

# **Energy determination of corn co-products fed to finishing pigs and use of in vitro OM digestibility to predict in vivo ME**

## **Final Report**

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#### **Abstract**

Twenty co-products from various ethanol plants were fed to finishing pigs to determine ME and to generate an equation to predict ME based upon each ingredient's chemical analysis. Additionally, a 3-step enzymatic assay was used to determine if in vitro OM digestibility would predict in vivo ME or improve the prediction estimate of ME for corn co-products. Co-products included: DDGS (7), HP-DDG (3), bran (2), germ (2), gluten meal and feed, dehulled degermed corn, dried solubles, starch, and corn oil. The in vitro OM digestibility for each co-product was determined in triplicate using procedures as described by Boisen and Fernandez (1997). For the in vivo study, the control diet was based on corn (97.1%), limestone, salt, vitamins, and trace minerals. All but two test diets were formulated by mixing the control diet with 30% of a co-product. Dried solubles and oil were included at 20% and 10%, respectively. Eight groups of 24 gilts (n=192, 112.7 final BW  $\pm$  7.9 kg) were randomly assigned to a test diet and each diet was fed to a total of 8 pigs. Gilts were placed in metabolism crates and fed an amount equivalent to 3% BW daily for 9 d followed by collecting feces and urine separately for 4 d. Ingredients were analyzed for GE, CP, moisture, crude fat, crude fiber, ash, total dietary fiber (TDF), NDF, and ADF. Gross energy was determined on the feed, feces, and urine to calculate ME for each ingredient. The in vitro OM digestibility ranged from 33.3 to 93.5% for corn bran and dried solubles, while ME ranged from 2,334 to 8,755 kcal/kg for corn gluten feed and corn oil, respectively. Although in vitro OM digestibility was correlated to in vivo ME ( $r = 0.62$ ,  $P < 0.01$ ), it did not improve the prediction of ME from ingredient analysis. Stepwise regression resulted in the equation: ME, kcal/kg =  $(0.949 \times GE) - (32.238 \times TDF) - (40.175 \times \text{ash})$  ( $r^2 = 0.95$ , SE = 306,  $P < 0.01$ ). These results indicate that OM digestibility and ME vary substantially between corn co-products and the best predictors of ME are GE, TDF, and ash.

**KEYWORDS:** corn co-products, metabolizable energy, pigs

## **INTRODUCTION**

One of the challenges in feed formulation is accounting for the variation in nutrient profile of feedstuffs, with the co-products produced from the ethanol industry being no exception (Cromwell et al., 1993; Spiehs et al., 2002; Stein et al., 2006; Pedersen et al., 2007). In addition, processing changes are constantly occurring in the milling/biofuels industry resulting in a variety of co-products produced (e.g. dehulled and degermed corn, high-protein DDGS, DDGS with

reduced oil, DDG-no solubles added, corn germ meal-with or without oil, corn bran, and dried corn distillers solubles-with or without oil) that are available for use in swine feeds (Moeser et al., 2002; Muley et al., 2007; Widmer et al., 2007).

Nutrient digestion, particularly dietary fiber, progressively increases during the movement of digesta from the stomach to the large intestine (Wilfart et al., 2007). Because several corn co-products produced by the ethanol industry have high concentrations of insoluble fiber (i.e. DDGS), there is a tremendous need to better understand corn fiber utilization in swine. However, because growing pigs digest feed nutrients differently than young or adult animals (Stein et al., 1999; Noblet and van Milgen, 2004; Morel et al., 2006), determination of digestible and metabolizable energy of biofuels co-products should be evaluated in growing-finishing pigs (greater than 50 kg) because this phase of production is where the greatest amount of feed is consumed, but little data are available.

In the area of energy evaluation systems in swine, researchers in France have been at the forefront of developing equations for predicting the caloric value of feeds. Initially, energy predictions were based on chemical analysis (Noblet and Perez, 1993), followed by estimation of net energy based on digestible energy values and chemical analysis (Noblet et al., 1994), and more recently, using *in vitro* methodology (Noblet and Peyraud, 2007; as initially described by Boisen and Fernandez, 1997). Relative to the U.S. industry, where corn co-products generated from ethanol production are plentiful, a potential shortcoming of these using these previously developed energy prediction equations relates to their limited use of corn co-products in their development and evaluation using *in vitro* digestion methodology. Therefore, validation of *in vitro* digestion techniques is needed to provide another “tool” in which to predict the feeding values of corn co-products derived from the ethanol industry for growing-finishing pigs.

## MATERIALS AND METHODS

After this project was funded, we chose to combine resources and expand the scope of the project by collaborating with Dr. Brian Kerr at USDA-ARS in Ames, IA. Due to the rapid increase of various fractionated corn co-products, we decided to evaluate the energy value of 20 new corn co-products (our proposal described evaluating 3 new distiller’s co-products) plus determine the ability of an *in vitro* organic matter dry digestibility technique (Boisen and Fernandez, 1997) to predict digestible energy content of various corn co-products in finishing pigs.

### *Chemical Analysis and Physical Characteristics of Co-products*

Twenty co-products from the corn wet- and dry-milling industry were obtained from vendors located throughout the U.S. (Table 1). Tables 2 and 3 describe ingredient composition as determined by a commercial laboratory (University of Missouri Agriculture Experiment Station Chemical Laboratories, Columbia, MO). Gross energy (GE) was determined by isoperibol bomb calorimeter (model 1281, Parr Instrument Co., Moline, IL), particle size was determined by Maschoffs using a 13-sieve RoTap, and bulk density was determined (USDA, 1953) for all samples.

## ***Experimental Diets***

The control diet was based on corn (97.1%), limestone, salt, vitamins, and trace minerals. This basal diet was used to independently determine the ME of corn as a reference for the energy values obtained as was also used as a covariate between groups of pigs. Test diets were formulated by mixing the control diet (70%) with 30% of each co-product evaluated, except for test diets containing dried solubles or corn oil, which were included at 20% and 10% of the total diet, respectively. Inclusion of corn starch and corn oil were used to validate our methodology as outlined by Adeola (2001). A moderate inclusion level for all co-products was because there was concern that using higher dietary inclusion rates would depress feed intake and subsequently result in less accurate ME determinations.

Dried solubles were initially included in the diet at 30%, however, within a few days of adapting to this treatment, most pigs developed diarrhea. As a result, fecal and urine samples from these pigs were not included in the analysis, but rather we decided to reduce the dietary inclusion level of dried solubles to 20% and use a different group of pigs for sample collection. No diarrhea was noted in pigs fed the 20% dried soluble diet. Corn oil was included in the diet at 10% due to the high energy concentration of the feedstuff. Pigs were fed once daily at 3% BW for the entire duration of the metabolism trial. This amount was approaching ad libitum intake because almost all pigs had some residual feed in the feeders each morning they were fed. All diets were palatable to the pigs and very minimal feed refusal across all treatments was observed. Only two pigs fed the DDGS-WI treatment refused greater than 20% of total feed offered and were removed from the study. During the entire study, a total of 7 pigs were not included in statistical analysis for various reasons including: greater than 20% total feed refused, lost fecal collections, or contaminated urine samples. Most treatments had eight observations with exception for DDGS-WI (6), RO-DDGS (6), corn germ (7), and corn basal (30).

## ***General Pig Management and Sample Collection***

The Iowa State University Animal Care and Use Committee approved the experimental protocols #12-07-6480-S. Eight groups of 24 gilts (Cambrough 22 females × L337 sires, n=192, 112.7 final BW ± 7.9 kg) that had previously been fed a standard corn-soybean meal finisher diet were randomly assigned to a test diet such that each diet was fed to a total of 8 pigs. Each group of 24 gilts were fed 1 of 5 test diets (4 gilts/treatment; n = 20), and the 4 gilts remaining gilts in the group were fed the common basal diet. Consequently, two groups of 24 gilts were required to obtain a total of 8 replicates (pigs) fed each test diet. Gilts were placed into stainless steel metabolism crates (1.1 × 2.3 m) and fed an amount equivalent to 3% BW daily for 9 d followed by total collection of feces and urine for an additional 4 d. During the collection period, urine was collected once daily into stainless steel buckets containing 30 mL of 6 N HCl, and stored at 0°C until the end of the collection period. At the end of the collection period, urine was thawed, weighed, and a subsample was collected and stored at 0°C until subsequent analysis. Likewise, feces were collected daily and stored at 0°C until subsequent analysis. Feed consumption and refusal was recorded at the end of the experimental period. Water was available from a nipple waterer at all times.

In addition, a 3-step enzymatic assay was used to determine if *in vitro* organic matter (OM) digestibility would predict *in vivo* ME or improve the prediction estimate of ME for corn co-products. The *in vitro* OM digestibility for each co-product was determined in triplicate using procedures as described by Boisen and Fernandez (1997), using corn as the control feedstuff.

### ***Feed, Fecal, and Urine Sample Analyses***

Feedstuff samples were ground through a 1-mm screen before energy determination. Fecal samples were thawed, dried at 70°C for 48 h, and weighed to determine the dry matter (DM) content. Fecal samples were ground through a 1-mm screen in preparation for energy determination. For urine energy determination, 3 mL of urine was added to 0.5 g of dried cellulose and subsequently dried at 50°C for 24 h before energy determination. The GE of feed, feces, and urine plus cellulose was determined using an isoperibol bomb calorimeter (model number 1281, Parr Instrument Co., Moline, IL), with benzoic acid used as a standard. Duplicate analyses were performed on all diets and fecal samples from each pig, whereas triplicate analyses were performed on urine plus cellulose from each pig. Urinary energy was determined by subtracting the energy contained in cellulose from the combined urine plus cellulose energy.

In addition, a 3-step enzymatic assay was used to determine if *in vitro* organic matter (OM) digestibility would predict *in vivo* ME or improve the prediction estimate of ME for corn co-products. The *in vitro* OM digestibility for each co-product was determined in triplicate using procedures as described by Boisen and Fernandez (1997), using corn as the control feedstuff.

### ***Calculations and Statistical Analysis***

Energy intake was calculated by multiplying the GE value of the diet fed by individual pig feed intake over the 4-d collection period. Apparent DE values were calculated by subtracting fecal energy from intake energy and apparent ME values were calculated by subtracting urinary energy from apparent DE. The apparent DE and ME values of the test ingredient fed to the pigs were estimated by difference from the basal diet as described by Adeola (2001). Using the individual pig as the experimental unit, data from each experiment were analyzed using the PDIFF option of SAS using the basal ME as a covariate and group and treatment in the model (SAS Inst. Inc., Cary, NC). In addition, a stepwise regression model was used to determine the contributions of each chemical analyte of feedstuff composition on apparent ME, with variables having *P* values < 0.15 maintained in the model.

## **RESULTS AND DISCUSSION**

The corn co-products selected for this study varied substantially in nutrient content. Ingredients included in this study were: low in fiber (starch, oil, dried solubles, and dehulled, degermed corn), DDGS (n = 7), high in protein (HP-DDG; n = 3, and corn gluten meal), and high in fiber (bran (n = 2), corn germ meal (n = 2), and corn gluten feed). Most ingredients were obtained from various dry-grind ethanol plants with exception of gluten meal, gluten feed, and one source of corn germ meal which were obtained from various corn wet milling plants. One feedstuff, dehulled, degermed corn is a co-product from a fractionated dry-grind process.

The variable nutrient composition of the corn co-products is shown in Table 3. Corn starch and oil were included in our metabolism study to serve as references standards to determine ME, however, they were not included in chemical analysis. Unless otherwise noted, all values were calculated on a DM basis. The nutrient concentrations ranged from 8.3 to 66.3%, 0.5 to 100%, 0.08 to 11.5%, 2.6 to 53.6%, 2.3 to 61.1%, 0.5 to 25.4%, 0.8 to 22.6%, 0.3 to 3.5%, 0.5 to 14.1% for crude protein, starch, crude fiber, total dietary fiber (TDF), neutral detergent fiber (NDF), acid detergent fiber (ADF), cellulose, lignin, and crude fat, respectively.

As expected, ME content varied substantially among corn co-products (Table 4). However, the objective of this study was to establish DE and ME values for these co-products, not compare the relative differences in ME content. The pooled SD for ME was 413 kcal/kg DM. The low fiber co-products (starch, oil, dried solubles and dehulled, degermed corn) differed in ME from 4,080 to 8,755 kcal/kg DM, respectively. The seven DDGS samples differed in ME from 3,414 to 4,141 kcal/kg DM, respectively. The high protein co-products (corn gluten meal and three sources of HP-DDG) ranged in ME from 3,676 to 4,606 kcal/kg DM for HP-DDG (ICM) and HP-DDG (MOR), respectively. The remaining fibrous feedstuffs (two sources of bran and germ meal, and one source of corn gluten feed) ranged from 2,334 to 3,692 kcal/kg DM.

Although it was not the intention of this study to specifically evaluate the energy content of DDGS, this co-product is known to vary in nutrient content among sources (Spiehs et al., 2002). Therefore, the DDGS sources we selected for this study had differences in quality and were produced using different processing techniques. Drying distillers grain is an expensive process and cylindrical drum dryers are traditionally used. The use of drum dryers is a concern because overheating can result in undesirable Maillard reactions. Overheating distiller's co-products may also have a negative effect on the palatability, availability of nutrients, and energy to the animal. A burned product can generate a bitter taste that is undesirable to the animal, and overheating can lead to Maillard reactions that leave the total protein of the ingredient in a bound, undigestible form. To address this problem, a company in the Midwest has initiated the use of an alternative drying method using microwave technology. For this study, we used samples from the same ethanol plant that were either dried using microwave technology or traditionally drum dried. Another Midwest ethanol plant generated traditional DDGS as well as DDGS that had reduced oil content. Oil was removed from DDGS using hexane extraction after fermentation resulting in DDGS with 3.2% crude fat compared to traditional DDGS that ranges 8 to 11% (Spiehs et al., 2002).

Few ME values for the corn co-products evaluated in this study were available from the scientific literature. The NRC (1998) has published ME values for corn (3,843 kcal/kg DM), starch (4,205 kcal/kg DM), and corn oil (8,405 kcal/kg DM). The ME values determined in this study were 3,771, 4,080, and 8755 kcal/kg DM for corn, starch, and corn oil, respectively, which was similar to published NRC (1998) values (pooled SD was 413 kcal/kg DM). Use of corn, starch, and corn oil as internal controls provided validation that our methods were reasonable. The NRC (1998) ME value for corn gluten meal (66% CP DM basis) was 4,255 kcal/kg DM and compared favorably to our determined ME value of 4,598 kcal/kg DM. The NRC (1998) value for corn gluten feed (24% protein DM basis) was 2,894 kcal/kg DM and was slightly higher than our obtained value of 2,334 kcal/kg DM. Additionally, the seven DDGS sources selected for this

study varied substantially in ME values ranging from 3,414 kcal/kg DM (SD-BPX) to 4,141 kcal/kg DM (WI), and averaged 3,770 kcal/kg DM. These results compared favorably to those reported by Pedersen, et al. (2007). They determined the ME content of 10 sources of DDGS in growing pigs and showed ME values ranging from 3,674 to 4,336 kcal/kg DM with an average of 3,897 kcal/kg DM. However, Moeser et al. (2002) determined an ME value (3,517 kcal/kg; SE = 69.7) for dehulled, degermed corn in growing pigs that was lower than our determined value (4,316 kcal/kg DM; SE = 413) for the same product. Differences in these obtained values may be due to differences in experimental procedures. Moeser et al. (2002) used 27 kg growing barrows while we used finishing gilts weighing 112.7 kg in this study. Furthermore, we used a 30% dietary inclusion rate for dehulled, degermed corn (and 70% corn basal diet) while Moeser et al. (2002) used a treatment consisting of 96.4% dehulled, degermed corn. Dehulled, degermed corn is a highly digestible product generated from flaking grits in the dry milling process and it is interesting that similar values were not obtained, although the size differences of pigs used and dietary inclusion rate of the test ingredient may significantly affected the ME values obtained in these two studies.

Stepwise regression analysis using chemical composition of feed ingredients was used to develop prediction equations for ME. Initially the y-intercept was included in the model but additional testing determined that the y-intercept was not significant. The y-intercept was removed and the equation was redefined. The equation was significant ( $P < 0.01$ ) and provided a good estimate ( $r^2 = 0.95$ ) for estimating actual ME of the corn co-products evaluated in this study (standard error was 306 kcal/kg DM). Gross energy had a positive effect on the estimate for ME while TDF and ash had negative effects on the estimating ME content.

Metabolizable energy is often acquired from tables or calculated from equations and is not determined due to the expense, time, and labor required to do *in vivo* determinations. Prediction equations can be a useful tool for predicting energy values of feed ingredients, however, care must be used to ensure the application is being used within the assumption and conditions of how the equations were derived. The prediction equation shown below (Table 5) indicates that for the corn co-products evaluated in this study, GE, TDF, and ash provide the best prediction estimate for ME in finishing pigs. To our knowledge, such an equation has not been generated for this group of feedstuffs. Although we are confident in our methods, further studies need to be conducted to validate our findings.

Not surprisingly, the *in vitro* organic matter digestibility (OMD) varied substantially among corn co-products (Table 4). Organic matter digestibility differed from 32.3 to 100% for corn bran (without solubles) and corn oil, respectively, with an average of 89.4%. The correlation coefficient describing the relationship between *in vivo* ME and *in vitro* OMD was 0.62 (Figure 1). When corn oil was removed from the model, the correlation coefficient decreased to 0.57 (Figure 2). The linear regression equation was: ME (kcal/kg DM) = 48.557 (OMD, %) + 628.240;  $R^2 = 0.38$ .

Although there is a vast array of *in vitro* digestibility assays, the *in vitro* OMD assay selected for evaluation in this study was developed by Boisen and Fernandez (1997) and later re-evaluated by Noblet and Jaguelin-Peyraud (2007). It is an approved method in Denmark and is used routinely for feed energy evaluation (Noblet and Jaguelin-Peyraud, 2007). The corn co-

products used in this study varied substantially in their composition. They included ingredients that were low in energy digestibility as well those that were high in energy digestibility. Unfortunately, the relationship between these feedstuffs that varied in fiber content had a moderate correlation coefficient (0.62 and 0.57) between *in vitro* OMD and *in vivo* ME. Bran (without solubles) had the lowest (32.3%) organic matter digestibility of all the samples which was not surprising due to the high fiber content. On the other hand, corn oil was interpreted to have 100% OMD in our analysis. However, this assay cannot accurately predict the digestibility of a liquid, especially oil. Although it is suspected that enzymatic activity partially hydrolyzed the corn oil, it is difficult to assess the extent to which this occurred. The density differences in the oil and liquid portion of the assay led to oil floating on the surface of the enzymatic liquid whereas the rest of the feedstuffs were submerged. An even bigger problem was encountered when filtering the digested contents after the 24 hour incubation period. Corn oil was essentially filtered through the crucible and an expected increase in weight after the drying and ashing periods was not detected for these samples. We initially included corn oil in our regression analysis (Figure 1) for reference, but also removed it from the model (Figure 2). Interestingly, by including corn oil in the model the correlation coefficient was improved from 0.57 to 0.62. We suspect that by including a data point such as corn oil, which is extremely high in energy and in OMD in our study, the rest of the data points become skewed and not as significant. Removing corn oil from our data set may more accurately describe the relationship between *in vitro* OMD for predicting *in vivo* ME of the remaining corn co-products.

Other studies using the Boisen and Fernandez (1997) procedures showed good correlation between OMD and apparent total tract digestibility of various diets and common feedstuffs (Van der Meer and Perez, 1992; Noblet and Jagueelin-Peyraud, 2007). However, we slightly modified the assay procedures from those described by Boisen and Fernandez (1997), which may have contributed to sources of error in our OMD estimates.

First, the pepsin product described in the Boisen and Fernandez (1997) procedure was a porcine enzyme (2000 FIP-U/g) available from Merck (No. 7190), which is readily available for use in Europe but is not available in the United States or Canada. Therefore, we obtained a pepsin product that closely resembled the activity level indicated in their publication (porcine, 2,500 to 3,500 units/mg protein) from Sigma (7012). However, the activity level of the pepsin products were not expressed in the same units and conversions were needed in order for a comparison to be made. These conversions were not easy to determine and in retrospect, we suspect that our pepsin activity may have been half of what was described by Boisen and Fernandez (1997).

Secondly, we used an incubated orbital shaker instead of a shaking water bath as was described for the Boisen and Fernandez (1997) procedure. We made the assumption that there would be no difference between the two shaker methods as long as the desired temperature remained constant throughout incubation.

Finally, our study was designed to evaluate the organic matter digestibility in 113 kg finishing pigs, whereas the procedure by Boisen and Fernandez (1997) was developed for evaluating OMD for grower pigs 40-60 kg. It is possible the enzyme activities may need to be

altered to accurately reflect the increased digestibility (especially fiber fermentation) of finishing pigs.

In conclusion, this study showed that there a wide variation in actual DE and ME values among the 20 sources of corn co-products evaluated, which is likely due to the wide range in crude protein, fat, fiber, starch and ash content among sources. There was a poor relationship between *in vitro* OMD and *in vivo* ME, which may be due to some of the procedural modifications used in this study to use this *in vitro* assay to accurately predict *in vivo* ME.

**Table 1.** Sources of corn co-products

<u>Feedstuff</u>	<u>Vendor</u>
Corn gluten feed	Tate & Lyle, Ft. Dodge, IA
Corn bran	ICM/Lifeline Foods, St. Joseph, MO
Corn bran w/solubles	Poet Biorefining, Glenville, MN
DDGS	Ace Ethanol, Racine, WI
DDGS – drum dry	Cellencor, Heron Lake, MN
DDGS – microwave dry	Cellencor, Heron Lake, MN
DDGS	Hawkeye Renewables, Iowa Falls, IA
DDGS- Dakota Gold BPX	Poet Biorefining, Groton, SD
DDGS	VeraSun Energy Corpotation, Aurora, SD
DDGS – oil extracted	VeraSun Energy Corporation, Aurora, SD
Corn gluten meal	Archer Daniels Midland, Cedar Rapids, IA
HP-DDG	ICM/Lifeline Foods, St. Joseph, MO
HP-DDG	MOR Technology, Cape Girardeau, MO
HP-DDG	Poet Biorefining, Coon Rapids, IA
Corn germ, dehydrated	Poet, Coon Rapids, IA
Corn germ meal	Cargill, Eddyville, IA
Corn dried distillers solubles	Pulse Combustion Systems, Payson, AZ
Dehulled, degermed corn	Bunge North America, Atchison, KS
Corn starch	Archer Daniels Midland, Clinton, IA
Corn oil	Mazola, ACH Food Co., Memphis, TN

**Table 2.** Composition of corn co-products<sup>1</sup>

DM BASIS	DDGS (WI)	DDGS (IA)	DDGS (Verasun)	RO- DDGS (Verasun)	DDGS (BPX)	DDGS (MNdm)	DDGS (MNmc)	Dried solubles 0.330	corn gluten feed 0.499
Bulk density, g/cm <sup>3</sup>	0.581	0.470	0.487	0.494	0.467	0.530	0.396		
Particle size, microns	1054	784	579	480	330	568	866	WNP	571
Moisture	6.82	9.75	13.41	12.64	10.87	11.43	12.95	22.3	4.14
OM digestibility	74.22	62.25	64.7	57.14	65.43	63.85	62.97	93.48	60.99
Gross energy	5314	5375	5434	5076	5547	5550	5502	54.76	4539
Crude protein	29.62	29.65	31.94	34.74	29.49	32.69	34.12	23.75	24.29
Alanine	2.07	2.09	2.38	2.48	2.09	2.38	2.47	1.47	1.52
Arginine	1.33	1.46	1.49	1.44	1.37	1.47	1.55	1.20	1.13
Aspartic acid	1.87	1.96	2.11	2.19	1.93	2.24	2.22	1.48	1.45
Cysteine	0.53	0.57	0.60	0.61	0.59	0.64	0.61	0.39	0.52
Glutamic acid	4.41	4.50	5.20	5.43	4.70	5.11	5.33	2.79	3.70
Glycine	1.18	1.24	1.34	1.39	1.22	1.38	1.38	1.26	1.03
Histidine	0.77	0.83	0.90	0.89	0.82	0.90	0.94	0.60	0.72
Isoleucine	1.06	1.14	1.19	1.25	1.11	1.23	1.29	0.68	0.70
Leucine	3.47	3.45	3.90	4.12	3.37	3.88	4.08	1.58	2.03
Lysine	1.03	1.21	1.19	1.00	1.10	1.20	1.29	1.09	0.67
Methionine	0.56	0.58	0.65	0.64	0.54	0.64	0.65	0.32	0.30
Phenylalanine	1.29	1.61	1.48	1.51	1.31	1.48	1.55	0.53	0.77
Proline	2.08	2.23	2.52	2.54	2.29	2.44	2.57	1.29	1.87
Serine	1.37	1.32	1.52	1.58	1.30	1.47	1.53	0.90	0.88
Threonine	1.11	1.10	1.22	1.26	1.09	1.25	1.26	0.81	0.78
Tryptophan	0.21	0.19	0.20	0.18	0.21	0.23	0.23	0.21	0.13
Tyrosine	1.04	1.17	1.19	1.22	1.05	1.16	1.22	0.62	0.65
Valine	1.49	1.57	1.69	1.76	1.53	1.73	1.80	1.08	1.11
Starch	7.85	3.47	6.24	3.04	4.94	2.12	1.05	6.34	12.57
Crude fiber	7.05	7.76	7.56	8.69	7.95	7.93	8.35	0.08	8.56
Total dietary fiber	30.34	38.14	35.69	37.20	35.90	35.38	43.18	16.07	40.07
NDF	34.61	40.13	40.12	50.96	33.41	44.87	49.12	2.33	42.66
ADF	11.25	10.55	14.42	15.82	8.62	13.16	14.66	0.49	9.90
Cellulose	10.64	10.12	11.72	12.72	8.21	11.95	13.37	0.79	9.17
Lignin	1.21	1.06	3.16	3.49	1.00	1.72	1.92	0.31	1.05
Crude fat	11.45	10.89	10.16	3.15	11.71	12.10	11.98	11.81	2.70
Ash	4.16	4.43	4.46	5.16	5.41	4.55	4.04	14.08	6.81
Calcium (mg/kg)	204	248	475	652	663	240	230	1699	683
Copper (mg/kg)	6	6	5	8	6	5	5	9	8
Iron (mg/kg)	81	72	125	288	90	104	132	129	125
Magnesium (mg/kg)	3485	3023	3456	3986	3710	3736	3125	11389	5192
Manganese (mg/kg)	21	13	16	23	15	20	18	40	34
Phosphorus (mg/kg)	7913	8582	7527	8373	9613	8377	7394	24356	11979
Potassium (mg/kg)	11465	10974	10069	11232	13140	11758	10172	38597	19862
Selenium (mg/kg)	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Sodium (mg/kg)	172	1287	2414	3776	2659	1361	1324	4259	364
Sulfur (mg/kg)	8475	7940	7616	9772	11087	7288	6982	18069	4907
Zinc (mg/kg)	63	55	59	67	89	82	75	95	120

<sup>1</sup> Identity of individual feedstuffs described in Table 1. BDL = below detection limit and WNP = would not pass. All values based on DM basis except particle size and bulk densities which are based on as-is basis. Values on a percentage basis unless listed otherwise.

**Table 3.** Composition of corn co-products

DM BASIS	DH-DG corn	corn germ dehydrated	corn germ meal	corn bran (ICM)	corn bran (Poet)	corn gluten meal	HP-DDG (MOR)	HP-DDG (Poet)	HP-DDG (ICM)
Bulk density, g/cm <sup>3</sup>	0.687	0.435	0.465	0.158	0.346	0.677	0.636	0.576	0.604
Particle size, microns	477	1175	483	1841	2166	577	471	587	783
Moisture	12.78	9.44	10.87	12.62	9.18	8.51	8.3	5.95	12.31
OM digestibility	93.15	75.54	56.98	32.32	73.32	79.95	61.46	71.54	54.36
Gross energy	4397	5224	4767	4847	4982	5467	58.11	53.21	5464
Crude protein	8.28	17.54	23.64	10.94	15.17	66.30	57.45	43.83	39.98
Alanine	0.66	1.05	1.41	0.78	1.04	5.54	4.65	3.49	2.92
Arginine	0.28	1.31	1.67	0.65	0.77	2.38	2.26	1.63	1.68
Aspartic acid	0.48	1.35	1.68	0.81	1.02	4.23	3.75	2.82	2.44
Cysteine	0.17	0.34	0.37	0.22	0.30	1.08	1.13	0.81	0.74
Glutamic acid	1.74	2.47	3.22	1.67	1.95	13.51	10.88	7.88	6.84
Glycine	0.25	0.91	1.31	0.55	0.77	1.93	1.93	1.51	1.46
Histidine	0.22	0.51	0.72	0.31	0.44	1.41	1.36	1.17	1.07
Isoleucine	0.31	0.53	0.84	0.38	0.50	2.83	2.33	1.86	1.53
Leucine	1.25	1.27	1.91	1.10	1.30	10.67	8.57	6.37	5.12
Lysine	0.17	0.97	1.17	0.58	0.62	1.39	1.58	1.33	1.20
Methionine	0.16	0.28	0.42	0.18	0.23	1.41	1.44	0.94	0.81
Phenylalanine	0.45	0.66	1.02	0.50	0.55	4.14	3.13	2.37	1.96
Proline	0.77	1.07	1.20	0.82	1.08	5.59	4.77	3.79	3.06
Serine	0.39	0.68	1.00	0.53	0.65	2.91	2.86	2.02	1.68
Threonine	0.26	0.57	0.88	0.50	0.61	2.12	2.14	1.61	1.33
Tryptophan	0.06	0.17	0.20	0.06	0.09	0.24	0.29	0.14	0.19
Tyrosine	0.25	0.53	0.71	0.37	0.41	3.16	2.61	1.77	1.46
Valine	0.38	0.86	1.37	0.56	0.76	3.18	2.88	2.32	2.02
Starch	87.96	25.00	15.29	23.25	25.73	11.08	0.51	7.30	5.10
Crude fiber	0.60	4.87	10.69	11.54	4.80	1.44	8.14	9.42	7.87
Total dietary fiber	2.61	24.78	47.76	53.60	26.65	9.24	28.80	31.28	36.75
NDF	4.27	27.37	61.05	56.86	25.21	12.25	43.52	32.00	51.09
ADF	0.49	6.13	12.49	13.14	5.35	7.57	25.42	12.61	15.11
Cellulose	0.77	5.21	11.71	12.78	5.38	5.95	22.55	12.05	14.25
Lignin	0.33	1.28	1.22	0.89	0.55	2.24	3.40	0.95	1.44
Crude fat	0.17	18.45	2.38	5.14	9.68	1.34	4.12	2.86	6.97
Ash	0.49	6.46	2.70	2.33	5.31	3.99	1.10	2.05	2.09
Calcium (mg/kg)	13	159	359	164	314	6408	173	114	78
Copper (mg/kg)	1	7	36	5	5	18	6	4	4
Iron (mg/kg)	15	90	122	54	98	242	102	53	61
Magnesium (mg/kg)	268	5626	1905	1675	3277	1039	456	1110	936
Manganese (mg/kg)	1	22	11	15	17	25	17	6	5
Phosphorus (mg/kg)	879	15187	6496	4379	7578	6318	2486	4185	5029
Potassium (mg/kg)	1449	16593	4093	6464	13682	4596	1700	4389	3028
Selenium (mg/kg)	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Sodium (mg/kg)	115	83	839	63	4270	1029	231	1260	563
Sulfur (mg/kg)	1048	2141	3274	1460	9506	9051	7178	9034	7002
Zinc (mg/kg)	5	85	77	39	195	42	71	28	37

<sup>1</sup> Identity of individual feedstuffs described in Table 1. BDL = below detection limit. All values based on DM basis except particle size and bulk densities which are based on as-is basis. Values on a percentage basis unless listed otherwise.

**Table 4.** Digestible and metabolizable energy values, and dry matter (DMD) and organic matter (OMD) digestibility of corn co-products in finishing pigs<sup>1</sup>

Feedstuff	BW, kg	ADFI, kg		F-DMO, g/d <sup>2</sup>	DMD, % <sup>3</sup>	Energy, kcal/kg		OMD, % <sup>4</sup>
		Basal	Test			DE <sup>3</sup>	ME <sup>3</sup>	
Gluten feed	111.3	1712	800	620	51.52	2517	2334	60.99
Bran (ICM)	111.4	1689	720	521	55.99	3004	2957	32.32
Bran (Poet)	111.4	1671	759	466	63.66	3282	3031	73.32
DDGS (ACE)	118.6	1647	749	371	80.50	4332	4141	74.22
DDGS (MNdrum)	119.3	1525	660	355	69.72	4116	3876	63.86
DDGS (MNmicro)	116.2	1532	652	346	70.47	4016	3713	62.97
DDGS (Hawk)	112.9	1763	776	458	69.19	3841	3659	62.25
DDGS (Poet)	109.5	1673	746	449	66.16	3705	3414	65.43
DDGS (VS)	113.0	1762	744	403	75.04	4164	3937	64.69
RO-DDGS (VS)	111.9	1728	736	406	73.87	3868	3650	57.14
Gluten meal	118.0	1574	702	276	90.71	5047	4598	79.95
HP-DDG (ICM)	113.3	1634	717	369	75.00	3994	3676	54.36
HP-DDG (MOR)	117.2	1570	702	305	86.59	4955	4606	61.46
HP-DDG (Poet)	106.8	1521	716	315	81.00	4210	3823	71.53
DCG (Poet)	106.0	1630	739	380	74.22	3889	3692	75.53
Germ meal	112.0	1574	684	387	74.57	3521	3417	56.98
Solubles (20%)	111.9	1729	383	269	75.49	4762	4525	93.47
DH-DG corn	110.7	1692	720	207	100.32	4401	4316	93.15
Starch	113.4	1603	717	156	101.39	4082	4080	90.24
Oil (10%)	117.3	2097	266	232	97.22	8988	8755	100*
Mean	113.0	1667	685	363	76.82	4250	4028	89.41
SD	7.53	192.1	78.9	66.0	7.69	362.5	413.0	1.12

<sup>1</sup> Data represents 8 individually fed pigs, collected for 4 d following a 9 d adaptation period. The basal diet contained 97.1% corn with the remaining 2.9% consisting of minerals and vitamins. Data reported on a DM basis. Identity of each feedstuff described in Table 1.

<sup>2</sup> Fecal DM output (F-DMO).

<sup>3</sup> Dry matter digestibility adjusted using a basal DM digestibility of 88.16 (actual basal average = 88.05, SE 1.75), DE adjusted using a basal DE of 3,772 kcal/kg DM (actual as-is average = 3,287, SD 65.9), and ME adjusted using a basal ME of 3,695 kcal/kg DM (actual as-is average = 3,221, SE 69.4) obtained from 8 groups of control pigs (4 pigs per ingredient grouping).

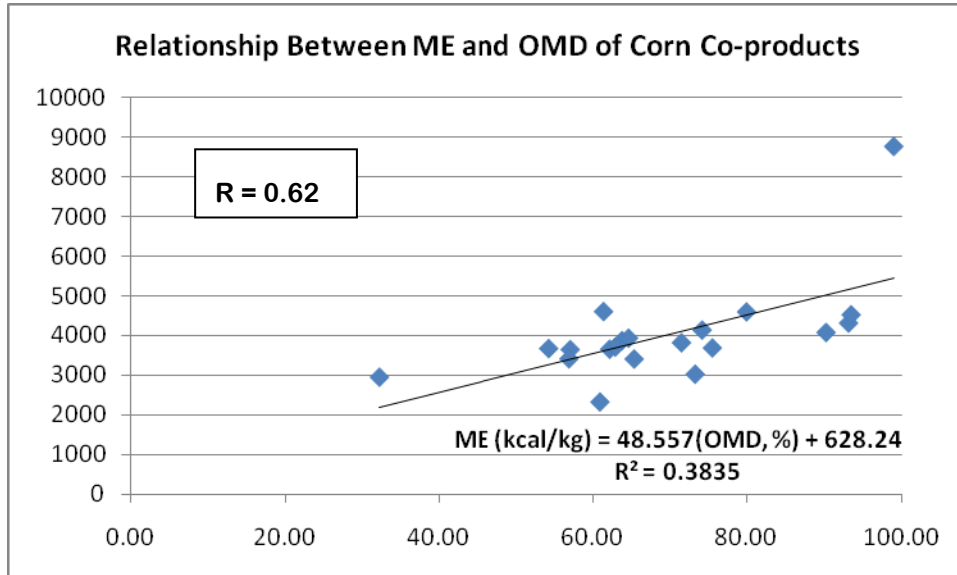
<sup>4</sup> Organic matter digestibilities (OMD) adjusted using an average corn OM digestibility of 89.41 (SD 1.12). The basal diets used in the *in vivo* experiments exhibited an average OM digestibility of 89.72 (SD 0.82). Method details described by Boisen and Fernandez (1997).

**Table 5.** Equation for predicting ME from chemical analysis of corn co-products in finishing pigs

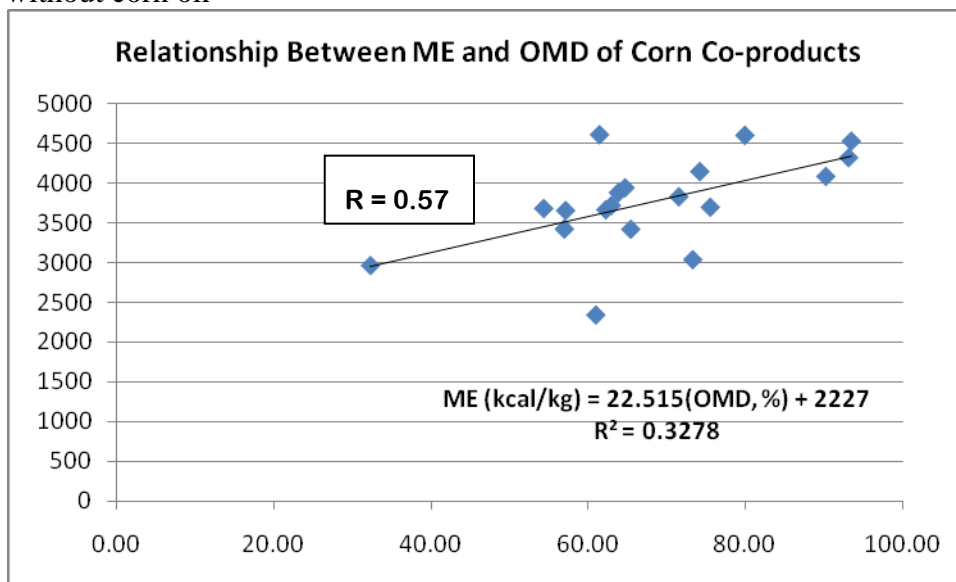
Equation <sup>1</sup>	R <sup>2</sup>	SE	P-value
ME = 0.949 × GE – 32.238 × TDF – 40.175 × Ash	0.95	306	< 0.01

<sup>1</sup>ME = kcal/kg DM; GE = kcal/kg DM; TDF = %; Ash = %

**Figure 1.** Metabolizable energy (ME) and organic matter digestibility (OMD) of corn co-products and corn oil



**Figure 2.** Metabolizable energy and organic matter digestibility (OMD) of corn co-products without corn oil



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