilizing alternative feedstuffs in swine diet formulation. For further information, contact Dr. Brian Kerr, USDA-ARS, Ames, IA, by phone (515-294-0224) or email (brian.kerr@ars.usda.gov).

Key Findings:

- Corn--dried distillers grains with solubles (C-DDGS) is an excellent source of DE and ME for growing pigs, with the DE (3,931 kcal/kg DM) and ME (3,793 kcal/kg) values being similar to values reported in the literature.
- Net energy (NE) value determined by this research are the first reported in the literature for C-DDGS, with the value of 2,133 kcal/kg DM being lower than the 2,622 kcal/kg DM reported in the 2012 Swine NRC. This energy value will be critical in formulating feeds on a NE basis in order to maintain pig performance.
- When formulated on an equal NE basis, feeding up to 30% C-DDGS to pigs in a field situation had no impact on pig performance or dressing percent, indicating that the estimates of NE , as well as AA and mineral levels, utilized for corn, soybean meal, soybean oil, and C-DDGS utilized in formulating these feeds were relatively accurate.

Keywords
Corn-DDGS, energy prediction equations, net energy, nutrient digestion, pigs

Scientific Abstract

Initially, 2 experiments were conducted with growing-finishing pigs to determine DE and ME (Exp. 1, 96.3 kg BW) and NE (Exp. 2, 45.4 kg BW) content of corn-distillers dried grains with solubles (C-DDGS) in an effort to develop or refine DE, ME, and NE prediction equations based on chemical composition. Composition of the 6 C-DDGS sources varied (ash, 4.71 to 5.63%; CP, 29.65 to 32.21%; ether extract, 6.99 to 13.34%; NDF, 38.27 to 39.58%; total dietary fiber, 31.12 to 32.81%; DM basis), with animal studies resulting in a DE range from 3,836 to 4,038 kcal/kg DM, ME from 3,716 to 3,893 kcal/kg DM, and NE from 2,012 to 2,243 kcal/kg DM. Regardless of the range in C-DDGS composition and the resultant DE, ME, or NE values, there was no C-DDGS chemical parameter measured (GE, CP, starch, total dietary fiber, NDF, ADF, hemicellulose, EE, or ash) that was significant at $P \leq 0.15$ to predict DE, ME, or NE content in the C-DDGS sources evaluated. Apparent total tract digestibilities of several nutritional components were also measured for comparative purposes, but were not included in the prediction model. On average, the C-DDGS utilized in these studies contained 3,931, 3,793, and 2,133 kcal of DE, ME, and NE/kg DM, respectively. The results from these first 2 experiments suggest that although C-DDGS composition can vary and subsequent DE, ME, and NE also vary, a wider range in ingredient composition and DE, ME, and NE values are necessary to generate prediction equations.

A field-scale study (Exp. 3) was conducted to determine if formulating diets containing corn, soybean meal, soybean oil, and C-DDGS on an equal NE basis would impact pig performance. Lastly, 2 additional studies were conducted to determine the DE and ME content of these same diets (Exp. 4) and the same C-DDGS sample (Exp. 5) to generate data to support results obtained from the field trial. In Exp. 3, 3 barns, each containing 48 pens and 20 pigs per pen (n = 2,880 pigs) were utilized. Diets were formulated to contain 0, 10, 20, and 30% C-DDGS, with dietary NE and standardized ileal digestible Lys being equal across all C-DDGS levels. The NE values (kcal/kg as-is) utilized in feed formulation were: corn, 2,557; soybean meal, 1,960; soybean oil, 7,544, and C-DDGS, 2,284; respectively. Diets were additionally formulated to meet or exceed the AA and mineral needs according to the NRC (1998) recommendations. There were no differences ($P \geq 0.10$) noted for pig ADG, ADFI, or G:F among pigs fed the different C-DDGS levels when evaluated on d-28 (36 replications per treatment) or on d-39 (24 replications per treatment due to scale calibration error). In addition, there was no effect of dietary treatment on dressing percent ($P \geq 0.10$) noted, suggesting that the estimates of NE, AA, and minerals utilized for feed formulation were relatively accurate. When the complete diets were fed to pigs in metabolism crates (Exp. 4), ATTD of DM, ether extract, NDF, and phosphorus, and dietary DE and

ME, increased with increasing C-DDGS levels ($P \leq 0.05$). In Exp. 5, the ME in the C-DDGS utilized in Exp. 3 and 4 was determined to be 3,682 kcal/kg DM, which was similar to the formulated value of 3,702 kcal ME/kg DM. Overall, the performance and dressing percent data suggest that the NE levels, as well as AA and mineral levels, utilized for corn, soybean meal, soybean oil, and C-DDGS were relatively accurate given that pig performance and dressing percent was unaffected by C-DDGS inclusion level. Differences in ATTD of dietary DM, ether extract, NDF, and phosphorus could be directly related to digestibility differences in these nutrients in C-DDGS compared to corn, soybean meal, and soybean oil. The data presented herein support the use of formulating diets on a NE basis, which is especially important in utilizing alternative feedstuffs in swine feed formulation.

Introduction

Corn dried distillers grains with solubles (C-DDGS) have typically contained 10 to 11% ether extract (EE) with a ME content similar to corn (Stein and Shurson, 2009). However, recent oil extraction technologies in ethanol facilities have led to the production of C-DDGS with a wider range and lower level of energy and nutrient composition (Anderson et al., 2012; Kerr et al., 2013). Because lipids contain 2.25 times more energy than carbohydrates, removal of lipids likely reduces the DE, ME, and NE content in C-DDGS which can affect its economic value and potential dietary inclusion rates. In addition, removal of lipids would concurrently concentrate other components in the C-DDGS such as fiber and ash, which have been shown to reduce the caloric value of a feedstuff to an animal (Fernandez and Jorgensen, 1986; Degen et al., 2007; Kim et al., 2012).

Numerous studies have been published (Stein et al., 2006; Pedersen et al. 2007; Stein et al., 2009; Dahlen et al., 2011; Jacela et al., 2011; Anderson et al. 2012; Kerr et al., 2013) that have determined the DE and ME content C-DDGS. Recent studies have also included prediction equations based on chemical analysis to estimate DE and ME content of C-DDGS (Pedersen et al., 2007; Anderson et al., 2012; Kerr et al., 2013). In contrast, no studies have been published that estimated the NE content of C-DDGS. Formulation of diets on a NE basis is common place in Europe, but this is not currently the case in the U.S. In ad libitum feeding systems which are typical in the U.S., alterations in dietary NE have been shown to have negligible effects on pig performance or on common carcass measures (Kerr et al., 2003; Oresanya et al., 2008). In contrast, composition of gain (lean versus lipid) can be altered dramatically (Oresanya et al., 2008).

The objectives of this study were to obtain sources of C-DDGS varying in energy and nutrient content to determine DE and ME (Exp. 1) and NE (Exp. 2) content and to determine if the composition of these C-DDGS samples could be utilized to develop or refine DE, ME, and NE prediction equations. The objective of Exp. 3 were to obtain a single source of C-DDGS and using recent data to accurately estimate its NE, formulate diets with graded levels of C-DDGS, but equal levels of dietary NE and determine the impact on pig performance and carcass dressing percent when fed under commercial conditions. In addition, the same C-DDGS source and diets fed at the commercial location were fed to pigs in a university setting to compare DE and ME (Exp. 4) and apparent total tract digestibility (ATTD, Exp. 5) of various nutrients to previously published data.

Objectives:

In order to obtain the most economic and nutritional value from using C-DDGS in swine diets, the ME content, and preferably the NE content of a DDGS source being used must be known. The ME content of DDGS sources can vary substantially, but empirical values for NE in DDGS have not been determined. Because of the compositional variability in DDGS, and consequently in its ME, nutritionists need accurate, validated DE, ME, and NE prediction equations for DDGS. Metabolizable energy prediction equations have been developed and published by Pedersen et al. (2007) and Anderson et al. (2012) using chemical components of DDGS, but they have not been validated for use in practical swine diet formulations. To date, no NE prediction equations have been determined specifically for DDGS.

In 2011, approximately 20% of U.S. ethanol plants were removing a portion of corn oil before manufacturing DDGS, with oil extraction projected to be occurring in 40% of the industry by 2012 and 55% by 2013. In research conducted and summarized to date, the crude fat of DDGS samples has ranged from 9.6 to 14.3% on a DM basis. Depending upon the extraction equipment and methodology, however, crude fat levels in DDGS can be as low as 5% on a DM basis. The investigators of the current research recently completed two studies that evaluated the effect of the crude fat level in DDGS on DE and ME content using 11 DDGS sources ranging in fat content from 6 to 14% (Minnesota Corn Research and Promotion Council, Shurson-PI) and 4 DDGS sources ranging in fat content from 5 to 11% (POET, Kerr-PI). This research determined that although crude fat levels were important, other components that affect DE, ME, and NE content of DDGS include ash, fiber, protein, and starch; with fiber (NDF or TDF) having the largest impact on the energy value to growing-finishing pigs. However, the impact of these components on DE and ME need to be validated (Phase 1-Objectives 1 and 2 of the current study) in addition to determining NE of these DDGS sources (Phase 1-Objective 3) by either comparative slaughter or by Dual X-Ray Absorptometry (DXA) techniques. The final experiment will be conducted utilizing an industry research location whereupon feed efficiency will be used as the criterion to validate our NE value (methodology described by Boyd et al., 2010) as determined/predicted in Phase 1 of the project.

As outlined in the initial proposal, this research is designed to: 1) refine digestible and metabolizable energy (DE and ME, respectively) values for dried distillers grains with solubles (DDGS) ranging in fat content from 5 to 14%; 2) validate DE and ME prediction equations determined for DDGS of varying fat content that are currently being determined in two funded projects (Minnesota Corn Research & Promotion Council and POET), 3) determine the net energy (NE) content in these same DDGS sources, and 4) validate NE in a commercial setting.

Materials & Methods

EXPERIMENTS 1 and 2

Animal Management

The Institutional Animal Care and Use Committee at Iowa State University (Ames, IA) approved all experimental protocols. Two experiments (Exp. 1 and Exp. 2) were conducted using gilts that were offspring from PIC Camborough 22 sows × L337 boars (Pig Improvement Company, Hendersonville, TN). Experiment 1 was conducted from March through June, 2012 and Exp. 2 from July through August, 2012. In each experiment, gilts were fed a standard corn–soybean meal-based diet prior to experimentation. Gilts were weighed at the beginning and end of each metabolism period in Exp. 1 or at the beginning and end of the experimental period in Exp. 2.

Experiment 1

In Exp. 1, 3 groups of 24 gilts (n = 72; final BW = 96.3 kg, SD = 10.1 kg) were housed individually in metabolism crates (0.7 × 1.5 m) that allowed for separate but total collection of feces and urine. Crates were equipped with a stainless steel feeder and a nipple waterer, to which the pigs had ad libitum access. Based upon past experience in digestibility studies (Lammers et al., 2008; Kerr et al., 2009; Anderson et al., 2012; Kerr and Shurson, 2013) each pig was utilized as their own control (i.e., fed the basal diet), and thus, two feeding periods were utilized within each group. To accomplish this, a switch-back design was used. During Period-1, pigs in crates 1 through 12 were first fed the basal diet while pigs in crates 13 through 24 were first fed the 60% basal plus 40% C-DDGS treatments. In contrast, during Period-2, pigs in crates 1 through 12 were fed the 60% basal plus 40% C-DDGS treatments while pigs in crates 13 through 24 were fed the basal diet. This concept is supported by Jacobs et al. (2013) who reported that use of covariates in digestibility studies are one way to reduce animal-to-animal variation. Within this design, gilts were randomly assigned to either the basal or a C-DDGS-containing diet resulting in a total of 68 observations for pigs fed the basal diet or 8 or 12 observations for pigs fed the C-DDGS sources.

During the time-based 4-d total fecal and urine collection period, stainless steel screens were placed under each metabolism crate for total fecal collection and stainless steel buckets containing 25 mL of 6 N HCl were placed under each crate for the total urine collection. Feces and urine were collected twice daily and stored at 0°C until the end of the collection period. Feces were pooled by pig over the 4-d period, dried in a 70°C forced-air oven, weighed, and ground through a 1-mm screen with a subsample taken for analysis. Likewise, urine samples were pooled by pig over the 4-d period, thawed at the end of the collection period, weighed with a subsample collected for analysis.

Experiment 2

For Exp. 2, a separate group of 79 gilts was utilized. Pigs (initial BW = 45.4 kg, SD = 4.1 kg) were randomly allotted to individual pens (0.57 × 2.21 m), allowed free access to feed and water, and maintained in rooms with 24-h lighting. Body lean, fat, and bone were predicted by dual energy X-ray absorptiometry (DXA). Net energy for maintenance was estimated as 179 kcal/kg $BW^{0.60}$ (Kil et al., 2011), with protein assumed to contain 5.54 kcal/g and lipid assumed to contain 9.34 kcal/g (Birkett and DeLange, 2001). The conversion of DXA lean to whole body protein was calculated as 4.59 g lean = 1 g whole body protein based upon internal body composition data (N. Gabler, personal communication). In Exp. 2, initial body composition was obtained on each pig using DXA, and after the 35 d feeding trial, final body composition was again obtained on each pig using DXA. Whole body protein, fat, and bone deposition calculated by subtracting initial body composition from final body composition. The NE of each diet was calculated, with the NE of each C-DDGS source calculated by subtracting the NE contributed by the basal diet from the NE of the diet containing a particular C-DDGS source. In addition, a fresh fecal sample was obtained on d-31 to determine dietary DE using indirect marker digestibility (Jacobs et al., 2013), and compare this value to the dietary DE as determined in Exp. 1.

Diets

The 6 sources of C-DDGS were selected based upon their range in ether extract (EE, 6.99 to 13.34% EE, DM basis) and particle size range (310 to 544 μM), Table 1. Each experiment utilized the same corn-soybean meal basal diet, which along with each C-DDGS source, were comprehensively analyzed for various analytes. Depending upon treatment, pigs were either fed 100% of the corn-soybean meal basal diet or a test diet which contained 60% of the basal diet and 40% of a specific C-DDGS sample, expect for C-DDGS source B, which was included in the diet at 30% (70% basal) due to lack of product, Table 2. All diets were fed in a meal form and titanium dioxide was included in all diets as an indigestible marker. Test ingredients were not ground to a constant particle size to represent a typical particle size as would be fed commercially. Feed was offered at approximately 3% of BW during each 9-d adaption and 4-d collection period during Exp. 1 or ad libitum during Exp. 2.

Chemical Analysis and Calculations

The basal diet, each C-DDGS sample, and all feces were ground through a 1-mm screen before chemical analysis. Samples were analyzed for a variety of analytes at various laboratories as described previously (Kerr et al., 2013). To determine DE and ME content, GE of the feedstuffs, feces, and urine samples were determined using an isoperibol bomb calorimeter with benzoic acid used as a standard. For urine, 1 mL of filtered subsample urine was added to 0.5 g of dried cellulose and subsequently dried at 50°C for 24 h. Urine addition and subsequent drying was repeated 3 times, for a total of 3 mL of filtered urine, over a 72-h period before urinary GE determination. Gross energy in cellulose was also determined and urinary GE was calculated by subtracting the GE in cellulose from the GE in the samples containing both urine and cellulose. Gross energy intake was calculated as the product of GE content of the treatment diet and the actual feed intake over the 4-d collection period. Within a specific assay diet, the DE and ME of each test ingredient was calculated by subtracting the DE or ME contributed by the basal diet from the DE or ME of the diet containing a particular corn-DDGS source. All energy values are reported on a DM basis.

Similar to the calculations for energy, apparent total tract digestibility (ATTD) of ADF, C, DM, EE,N, NDF, P, and S of each C-DDGS source were calculated by subtracting the respective component contributed by the basal diet from the similar component of the diet containing that particular C-DDGS source, within a specific assay diet. Digestibility coefficients were then determined by dividing grams of component digested by the grams of component consumed and reported on a percentage basis.

Statistical Analysis

Using the individual pig as the experimental unit, data were subjected to ANOVA utilizing Proc GLM with group, period, and treatment in the model for Exp. 1 or treatment in Exp. 2 (SAS Inst. Inc., Cary, NC), with treatment means reported as least squares means. Using Proc REG, stepwise regression was used to determine the effect of nutrient composition among C-DDGS sources on DE and ME in Exp. 1 or on NE for Exp. 2; with variables with P-values ≤ 0.15 being allowed to remain in the model. The R^2 and the SE of the estimate were used to define the best fit equation if applicable.

EXPERIMENTS 3, 4, and 5

Animal Management

The Guide for the Care and Use of Laboratory Animals was utilized for Exp. 3 while the Institutional Animal Care and Use Committee at Iowa State University (Ames, IA) approved protocols used in Exp. 4 and 5. Pigs in Exp. 3 were mixed sex offspring from Large White/Landrace sows × Duroc boars while pigs in Exp. 4 and 5 were gilts from PIC Camborough 22 sows × L337 boars (Pig Improvement Company, Hendersonville, TN). Experiment 3 was conducted in May and June, 2013, Exp. 4 in June and July, 2013 and Exp. 5 in January, 2014. Pigs were weighed at the beginning and end of Exp. 3 or at the end of the Exp. 4 and 5.

C-DDGS

A single source of C-DDGS was utilized for all trials. Prior to selection of the C-DDGS, a time series analysis was conducted to confirm that the C-DDGS sample obtained was from a plant with a consistent production practice and not obtained during or immediately after a clean-out period. All C-DDGS samples were analyzed at commercial laboratories for various nutritional components, Table 3, by methods described previously (Kerr et al., 2013) The final C-DDGS sample was obtained in a sufficient quantity (approximately 72,000 kg) at one time to conduct all trials, being stored in semi-trailers for subsequent mixing at a commercial feed mill. At the time of acquisition, a composite sample was obtained for subsequent analysis.

Diet Formulation

Dietary treatments were based on C-DDGS inclusion level (0, 10, 20, and 30%) for the 39 d trial, Table 4. Because it was impossible to obtain actual ME and NE values for each ingredient source and volumes utilized, data from various literature sources were reviewed (Anderson et al., 2012; NRC, 2012; Kerr et al., 2013; Exp. 1) to estimate ME and NE values for corn, soybean meal, soybean oil, and the C-DDGS. The ME and NE values (kcal/kg as-is) subsequently utilized in diet formulation were: corn, 3,247and 2,557; soybean meal, 3,093 and 1,960; soybean oil, 8,574 and 7,544, and C-DDGS, 3,258 and 2,284; respectively. Diets were fed in meal form and balanced to a similar NE and standardized ileal digestible Lys level across all C-DDGS levels. Diets were additionally formulated to meet or exceed the AA and mineral needs according to the NRC (1998) recommendations. To estimate ATTD of nutrients and obtain the DE of the mixed diet, 0.92% titanium dioxide was added to the final diet mixing for one barn of pigs. To maintain dietary nutrient and NE formulation specifications due to this addition, minor adjustments in corn, soybean meal, and soybean oil were made to all diets (table not shown).

Experiment 3

A total of 2,880 pigs were used in the 39-d field-study. Three barns, each containing 48 pens measuring 2.2 × 6.6 m, were utilized for the experiment. Pens in each barn were randomly assigned to 1 of the 4 dietary treatments in a completely randomized manner. Pigs were weighed and allotted to pens to have an equal weight distribution within and between pens among the 3 barns. Pigs were weighed on a pen-basis at the beginning and end of the experiment. A preliminary pen-BW in all barns was taken on d-28 to coordinate shipping of pigs to the slaughter facility. Before slaughter, pigs were individually tattooed on a pen-basis and slaughtered in a commercial processing plant in the upper Midwest. Hot carcass weight was obtained on-line at the slaughter facility with dressing percent calculated as a percentage of BW on a pen-basis.

Experiment 4

In Exp. 4, 2 groups of 20 gilts (final BW = 81.9 kg, SD = 5.6 kg) were housed individually in metabolism crates (0.7 × 1.5 m) that allowed for separate but total collection of feces and urine. Crates were equipped with a stainless steel feeder and a nipple waterer, to which the pigs had ad libitum access. Diets (Table 4) were obtained directly from the commercial production facility (Exp. 3). Pigs were fed the experimental diets for 10 d prior to total fecal and urine collection. During the time-based 4-d total fecal and urine collection period, stainless steel screens were placed under each metabolism crate for total fecal collection and stainless steel buckets containing 25 mL of 6 N HCl were placed under each crate for the total urine collection. Feces and urine were collected twice daily and stored at 0°C until the end of the collection period. Feces were pooled by pig over the 4-d period, dried in a 70°C forced-air oven, weighed, and ground through a 1-mm screen with a subsample taken for analysis. Likewise, urine samples were pooled by pig over the 4-d period, thawed at the end of the collection period, weighed with a subsample collected for analysis.

Experiment 5

In Exp. 5, 20 gilts (final BW = 112.8 kg, SD = 6.4 kg) were housed individually in metabolism crates and managed in a manner as described for Exp. 4. To determine the energy and nutrient digestibility of the specific C-DDGS source utilized in Exp. 3 and 4, a 79.35% corn, 17.90% soybean meal diet, fortified with minerals, trace minerals, and vitamins was utilized as a basal diet. Pigs were either fed 100% of the basal diet or 60% of the basal and 40% C-DDGS during the 14 d experimental period.

Chemical Analysis and Calculations

Detail on chemical analysis of diets and ingredients and on calculations utilized to determine DE, ME, and ATTD are described in detail elsewhere (Kerr et al., 2013).

Statistical Analysis

The pen was utilized at the experimental unit for all data in Exp. 3, with barn and treatment retained in the model. In Exp. 4, the individual pig was utilized at the experimental unit with group and treatment retained in the model. Data for Exp. 3 and 4 were subjected to ANOVA utilizing Proc GLM (SAS Inst. Inc., Cary, NC), with treatment means reported as least squares means. Linear and quadratic effects due to dietary C-DDGS level were tested using contrast statements. Data for Exp. 5 represents mean data only.

Results and Discussion

EXPERIMENTS 1 and 2

General and Compositional Evaluation

The intent of the experiments was to obtain C-DDGS samples with a large range in EE to support our previous work (Anderson et al., 2012; Kerr et al., 2013) from which to generate and validate the use of equations to predict DE and ME of C-DDGS from compositional analysis. The range of EE in the current study, 6.99 to 13.34% EE on a DM basis, was slightly greater than our previous work (8.56 to 13.23% EE, DM basis; Kerr et al., 2013) and was greater than that reported by others (Stein et al., 2006, 2009; Pedersen et al., 2007; Anderson et al., 2012). Consequently, we felt that this range may have been inadequate from which to generate equations to predict DE, ME, and NE based upon nutrient composition. A wide range of composition has been indicated to be necessary for this to occur in broilers as well (Rochell et al., 2011; Meloche et al., 2013). Other compositional traits of the C-DDGS sources utilized in the current experiment are within the ranges denoted by those listed above as well as by others (Robinson et al., 2008; Dahlen et al., 2011; Jacela et al., 2011; Liu, 2011; Liu et al., 2012), but are not discussed in this manuscript. The additional nutrient composition data of the C-DDGS sources evaluated in the current study are provided because these data are lacking in the literature (NRC, 2012) and may be helpful relative to other research topics, such as pork fat quality (McClelland et al., 2012) and lipid peroxidation (Liu et al., 2014), but these data are not discussed in this manuscript. The lipid free fatty acid, lipid peroxidation, and mycotoxin (Table 1) concentrations suggest that the C-DDGS samples obtained were of high quality, and are similar to our previous work (Kerr et al., 2013) suggesting that the dry-milling location we chose to obtain C-DDGS samples have good processing methods.

In contrast to our previous work (Anderson et al., 2012; Kerr et al., 2013) we chose to utilize a corn-soybean meal basal diet instead of a corn-only diet. This decision was based upon the fact that the same basal diet and the basal plus C-DDGS diets would be fed to pigs over a longer time period during Exp. 2 in contrast to typical balance experiments, and we hypothesized that a corn-only diet might bias the results, which would likely be the greatest on NE, intermediate with ME, and little on DE values (Anderson et al., 2012). The inclusion level of C-DDGS was increased to 40% instead of 30% in our past research (Anderson et al., 2012; Kerr et al., 2013) to increase the chance of denoting differences in DE, ME, or NE within the C-DDGS samples we obtained, except for the C-DDGS source B which was included at 30% due to sample limitation. We postulated that this would be the upper level of C-DDGS utilized in industry and would have minimal effects on feed intake (Stein and Shurson, 2009). Lastly, all diets contained titanium dioxide as we planned on obtaining feces from gilts fed in Exp. 2 to calculate DE by indirect marker methodology and compare this value to the DE value obtained from gilts fed in metabolism crates in Exp. 1.

Experiment 1—DE and ME

Averaged across all treatments, including pigs fed the basal diet, pig BW (87.0, 103.9, and 98.3 kg) and ADFI (2,432, 2,560, and 2,334 g/d) were different ($P < 0.01$) among Groups 1, 2, and 3, respectively. In a similar manner, averaged across the 3 groups, pigs in Period 1 were lighter than pigs in Period 2 (91.1 vs 101/7 kg, respectively; $P < 0.01$), with ADFI being similar between Period 1 than Period 2 (2,425 vs 2,459 g/d, respectively; $P = 0.28$).These differences were expected because of pig availability and because pig group and period were clearly defined timeframes. Consequently, group and period remained as blocking variables in the statistical model for all parameters measured. Overall, there were no differences were noted for BW or ADFI between pigs fed the basal diet or pigs fed the various C-DDGS treatments, Table 5.

Comparisons of DE and ME content of C-DDGS samples with other published reports are useful for database building. In that respect, the DE and ME values determined for the current C-DDGS samples (Table 5) compared with that of most recent C-DDGS available to the livestock industry indicate that on average, DE and ME (3,931 and 3,793 kcal/kg DM, respectively) were higher than our previous data indicated (3,650 and 3,345 kcal/kg DM, respectively; Kerr et al., 2013). It is relevant to note, though, that the DE and ME of the corn-soybean meal basal diet in the current experiment (3,750 and 3,683 kcal/kg DM, respectively) were greater than that determined for corn (3,563 and 3,489 kcal/kg, respectively) in our last experiment, such that bias between experiments may subsequently bias the energy values determined for the test ingredients as well. Differences in energy determinations between experiments are not unexpected given that BW (Le Goff et al., 2002), particle size (Yanez et al., 2011); basal diet (Li et al., 2014), feed intake (Chastanet et al., 2007), and laboratory variation (Cromwell et al., 2000) may all affect the energy concentration determined for a diet or feedstuff.

Development and use of prediction equations are by no means a new concept, but often these equations are based upon the total composition of the diet (Just et al., 1984; Noblet and Perez, 1993; Bulang and Rodehutscord, 2009). Our recent effort has been on prediction equations based upon the composition of a specific feedstuff (Anderson et al., 2012; Kerr et al., 2013). In Exp. 1, no physical or chemical measurement was statistically significant at $P \leq 0.15$ to predict DE or ME content of C-DDGS. Because we could not predict DE or ME, we did not elect to predict DE or ME as a percentage of GE or ME as a percentage of DE as in our previous research (Kerr et al., 2013). The inability of these measures to predict DE or ME was a bit surprising because we expected that the relative large differences in several variables among the C-DDGS samples would have been great enough to develop regression equations among these 6 C-DDGS sources. This is supported by our past work (Kerr et al., 2013) which in one experiment predictive equations could not be generated from compositional analysis. Similar challenges in generating predictive equations have been reported in the evaluation of meat and bone meal (Adedokun and Adeola, 2005; Olukosi and Adeola, 2009). This supports our conclusions that in order to generate prediction equations, that a wide range in composition in necessary (Rochell et al., 2011; Anderson et al., 2012; Meloche et al., 2013; Kerr et al., 2013).

In an effort to validate past prediction equations generated in our laboratory (Anderson et al., 2012; Kerr et al., 2013) and in a literature review (Urriola et al., 2014), we utilized the best fit DE and ME equations from each of these sources and predicted the DE and ME relative to the actual DE and ME values determined in the experiment. Summarization of this is effort is shown in Table 6, and indicates that use of DE and ME equations suggested by Anderson et al. (2012) and Kerr et al. (2013) both under predict the actual DE and ME as determined in the current trial. Some of this could be experimental bias where on average, the DE and ME of the corn-soybean meal diet in the current experiment averaged 191 kcal/kg DM higher than that determined for corn determined in the experiments by Kerr et al. (2013), potentially accounting for the average DE and ME prediction difference of 241 kcal/kg DM depicted in Table 6. However, this cannot be used as an excuse between the average DE and ME difference of 200 kcal/kg DM between the current experiment and that predicted by Anderson et al. (2012) where the corn DE and ME values (3,883 and 3,805 kcal/kg DM, respectively) are greater than that for the corn-soybean meal basal diet, as would be expected (NRC, 2012). The larger differences between the actual determined values and the values predicted by Urriola et al. (2014) may also be exacerbated due to differences in BW, particle size, basal diets, ADFI, and laboratory variation between experiments, as denoted earlier.

A challenge in any experiment is controlling errors associated with laboratory analysis, collection practices, and animal-to-animal variation. In light of these challenges, our laboratory has been consistent in utilizing a single laboratory for diet and ingredient analysis as well as consistency in laboratory methods utilized within our laboratory. Past work has shown that lab-to-lab variation alone can account for a 10% error in predicting a caloric value for C-DDGS (data not shown). Relative to animal collection methods and sample preparation, our research has also been relatively consistent in these practices as well (Lammers et al., 2008; Kerr et al., 2009; Anderson et al., 2012; Kerr et al., 2013). It is worthy to note that collection method has been shown to have some effects on subsequent energy values (Li et al., 2014). With the potential for animal-to-animal variation in nutrition research, we elected to utilize each pig as its own control, a concept suggested by Jacobs et al. (2013) for use in animal nutrition research. Thus we felt that controlling this variation could be useful in the current experiment. In reviewing the data from the 68 pigs fed the basal diet, relatively little variation (as denoted by coefficient of variation) was noted for DE and ME, and for C, DM, N, and S digestibility, Table 7. Part of this is likely due to the large mean value and thus, the noted variation is ‘lost’ when a large denominator is present. The low CV for these measures may also be due to methods for determining energy (bomb calorimeter), C, N, and S (thermo combustion) are more quantitative methods that likely have a low amount of inherent variation to begin with. Dry matter, a qualitative measure because it is not measured against a standard, has a large denominator and is a fairly standard assay such that CVs are typically low. In contrast, ADF and NDF (filter bag technique) and EE (solvent extraction) are more qualitative measures as ‘fiber’ and ‘lipids’ are complex compounds with the methods utilized measuring more than just one compound and there are no ‘standards’ utilized in these methods. In addition, fiber analysis often utilizes enzymes or detergents and lipid analysis utilizes various solvents which have different extraction efficiencies. The variation noted in P digestibility (17.9% CV) is a bit confusing given that the methodology is an acid digestion process and known standards are utilized. One must remember, however, that errors can be additive and even though our laboratory maintains a CV of 5% or less for laboratory analysis; these are included on the overall CV listed in Table 7.

Apparent total tract digestibility of ADF, C, DM, EE, N, NDF, P, and S for C-DDGS in the current experiment (Table 5) compare favorably to our previous data (Kerr et al. 2013) for C-DDGS. These data do not, however, clearly explain any potential experimental bias between experiments; were the C, DM, EE, N, and S digestibilities for C-DDGS were greater, but ADF, NDF, and P digestibilities for C-DDGS were lower in the current experiment compared to that reported by Kerr et al. (2013). Use of ATTD coefficients to predict DE and ME as done by others (Noblet and Perez, 1993) was beyond the scope and aim of this study and was not, therefore, done. The digestibility of P is one a key measures of high interest due to the cost of P in dietary formulations. In this light, the average ATTD P digestibility of C-DDGS in the current experiment (51.8%) compares favorably to the 50.8, 55.5, 56.0, and 59.3% reported by others (Pedersen et al., 2007; Widyaratne and Zijlstra, 2007; Stein et al., 2009; Kerr et al., 2013; respectively), but less than the 68.6% reported by Almeida and Stein (2010).

Experiment 2—NE

Chemical analysis has long been the standard for measuring body composition in pigs, but is time consuming, expensive, destructive, and not without error. A reliable, convenient, and nondestructive method for determining total lean, fat, and bone composition is DXA, which has been demonstrated to have greater accuracy than many routinely used methods (Suster et al., 2003, 2004). Furthermore, using the actual initial body composition of each individual animal in calculation of body lean, fat, and bone gain, should only improve the accuracy of tissue gain assessment. For the 79 gilts utilized in Exp. 2, initial bone, fat, and lean averaged 1.30, 17.18, and 81.52%, respectively. More importantly, however, the range in initial bone, fat, and lean was 0.54, 5.63, and 5.95 percentage units, respectively, Table 8. Thus, like that suggested for Exp. 1, we postulated that using the pig as its own control was crucial in controlling animal-to-animal variation. This is especially important when ranges of BW are utilized in experiments, which in this experiment, ranged from 34.5 to 57.0 kg.

To calculate whole body energy, NE for maintenance was estimated as 179 kcal/kg $BW^{0.60}$ (Kil et al., 2011), with protein assumed to contain 5.54 kcal/g and lipid assumed to contain 9.34 kcal/g (Birkett and DeLange, 2001). These values are well defined and largely accepted in the literature (de Lange et al., 2012; NRC, 2012). For the DXA equipment utilized in the current experiment, computer outputs were bone, fat, and lean. To determine energy retained, however, the conversion of lean to protein is required. Prior to experimentation, calibration of DXA lean to whole body protein was undertaken at Iowa State University whereupon 45 pigs were scanned by DXA for lean determination and then ground to determine whole body protein. The results of this calibration resulted in a lean to protein ratio of 4.59 for pigs between the BW of 45 to 75 kg (data not shown). This ratio is well above the lean to protein ratio of 2.55 listed in the NRC (2012). However, because we utilized DXA for lean tissue determination, and consequently protein deposition, a lean to protein ratio of 4.59 was utilized for subsequent calculations. Lean deposition averaged 590 g/d in the current experiment, which would be higher than NRC (2012) model estimates, but this difference is largely due to the different lean to protein conversion factor (4.59 vs 2.55, Exp. 2 vs NRC, respectively). Furthermore, the sum of whole body bone, fat, and lean gain should approximate ADG. This discrepancy in the current experiment is partially due to the fact that performance data was obtained from scales located at the swine facility while gain of bone, fat, and lean were derived from BW predicted by DXA; which in this experiment, the DXA equipment estimated initial and final BW to be 4.3% greater but 2.7% less than that of the farm scales, respectively.

Differences in ADG and GF ($P < 0.10$), daily bone and fat gain ($P < 0.01$), and daily GE retained ($P < 0.05$) were noted among pigs fed the different C-DDGS sources, Table 9. In contrast, no differences among the C-DDGS sources for the determined NE were noted. On average, the NE of the 6 C-DDGS samples was 2,133 kcal/kg DM, which is lower than the 2,622 kcal NE/kg DM reported by the NRC (2012) for C-DDGS between 6 and 9% EE. Given the lack of NE differences, it was not surprising that no physical or chemical measurement was significant at $P \leq 0.15$ to predict NE content of C-DDGS. Because we could not predict NE alone, we did not elect to predict NE as a percentage of GE, DE, or ME. The inability to generate a prediction equation for NE supports our overall conclusion that in order to generate robust prediction equations, a wide range in nutrient and energy composition of the test diets or ingredients is necessary. This is supported by the pioneering work of Noblet and Perez (1993) and Noblet et al. (1994) where diets were formulated to be wide enough in energy levels and composition to generate prediction equations for DE, ME, and NE based upon chemical composition.

In addition to the body composition data, a fresh fecal sample was obtained on d31 to determine dietary DE using indirect marker digestibility and compare this value to the dietary DE determined in Exp. 1 by total collection. As shown by others (Kavanagh et al., 2001; Agudelo et al., 2010), differences were noted between the dietary DE value determined indirectly by marker methodology (Exp. 2) and total collection (Exp. 1), Table 9. This was not unexpected, as pigs, methods, and analytical methods differed between these two experiments. However, one might expect that the differences would be relatively consistent. This was not noted were the difference ranged from 76 kcal/kg DM greater for pigs fed the basal plus C-DDGS source B, but 270 kcal/kg DM lower for pigs fed the basal diet, in comparing marker versus total collection, respectively. These results, too, show the challenges in conducting digestibility trials.

Data from the experiments described herein indicate that C-DDGS are a good source of DE and ME, but the determination their NE content suggests a potential limitation, likely due to their fiber content. These experiments also indicate that a lack of ingredient variation makes it difficult to generate prediction equations based upon their chemical composition. Lastly, variation associated with energy and nutrient digestion trials make research difficult, but should not preclude the effort in conducting research to generate predictive equations from which to rapidly estimate energy and nutrient value for use in feed formulations, and to limit the need for future animal studies.

EXPERIMENTS 3, 4, and 5

General and Compositional Evaluation

Composition of the C-DDGS samples were consistent over time, with the final C-DDGS samples utilized being similar to previous sample analyses (Table 3), except for total starch, which was lower than the previous 7 samples. We have no explanation for this apparent difference. Composition of this C-DDGS source is similar to that we have evaluated previously when obtained from an ethanol plant of similar design (Anderson et al., 2012; Kerr et al., 2013, Exp. 1 and 2).

We chose to utilize a range of C-DDGS levels (0 to 30%) to improve our precision through the use of regression, and to utilize a range of C-DDGS which is commonly utilized in the swine industry. Higher levels of C-DDGS have been utilized in the swine industry, but we wanted to avoid a potential reduction in feed intake what has been shown at high levels of C-DDGS supplementation (Stein and Shurson, 2009). For this assay method, a simple corn-soybean meal diet (0% C-DDGS) serves as a standard to other diets with the G:F ratio of pigs fed diets used as the criterion to compare productive energy values (Boyd et al., 2010). Although this assay is challenging with respect to control of dietary feedstuffs and energy levels across diets, the literature was thoroughly reviewed to derive the most accurate NE level for corn, soybean meal, soybean oil, and C-DDGS. These values were then utilized to formulate diets with 0 to 30% C-DDGS, but with equal levels of NE. As expected, the levels of corn, soybean meal, and soybean oil varied as did the analyzed composition of the diets, Table 4.

Experiment 3

Using this methodology, one would expect that if NE levels of ingredients were estimated accurately, then there would be no change in the G:F ratio in pigs fed the various dietary treatments. As shown in Table 10, this was indeed the case where no difference ($P \geq 0.10$) was noted among pigs fed the C-DDGS levels when weighed on either d 28 (36 replications per treatment) or d 39 (24 replications per treatment due to scale calibration error). The reduction in hot carcass weight ($P < 0.05$) was largely the result of pigs fed the 0% C-DDGS having a greater hot carcass weight (approximately 1 kg) compared to pigs fed diets containing other levels of C-DDGS. However, no effect of dietary treatment on dressing percent ($P \geq 0.10$) was noted, suggesting that the estimates of NE, AA, and minerals utilized for diet formulation were relatively accurate. The increase in dietary DE as determined by indirect marker methodology in 1 barn of pigs (Table 10) is generally supportive of the calculated increase in dietary ME (Table 4). The increase in dietary DE likely reflects the increase in soybean oil addition with increasing levels of C-DDGS, even though it is known that dietary fiber can affect lipid digestion (Fernandez and Jorgensen, 1986; Degen et al., 2007). Variation in diet ATTD of DM, EE, and NDF are largely supportive of the dietary DE change, with the largest difference noted in pigs fed the diet with 0% C-DDGS compared to pigs fed 10, 20, or 30% C-DDGS (Table 10). There was a clear increase in ATTD phosphorus digestibility ($P < 0.01$) which would be expected given the higher phosphorus digestibility in C-DDGS compared to corn and soybean meal, and diets composed thereof (NRC, 2012; Kerr et al., 2013, Exp. 1).

Experiment 4

When the diets fed in Exp. 3 were fed to pigs in metabolism crates, changes in ATTD of DM, EE, NDF, and phosphorus; and dietary DE and ME, were more in line with expectations (Table 11). As C-DDGS levels increased, ATTD of EE, NDF, and phosphorus all increased ($P \leq 0.05$). The increase in ATTD of EE was likely due to higher levels of soybean oil supplemented (Adams and Jensen, 1984; Kim et al., 2013), in NDF digested due to the only moderately higher levels of NDF fed, and in phosphorus due to the higher phosphorus digestibility in C-DDGS relative to corn and soybean meal (NRC, 2012). The increased noted in DE and ME were extremely similar to calculated values (Table 4), suggesting that even though indirect marker methodology is a valuable tool (Jang et al., 2014), that studies in metabolism crates may provide a better estimate of diet digestibility and energy levels due to better experimental control. We did, however, obtain fresh fecal samples directly from the pig and not from samples that had fallen to the slatted floor such that fecal contamination would not have occurred.

Experiment 5

For the same C-DDGS source utilized in Exp. 3 and 4, the ME was determined using a separate set of finishing pigs housed in metabolism crates and was 3,682 kcal/kg DM (Table 12). This is strikingly similar to our estimated value of 3,702 kcal ME/kg DM (3,258 kcal/kg DM ÷88%DM) that was used in diet formulation (Table 4), and similar to the 3,793 kcal ME/kg DM obtained in our recent experimentation (Exp. 1), but higher than the average of 3,435 kcal ME/kg DM recently reported by Kerr et al. (2013).

Overall Conclusion

Overall, the performance and dressing percent data suggest that the NE levels, as well as AA and mineral levels, estimated for corn, soybean meal, soybean oil, and C-DDGS were relatively accurate given that pig performance and dressing percent was unaffected by C-DDGS inclusion level. Differences in ATTD of DM, EE, NDF, and phosphorus in the complete diet support differences noted in the dietary DE as determined by the index method, but better control of variables associated with metabolism studies (feed intake, fecal collection, etc.) appear to provide a better estimate of DE and ME relative to calculated levels. Differences in ATTD of dietary DM, EE, NDF, and phosphorus can be directly related to digestibility differences in these nutrients C-DDGS compared to corn, soybean meal, and soybean oil. The data presented herein support the use of formulating diets on a NE basis, which is especially important in utilizing alternative feedstuffs in swine feed formulation (Woyengo et al., 2014).

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Table 1. Analyzed composition of basal diet and corn-dried grains with solubles (C-DDGS), Exp. 1 and 2, DM basis

		C-DDGS source					
Item	Basal	A	B	C	D	E	F
Bulk density, g/cc[1]	0.563	0.492	0.508	0.477	0.516	0.508	0.492
Particle size, µm[1]	536	544	514	491	310	338	368
Dry matter, %[2]	88.54	88.66	88.88	89.34	89.80	90.52	91.28
GE, kcal/kg[1]	4,267	5,227	5,094	5,052	4,981	4,918	5,155
CP, %[2]	17.04	29.65	32.00	31.59	30.58	32.21	29.83
Lysine, %[2]	1.02	1.07	1.14	1.13	1.18	1.15	1.10
Total starch, %[2]	50.44	2.50	2.33	3.82	4.93	4.40	4.68
TDF, %[3]	10.84	31.47	31.62	31.12	32.41	32.81	32.10
NDF, %[2]	9.32	38.27	38.49	39.58	30.95	31.05	27.84
ADF, %[2]	3.35	11.48	12.14	11.60	8.90	8.55	8.55
Hemicellulose, %[4]	5.96	26.79	26.35	27.98	22.05	22.50	19.29
Ash, %[2]	4.86	4.79	4.71	5.38	5.63	5.51	5.53
Chloride, %[2]	0.34	0.16	0.16	0.17	0.21	0.21	0.19
Phosphorus, %[2]	0.50	0.83	0.87	0.92	0.90	0.94	0.85
Potassium, %[2]	0.72	1.16	1.14	1.18	1.29	1.27	1.30
Sodium, %[2]	0.16	0.19	0.14	0.18	0.26	0.18	0.19
Sulfur, %[2]	0.23	0.56	0.54	0.73	1.10	1.05	0.11
EE, %[2]	3.14	13.34	10.41	9.11	8.01	6.99	11.38
Myristic, 14:0[2,5]	0.00	0.00	0.00	0.08	0.09	0.00	0.06
Palmitic, 16:0	14.34	15.02	14.08	14.20	15.05	14.08	14.30
Palmitioleic, 16:1	0.00	0.14	0.15	0.13	0.19	0.14	0.15
Stearic, 18:0	2.07	2.02	2.10	1.90	2.81	2.13	2.21
Oleic, 18:1	25.55	25.02	25.41	24.40	27.15	25.73	25.81
Linoleic, 18:2	55.05	54.54	55.17	56.29	51.39	54.78	54.29
Linolenic, 18:3	2.37	1.73	1.61	1.65	1.52	1.62	1.54
Arachidonic, 20:4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Eicosapentaenoic, 20:5	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Docosapentaenoic, 22:5	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Docosahexaenoic, 22:6	0.00	0.14	0.18	0.16	0.23	0.28	0.20
Free fatty acids, %[2]	1.32	1.88	1.10	1.25	0.99	0.72	1.21
Thiobarbituric acid, absorbance[2]	45.65	11.73	8.19	14.04	8.15	10.85	5.90
Peroxide value, mEq/kg[2]	22.53	10.21	13.27	3.46	6.73	4.23	2.77
Mycotoxins[6]							
Aflatoxin B1, µg/kg	ND	ND	1.35	ND	5.12	ND	ND
Aflatoxin B2, µg/kg	ND	ND	ND	ND	ND	ND	ND
Aflatoxin G1, µg/kg	ND	ND	ND	ND	ND	ND	ND
Aflatoxin G2, µg/kg	ND	ND	ND	ND	ND	ND	ND
Deoxynivalenol, mg/kg	0.45	0.23	0.56	1.57	0.22	0.88	0.77
Fumonisin B1, mg/kg	0.34	0.34	3.26	4.93	3.67	1.66	1.64
Fumonisin B2, mg/kg	ND	ND	0.56	0.78	0.67	0.22	0.22
Fumonisin B3, mg/kg	ND	ND	0.23	0.34	0.22	ND	ND
Ochratoxin A, µg/kg	ND	ND	ND	ND	ND	ND	ND
T-2 Toxin, µg/kg	ND	ND	ND	ND	ND	ND	ND
Zearalenone, µg/kg	ND	ND	ND	77.12	ND	ND	ND

[1] Analysed by USDA-ARS, Ames, IA.

[2] Analyzed by University of Missouri, Columbia, MO.

[3] Analyzed by Eurofins, DesMoines, IA.

[4] Calculated as NDF – ADF.

[5] Fatty acid composition is expressed as a percentage of total fat.

[6] Analyzed by Trilogy Analytical Laboratory, Washington, MO. ND = not detected or below detection limit.

Table 2. Percent composition of diets, Exp. 1 and 2, as-fed basis[1]

		C-DDGS source					
Item	Basal	A	B	C	D	E	F
Corn	79.35	47.60	55.54	47.60	47.60	7.60	47.60
Soybean meal	17.90	10.74	12.53	10.74	10.74	10.74	10.74
C-DDGS	--	40.00	30.00	40.00	40.00	40.00	40.00
Monocalcium phosphate	0.71	0.43	0.50	0.43	0.43	0.43	0.43
Limestone	0.71	0.43	0.50	0.43	0.43	0.43	0.43
Sodium chloride	0.35	0.21	0.25	0.21	0.21	0.21	0.21
Trace mineral mix[2]	0.20	0.12	0.14	0.12	0.12	0.12	0.12
Vitamin mix[3]	0.15	0.09	0.11	0.09	0.09	0.09	0.09
L-Lysine·HCl	0.13	0.08	0.09	0.08	0.08	0.08	0.08
Titanium dioxide[4]	0.50	0.30	0.35	0.30	0.30	0.30	0.30

[1] Basal diet formulated to contain 0.50% Ca and 0.45% P. Corn-dried grains with solubles, C-DDGS.

[2] Provided the following per kilogram in the basal diet: vitamin A, 6,125 IU; vitamin D_3, 700 IU; vitamin E, 50 IU; vitamin K, 30 mg; vitamin B_{12}, 0.05 mg; riboflavin, 11 mg; niacin, 56 mg; and pantothenic acid, 27 mg.

[3] Provided the following per kilogram in the basal diet: Cu (as $CuSO_4$), 16.5 mg; Fe (as $FeSO_4$), 165 mg; I (as $Ca(IO_3)_2$), 0.3 mg; Mn (as $MnSO_4$), 39 mg; Zn (as $ZnSO_4$), 165 mg; and Se (Na_2SeO_3), 0.3 mg.

[4] TiO_2 recovered was 0.53, 0.30, 0.33, 0.31, 0.31, 0.30, and 0.30%, respectively.

Table 3. Composition of corn-distillers dried grains with solubles (C-DDGS), Exp. 3, 4, and 5, DM basis

Item	3/7	3/14	3/21	3/28	4/4	4/10	4/17	4/26
DM, %[1]	87.44	87.27	87.85	87.80	88.09	87.31	87.54	88.39
CP, %[1]	35.70	34.30	34.68	34.16	34.68	33.31	34.00	32.85
Total starch, %[1]	3.59	5.89	4.43	4.53	4.36	6.59	4.27	0.19
Total dietary fiber, %[2]	33.51	32.89	34.38	34.62	34.06	34.36	33.93	33.94
NDF, %[1]	32.03	31.82	31.84	30.92	33.27	30.83	31.95	31.43
ADF, %[1]	8.82	8.46	8.78	9.01	9.49	9.03	9.06	8.89
Ash, %[1]	5.71	5.99	5.54	5.54	5.38	5.84	5.68	5.60
Phosphorus, %[1]	1.01	0.99	0.94	0.91	0.86	0.93	0.96	0.89
Ether extract, %[1]	6.15	5.71	6.25	6.10	6.35	6.07	5.96	6.51

[1] Analysed by University of Missouri, Columbia, MO.

[2] Analyzed by Eurofins, DesMoines, IA.

Table 4. Diet composition 0f pigs fed graded levels of corn-distillers dried grains with solubles (C-DDGS), Exp. 3 and 4, as-is basis

	C-DDGS level, %			
Item, %	0	10	20	30
Corn	83.10	74.72	66.01	57.21
Soybean meal, 45.5% CP	14.05	12.44	10.88	9.32
C-DDGS, 6.5% EE	0.00	10.00	20.00	30.00
Soybean oil	0.60	0.83	1.17	1.53
Limestone	0.99	1.08	1.10	1.10
Dicalcium phosphate	0.27	0.03	0.00	0.00
Sodium chloride	0.38	0.33	0.30	0.30
L-Lys, 50%	0.35	0.35	0.34	0.33
L-Thr	0.05	0.02	0.00	0.00
Vitamin/trace mineral mix[1]	0.17	0.17	0.17	0.17
Ronozyme PM 10,000[2]	0.02	0.02	0.02	0.02
Stafac 20[3]	0.03	0.03	0.03	0.03
TOTAL	100.00	100.00	100.00	100.00
Calculated composition				
ME, kcal/kg[4]	3,197	3,225	3,247	3,272
NE, kcal/kg[4]	2,458	2,458	2,458	2,458
sidLys, %	0.67	0.67	0.67	0.67
Analyzed composition				
DM, %	90.04	89.93	89.80	89.98
Ether extract, %	3.23	3.86	4.07	4.82
GE, kcal/kg	3,793	3,867	3,952	4,013
NDF, %	6.73	8.62	9.84	10.79
Phosphorus, %	0.31	0.35	0.43	0.52
Titanium dioxide, %[5]	0.93	0.76	0.83	0.81

[1] The sources and levels of the vitamins and trace minerals are proprietary.

[2] Provided 1,818 FTU/kg complete feed (DSM Nutrition Products AG, Kaiseraugst, Switzerland).

[3] Provided 11 mg virginiamycin/kg complete feed (Phibro Animal Health, Teaneck, NJ).

[4] The following ME and NE values, kcal/kg as-is, were used in diet formulation: corn, 3,247and 2,557; soybean meal, 3,093 and 1,960; soybean oil, 8,574 and 7,544, and DDGS, 3,258 and 2,284; respectively.

[5] Minor adjustments in corn, soybean meal, and soybean oil were made to all diets when 0.92% TiO_2 was added to each diet to maintain dietary nutrient and NE formulation specifications.

Table 5. Energy content and digestibility coefficients of pigs fed the basal diet or C-DDGS, DM basis, Exp. 1

		C-DDGS source						Statistics[2]	
Item	Basal[1]	A	B	C	D	E	F	SD	P
Observations	68	12	8	12	12	12	12	-	-
BW, kg	96.1	97.3	96.6	97.2	96.2	94.8	97.2	4.6	0.76
ADFI, g	2,464	2,379	2,419	2,459	2,474	2,376	2,434	164	0.61
Energy content									
GE, kcal/kg	4,267	5,227	5,094	5,052	4,981	4,918	5,155	-	-
DE, kcal/kg	3,750	3,974	3,842	4,017	3,836	3,874	4,038	219	0.12
ME, kcal/kg	3,683	3,830	3,723	3,874	3,716	3,734	3,893	220	0.21
DE:GE	87.88	76.03	75.42	79.51	77.02	78.77	78.33	4.37	0.26
ME:DE	98.19	96.37	96.78	97.58	96.85	96.45	96.43	2.07	0.75
ME:GE	86.32	73.27	73.09	76.68	74.60	75.93	75.52	4.38	0.36
Digestibility, %									
ADF	65.03	76.08	73.28	76.90	55.44	55.16	61.30	5.78	0.01
C	88.78	76.14	75.31	78.20	75.91	78.12	77.67	4.60	0.58
DM	88.00	74.33	72.47	76.09	72.52	74.77	74.84	5.34	0.59
EE	22.87	59.82	55.85	46.32	75.95	73.47	81.25	7.75	0.01
N	89.29	84.60	84.47	86.45	83.61	85.89	84.70	3.64	0.46
NDF	47.77	60.88	53.46	58.52	41.66	44.83	46.04	8.89	0.01
P	40.86	54.78	63.28	50.69	51.19	50.45	44.27	9.39	0.01
S	80.89	85.34	82.14	87.64	88.85	88.84	89.01	2.77	0.01

[1] The apparent total tract digestibility and DE and ME of the C-SBM basal diet for each pig was used as its own control in the determination of the digestibility and energy values for each corn-dried grains with solubles (C-DDGS) source.

[2] Statistical analysis are relative to the C-DDGS sources only and do not include pigs fed the basal diet.

Table 6. Predicted energy values based upon published prediction equations, DM basis

	DE	Eq. 1[2]		Eq. 2[3]		Eq. 3[4]	
C-DDGS[1]	Actual	Predicted	Difference	Predicted	Difference	Predicted	Difference
A	3,974	3,813	-161	3,898	-76	3,655	-319
B	3,842	3,738	-104	3,801	-41	3,610	-232
C	4,017	3,744	-273	3,799	-218	3,593	-424
D	3,836	3,651	-185	3,682	-154	3,734	-102
E	3,874	3,593	-281	3,619	-255	3,688	-186
F	4,038	3,768	-270	3,816	-222	3,867	-171
		Mean	-212	Mean	-161	Mean	-239

	ME	Eq. 4[2]		Eq. 5[3]		Eq. 6[4]	
C-DDGS	Actual	Predicted	Difference	Predicted	Difference	Predicted	Difference
A	3,830	3,762	-68	3,679	-151	5,021	1,191
B	3,723	3,638	-85	3,518	-205	4,878	1,155
C	3,874	3,615	-259	3,476	-398	4,847	973
D	3,716	3,512	-204	3,354	-362	4,763	1,047
E	3,734	3,444	-290	3,280	-454	4,691	957
F	3,893	3,678	-215	3,545	-348	4,928	1,035
		Mean	-187	Mean	-320	Mean	1,060

[1] C-DDGS = corn-distillers dried grains with solubles source. Energy values (GE, DE, and ME) on a kcal/kg basis; EE, NDF, CP, and TDF on a percent basis.

[2] Anderson et al., 2012; Eq. 1: $DE = -1{,}358 + (1.26 \times GE) - (30.91 \times TDF) - (33.14 \times EE)$, Eq. 4: $ME = (0.90 \times GE) - (29.95 \times TDF)$.

[3] Kerr et al., 2013; Eq. 2: $DE = 2{,}084 + (0.67 \times GE) - (53.65 \times \%TDF)$, Eq. 5: $ME = 4{,}558 - (50.08 \times \%TDF) + (52.26 \times \%EE)$.

[4] Urriola et al., 2014; Eq. 3: $DE = -2{,}161 + (1.39 \times GE) - (20.7 \times NDF) - (49.3 \times EE)$, Eq. 6: $ME = -261 + (1.05 \times GE) - (7.89 \times CP) + (2.47 \times NDF) - (4.99 \times EE)$.

Table 7. Variation in energy and digestibility values in pigs fed the basal diet[1]

Criterion	Mean	SD	CV	Minimum	Maximum
Energy, kcal/kg DM					
DE	3,750	65.6	1.75	3,611	3,883
ME	3,683	60.0	1.63	3,544	3,817
Digestibility, %					
ADF	65.03	6.07	9.33	52.99	76.56
C	88.78	1.34	1.51	85.87	91.97
DM	88.00	1.48	1.68	85.15	90.99
EE	22.87	7.55	33.01	10.59	38.90
N	89.29	1.26	1.41	85.32	92.00
NDF	47.77	9.93	20.79	28.93	65.82
P	40.86	7.32	17.91	27.89	54.84
S	80.89	1.66	2.05	76.81	85.03

[1] Data represents 68 pigs fed the corn-soybean meal basal diet.

Table 8. Variation in the initial body composition of pigs utilized in Exp. 2

Criterion[1]	Mean	SD	CV	Minimum	Maximum
BW, kg	45.35	4.08	9.00	34.50	57.00
Bone, %	1.30	0.13	10.00	0.97	1.51
Fat, %	17.18	1.11	6.46	14.65	20.28
Lean, %	81.52	1.19	1.44	78.24	84.19

[1] Represents 79 pigs at the initiation of the trial.

Table 9. Energy content of basal and corn-DDGS, NE Project, Exp. 2[1]

		C-DDGS source						Statistics[2]	
Item	Basal	A	B	C	D	E	F	SD	P
Observations	13	14	7	8	11	14	12	-	-
DDGS, %	--	40	30	40	40	40	40	-	-
ADG, g	910	845	886	828	786	787	852	96	0.10
ADFI, g	2,060	2,021	2,033	2,024	2,045	1,981	1,984	147	0.82
G:F, g/kg	443	419	436	409	386	396	429	39	0.02
Whole body									
Bone gain, g/d	9.3	6.2	7.8	6.4	4.8	4.5	5.1	1.2	0.01
Fat gain, g/d	137.3	133.0	144.5	125.2	113.1	120.5	135.3	21.0	0.01
Lean gain, g/d	661.6	584.4	608.6	578.1	547.4	561.8	593.3	62.5	0.22
E intake, kcal/d	7,783	8,415	8,177	8,286	8,347	8,010	8,256	602	0.56
E retained, kcal/d	4,196	4,027	4,168	3,972	3,781	3,874	4,046	298	0.04
NE, kcal/kg DM[3]	2,298	2,136	2,221	2,094	2,012	2,094	2,243	243	0.26
NE:GE[4]	53.9	40.9	43.6	41.5	40.4	42.6	43.5	4.8	0.52
NE:DE[4]	61.3	53.7	57.8	52.1	52.5	54.0	55.5	6.2	0.46
NE:ME[4]	62.4	55.8	59.6	54.1	54.1	56.1	57.6	6.4	0.47
DE, kcal/kg DM[5]									
Indirect	3,480	4,050	4,153	3,880	3,885	3,859	4,108	276	0.07
Total collection	3,750	3,974	3,842	4,017	3,836	3,874	4,038	246	0.18

[1] Initial BW averaged 45.4 kg (SD = 4.1 kg), containing 1.30% bone (SD = 0.13), 17.18% fat (SD = 1.11%), and 81.52% lean (SD 1.19%). The trial lasted 35 d. Gain of bone, fat, and lean obtained by dual energy X-ray absorptiometry. Performance, body tissue gain, and energy intake and retention based on total diet consumption.

[2] Statistical analysis are relative to the C-DDGS sources only and do not include pigs fed the basal diet.

[3] Data for the basal diet represents the complete basal diet. Data for the C-DDGS sources are attributed to the C-DDGS source only. Energy retention data based upon: fat = 9.34 cal/g, lean = 1.207 cal/g (5.54 cal/g protein; 1 g protein = 4.59 g lean), bone = 0 cal/g, and maintenance determined as 179 kcal × $BW^{0.60}$/day.

[4] Energy values (GE, DE, and ME) obtained from Exp. 1, Table 4.

[5] Indirect data obtained from indirect marker methodology for pigs fed in Exp. 2 while total collection data represents data from pigs fed the same diets as described in Exp. 1, Table 4.

Table 10. Performance, energy and nutrient digestibility, and carcass weight of pigs fed graded levels of dried distillers grains with solubles (C-DDGS) at an industry research facility, Exp. 3

	C-DDGS inclusion, %				Statistics[5]			
Item	0	10	20	30	SEM	P	LN	QD
28 d data[1]								
ADG, g	985	985	964	960	14	0.40	-	-
ADFI, g	3,103	3,084	3,023	3,087	27	0.17	-	-
G:F, g/kg	319	318	321	310	4	0.20	-	-
39 d data[2]								
ADG, g	877	872	847	868	10	0.16	-	-
ADFI, g	3,109	3,049	3,037	3,089	27	0.21	-	-
G:F, g/kg	283	286	278	279	2	0.12	-	-
Diet digestibility, %[3]								
DM	95.06^{b}	95.70^{a}	94.73^{b}	94.62^{c}	2.81	0.01	0.08	0.01
Ether extract	29.83^{c}	46.94^{a}	40.76^{b}	49.93^{a}	5.41	0.01	0.01	0.01
NDF	27.90^{b}	50.04^{a}	45.05^{a}	43.02^{a}	9.16	0.01	0.01	0.01
Phosphorus	27.47^{c}	44.39^{b}	48.62^{ab}	52.01^{a}	6.67	0.01	0.01	0.01
Dietary energy, kcal/kg[3]								
DE	$3{,}163^{c}$	$3{,}325^{a}$	$3{,}270^{b}$	$3{,}295^{ab}$	64	0.01	0.01	0.01
Carcass[4]								
Hot carcass weight, kg	98.67^{a}	97.53^{b}	97.58^{b}	97.39^{b}	0.36	0.04	0.03	0.17
Dressing percent	76.17	75.60	75.74	75.42	0.32	0.40	-	-

[1] Initial BW = 93.9 kg, final BW = 121.5 kg, 20 pigs pen, 48 pens/barn, 3 barns, 36 replications per treatment.

[2] Initial BW = 94.7 kg, final BW = 129.6 kg, 20 pigs pen, 48 pens/barn, 2 barns, 24 replications per treatment.

[3] Apparent total tract digestibilities and dietary DE based upon pooled fresh feces from a minimum of 2 pigs per pen from 1 barn, 12 replications per treatment.

[4] Hot carcass weights based upon 3 barns of 48 pens, with an average of 19 pigs harvested per pen (2,576 total pigs), 36 replications per treatment. Dressing percent based upon 2 barns of 48 pens, with an average of 19 pigs harvested per pen (1,882 total pigs), 24 replications per treatment.

[5] P, overall model P value; Linear, LN; QD, quadratic.

Table 11. Energy and nutrient digestibility of pigs fed graded levels of dried distillers grains with solubles (C-DDGS) at an university research facility, Exp. 4

	C-DDGS inclusion, %				Statistics[3]			
Item	0	10	20	30	SEM	P	LN	QD
Observations[1]	10	10	10	10	-	-	-	-
BW, kg	80.2	81.9	83.3	82.2	5.6	0.66	-	-
ADFI, g	1,976	1,962	1,905	1,934	90	0.30	-	-
Diet digestibility, %[2]								
DM	87.11	89.07	87.79	87.68	2.29	0.29	-	-
Ether extract	47.56^{c}	54.39^{b}	55.21^{b}	64.87^{a}	7.25	0.01	0.02	0.29
NDF	25.96^{b}	54.83^{a}	54.70^{a}	55.93^{a}	11.16	0.01	0.01	0.01
Phosphorus	42.12^{c}	56.32^{b}	59.94^{ab}	66.73^{a}	8.07	0.01	0.01	0.12
Dietary energy, kcal/kg[2]								
DE	3,302^{c}	3,446^{b}	3,486^{ab}	3,543^{a}	83	0.01	0.01	0.11
ME	3,223^{b}	3,343^{a}	3,376^{a}	3,410^{a}	82	0.01	0.01	0.19

[1] Individually fed pigs in metabolism crates. Ten day adaptation and 4 d collection.

[2] Apparent total tract digestibilities and dietary DE and NE based upon total collection procedures.

[3] P, overall model P value; Linear, LN; QD, quadratic.

Table 12. Energy and nutrient digestibility of pigs fed a basal diet and dried distillers grains with solubles (C-DDGS), Exp. 5, DM basis

Item	Basal	C-DDGS
Observations[1]	10	10
BW, kg	111.2	114.5
ADFI, g	2,500	2,500
Energy[2]		
GE, kcal/kg	4,223	4,886
DE, kcal/kg	3,812	3,968
ME, kcal/kg	3,692	3,682
DE:GE	90.27	81.20
ME:DE	96.87	92.82
ME:GE	87.45	75.37
Digestibility, %[2]		
ADF	71.78	70.06
C	91.28	80.91
DM	90.99	93.13
Ether extract	42.25	66.32
N	89.15	85.02
NDF	64.19	63.46
Phosphorus	51.55	49.92
S	81.41	90.10

[1] Individually fed pigs in metabolism crates. Ten day adaptation and 4 d collection.

[2] Apparent total tract digestibilities and dietary DE and NE based upon total collection procedures.