# Relationships among dietary fiber components and the digestibility of energy, dietary fiber, and amino acids and energy content of nine corn coproducts fed to growing pigs[1]

N. A. Gutierrez,* N. V. L. Serão,* B. J. Kerr,† R. T. Zijlstra,‡ and J. F. Patience*[2]

*Department of Animal Science, Iowa State University, Ames 50011;
†USDA-ARS-National Laboratory for Agricultural and the Environment, Ames, IA 50011;
‡Department of Agriculture, Food and Nutritional Science, University of Alberta, Edmonton, AB T6G 2P5, Canada.

**ABSTRACT:** An experiment was conducted to determine a best fitting dietary fiber (DF) component to estimate the effect of DF concentration on the digestibility of energy, DF, and AA and energy value of 9 corn coproducts: corn bran (37.0% total nonstarch polysaccharides [NSP]); corn bran with solubles (17.1% NSP); cooked corn distillers dried grains with solubles (DDGS; 20.4% NSP); reduced oil DDGS (25.0% NSP); uncooked DDGS (22.0% NSP); high protein distillers dried grains (21.9% NSP); dehulled, degermed corn (1.1% NSP); corn germ meal (44.4% NSP); and corn gluten meal (4.9% NSP). A total of 20 growing pigs (initial BW: 25.9 ± 2.5 kg) were fitted with a T-cannula in the distal ileum and allotted to 10 dietary treatment groups in a 4-period incomplete block design with 8 observations per treatment. Treatments included a corn–soybean meal–based basal diet and 9 diets obtained by mixing 70% of the basal diet with 30% of the test ingredient. In tested ingredients, 11 DF components were determined: 1) ADF, 2) NDF, 3) total dietary fiber, 4) hemicellulose, 5) total NSP, 6) NSP arabinose, 7) NSP xylose, 8) NSP mannose, 9) NSP glucose, 10) NSP galactose, and 11) arabinoxylan. The apparent ileal digestibility (AID) and apparent total tract digestibility (ATTD) of GE, DM, and NDF and the AID of AA of ingredients were measured. A single best fitting DF component was assessed and ranked for each trait, showing that arabinoxylan concentration best explained variance in AID of GE ($R^2$ = 0.65; cubic, $P$ < 0.01) and DM ($R^2$ = 0.67; cubic, $P$ < 0.01). The NSP xylose residue best explained variance in ATTD of GE ($R^2$ = 0.80; cubic, $P$ < 0.01), DM ($R^2$ = 0.78; cubic, $P$ < 0.01), and NDF ($R^2$ = 0.63; cubic, $P$ < 0.01); AID of Met ($R^2$ = 0.40; cubic, $P$ = 0.02), Met + Cys ($R^2$ = 0.44; cubic, $P$ = 0.04), and Trp ($R^2$ = 0.11; cubic, $P$ = 0.04); and DE ($R^2$ = 0.66; linear, $P$ = 0.02) and ME ($R^2$ = 0.71; cubic, $P$ = 0.01) values. The AID of Lys was not predictable ($P$ > 0.05) from the DF concentration. In conclusion, the arabinoxylan and NSP xylose residue were the DF components that best explained variation due to DF concentration and, with the exception of AID of Lys, can be used to predict the digestibility of energy and DF and the DE and ME values in corn coproducts.

**Key words:** corn coproducts, dietary fiber, digestibility, energy, pig


J. Anim. Sci. 2014.92:4505–4517
doi:10.2527/jas2013-7265

## INTRODUCTION

Corn coproducts are typically rich in dietary fiber (**DF**) but variable in starch, AA, and fat. Knowledge of the concentration and composition of DF of feed ingredients is important, because it may reduce AA and energy digestibility (Farrell, 1973; Noblet and Perez, 1993; Souffrant, 2001). The DF in corn and coproducts is resistant to fermentation, consisting of insoluble nonstarch polysaccharides (**NSP**) such as cellulose, arabinoxylans, and lignin (Bach Knudsen,

[1]Financial support for this research was provided on behalf of the National Pork Board and Dakota Gold Research Foundation. Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by Iowa State University, the University of Alberta, or the USDA and does not imply approval to the exclusion of other products that may be suitable. The USDA is an equal opportunity provider and employer.
[2]Corresponding author: jfp@iastate.edu
Received October 15, 2013.
Accepted August 2, 2014.

1997; Jaworski, 2012). These polysaccharides are mainly polymers of hexoses (D-glucose, D-galactose, and D-mannose) and pentoses (L-arabinose and D-xylose) joined by glycosidic linkages. Common assays to determine the DF concentration of a feed ingredient include ADF and NDF. Classification by differences in solubility in acid and alkali or in neutral and acid detergents lacks precision with respect to chemical composition and biological function. Therefore, the nutritional relevance of values obtained using these methods in monogastric nutrition is questionable (Choct, 1997). The analysis for total NSP and its monosaccharide residues may be a tool to better explain the effect of DF on the nutritional value of corn coproducts.

Increasing the efficiency of starch and oil extraction from the corn grain, resulting in changes in chemical composition of corn coproducts, present a challenge to estimate their nutritional value. Fairbairn et al. (1999) reported that NDF or ADF alone accounted for 68 and 85% of the total variation in DE content of barley, respectively. However, a comprehensive analysis of the effects of DF concentration on the nutrient value of corn coproducts is unavailable.

In the present study, 9 corn coproducts were selected to cover a wide range in DF concentration. The objective of the study was to determine a best fitting DF component to measure the effect of DF concentration on the variation in digestibility of energy, DF, and AA and on energy values in corn coproducts.

## MATERIALS AND METHODS

The experimental protocol was reviewed and approved by the Institutional Animal Care and Use Committee at Iowa State University (9-10-7024-S).

### *Animals, Housing, and Experimental Design*

Twenty growing barrows (progeny of sire line 337 × dam line C-22; PIC, Hendersonville, TN) were housed in individual pens (1.2 by 1.2 m) equipped with a feeder, a cup waterer, and a half-slatted concrete floor in an environmentally controlled building. All pigs were surgically fitted with a T-cannula in the distal ileum following procedures described by Stein et al. (1998). After recovery from surgery, pigs were weighed (initial BW = 25.9 ± 2.5 kg) and randomly allotted to 10 dietary treatment groups in a 4-period incomplete block design, resulting in 8 experimental units per treatment. Pigs were not allowed to repeat dietary treatments across periods. Each collection period involved 9 d of adaptation to dietary treatments followed by 2 d of feces subsample collection and 3 d of ileal digesta subsample collection.

**Table 1.** Ingredient composition (%) of the basal and experimental diets (as-fed basis)[1]

| Item | Basal | Experimental diets |
|---|---|---|
| Ingredient | | |
| Corn | 65.15 | 45.60 |
| Soybean meal, 46.5% | 29.00 | 20.30 |
| Corn coproduct | – | 30.00 |
| Soybean oil | 2.00 | 1.40 |
| Limestone | 1.10 | 0.77 |
| Monocalcium phosphate | 1.20 | 0.84 |
| $Cr_2O_3$ | 0.55 | 0.39 |
| Vitamin premix[2] | 0.20 | 0.14 |
| Trace mineral premix[3] | 0.20 | 0.14 |
| Salt | 0.60 | 0.42 |
| Energy and nutrients[4] | | |
| DM, % | 90.36 | 87.94–92.87 |
| GE, Mcal/kg | 3.89 | 3.85–4.25 |
| CP, % | 18.32 | 13.76–30.29 |
| NDF, % | 6.97 | 5.93–18.67 |
| Lys, % | 0.86 | 0.66–1.04 |
| Thr, % | 0.61 | 0.51–1.03 |
| Met, % | 0.24 | 0.21–0.64 |
| Met + Cys, % | 0.47 | 0.42–1.16 |
| Trp, % | 0.23 | 0.16–0.25 |
| Indispensable AA, % | 7.13 | 5.96–13.69 |
| Dispensable AA, % | 8.37 | 7.25–16.68 |

[1]Experimental diets were obtained by mixing 70% of the basal diet and 30% of the corn coproduct tested.

[2]Provided per kilogram of complete diet: 6,614 IU of vitamin A, 827 IU of vitamin D, 26 IU of vitamin E, 2.6 mg of vitamin K, 29.8 mg of niacin, 16.5 mg of pantothenic acid, 5.0 mg of riboflavin, and 0.023 mg of vitamin $B_{12}$.

[3]Provided per kilogram of complete diet: Zn, 165 mg as $ZnSO_4$; Fe, 165 mg as $FeSO_4$; Mn, 39 mg as $MnSO_4$; Cu, 17 mg as $CuSO_4$; I, 0.3 mg as $Ca(IO_3)_2$; and Se, 0.3 mg as $Na_2SeO_3$.

[4]Analyzed values.

### *Dietary Treatments*

Dietary treatments included a corn–soybean meal basal diet (Table 1) that was formulated to meet or exceed the nutrient requirements of growing pigs (NRC, 1998). Nine additional experimental diets were obtained by mixing 70% of the basal diet and 30% of the corn coproduct to be tested. Corn coproducts evaluated in the experiment included corn bran with solubles (**CB-S**; Poet Nutrition, Glenville, MN); corn bran (**CB**; Lifeline Foods, St. Joseph, MO); cooked corn distillers dried grains with solubles (**DDGS**; **DDGS-CV**; Hawkeye Renewables, Iowa Falls, IA); reduced oil DDGS (**DDGS-RO**; Hawkeye Renewables); uncooked DDGS (**DDGS-BPX**; Poet Nutrition, Hanlontown, IA); high protein distillers dried grains (**HP-DDG**; Poet Nutrition, Glenville, MN); dehulled, degermed corn (**DDC**; Bunge North America, Atchison, KS); corn germ meal (**CGmM**; Cargill, Eddyville, IA); and corn gluten meal (**CGnM**; Cargill). Diets also contained 0.55% $Cr_2O_3$ as an inert marker. All pigs received the same daily amount of feed, which was provided at a level of approximately 90% of predicted ad libitum intake of the basal diet. The daily feed allowance was divided into 2 equal meals provided at 0700 and 1600 h. At the end of each collection period, all pigs were weighed and daily feed allowance for the next collection period was adjusted.

### *Sample Collection*

After 9 d of adaptation to the diet, feces were collected via grab sampling on d 10 and 11 and stored at –20°C. On d 12, 13, and 14, ileal digesta samples were collected for 8 h by attaching a 207-mL plastic bag (Whirl-Pak; Nasco, Fort Atkinson, WI) to the opened cannula with a cable tie. Bags were removed whenever they were filled with digesta or at least every 30 min and stored at –20°C to prevent bacterial degradation. At the conclusion of each experimental period, frozen ileal and fecal samples were allowed to thaw at room temperature and pooled within animal, with a subsample collected for chemical analysis. Ileal subsamples were lyophilized before chemical analysis. Fecal subsamples were oven dried in a convection oven at 65°C to constant weight (Jacobs et al., 2011). After drying, feed, ileal, and fecal subsamples were ground through a 1-mm screen before chemical analysis.

### *Chemical Analysis*

Samples of diets and feed ingredients were analyzed for DM (method 930.15; AOAC, 2007), ether extract (**EE**; method 920.39; AOAC, 2007), starch (method 996.11; AOAC, 2007), ADF (Goering and Van Soest, 1970), NDF (Van Soest and Robertson, 1980), total dietary fiber (**TDF**; method 985.29; AOAC, 2007), and N (method 968.06; AOAC, 1990). Crude protein was calculated as N × 6.25 and Gly was used as the calibration standard (N content 18.7%; Fisher Scientific, Fair Lawn, NJ) and was determined to contain 18.7 ± 0.2% N. The 9 ingredients were analyzed for total constituent monosaccharides in NSP and insoluble NSP by GLC (Englyst and Hudson, 1987). Ileal digesta and fecal samples were also analyzed for DM, NDF, and N. The GE of diets, feed ingredients, ileal digesta, and feces was analyzed by bomb calorimetry (Parr 6200 calorimeter; Parr Instruments Co., Moline, IL). Benzoic acid (6,318 kcal GE/kg; Parr Instruments Co.) was used as the standard for calibration and was determined to contain 6,324 ± 9.8 kcal GE/kg. Diets, feed ingredients, and ileal digesta were analyzed for AA (University of Missouri Agriculture Experiment Station Chemical Laboratories, Columbia, MO) according to method 982.30 E (a, b, c; AOAC, 2007). Chromic oxide was determined in diets, ileal digesta, and fecal subsamples using the method of Fenton and Fenton (1979) and absorption was measured at 440 nm using a spectrophotometer (Synergy 4; BioTek, Winooski, VT). Chromic oxide standard samples were assayed to confirm the accuracy of the analytical procedure, and a recovery of 100.8 ± 1.95% was attained.

### *Calculations*

For each dietary treatment, the apparent ileal digestibility (**AID**) and apparent total tract digestibility (**ATTD**) of DM, GE, and NDF and the AID of AA were calculated using the index method (Oresanya et al., 2008). The difference procedure was used to calculate the AID and ATTD of DM, GE, and NDF and the AID of AA of each ingredient (Adeola, 2001). The DE value was determined by multiplying the GE by the observed ATTD of GE of the ingredient, and the ME was estimated from the calculated DE and CP of the ingredient (Noblet and Perez, 1993).

Effects of DF concentration in feed ingredients were determined using 11 different DF components: 1) ADF; 2) NDF; 3) TDF; 4) hemicellulose (NDF – ADF); 5) total NSP; concentrations of 5 monosaccharide residues that can be detected in NSP, namely, 6) NSP arabinose, 7) NSP xylose, 8) NSP mannose, 9) NSP glucose, 10) NSP galactose, and 10) arabinoxylan; and 11) total NSP (sum of monosaccharide residue in NSP).

Traits were grouped into 4 categories to simplify statistical analysis of data as follows: 1) AID, including AID of DM, GE, and NDF; 2) ATTD, including ATTD of DM, GE, and NDF; 3) AID of AA, including AID of Lys, Thr, Met, Met + Cys, Trp, and average of all dispensable and all indispensable AA; and 4) energy concentration, including DE and ME values.

### *Statistical Analyses*

***Analysis of Ingredient and Normality Test.*** The data were analyzed in a mixed model including the fixed effect of ingredient (**I**) and the random effects of period and pig following the model

$$Y_{ijkl} = \mu + \tau_i + P_j + A_k + e_{ij(k)l}\,, \qquad [1]$$

in which $Y_{ijkl}$ is the observed values for the trait, μ is the overall mean, $\tau_i$ is the effect of the $i$th ingredient ($i$ = 1 to 9), $P_j$ is the effect of the $j$th period ($j$ = 1 to 4, $[0,\sigma_p^2]$), $A_k$ is the effect of the $k$th experimental unit ($k$ = 1 to 20, $[0,\sigma_a^2]$), and $e_{ij(k)l}$ is the random error associated with $Y_{ijkl}$ (l = 2 to 4, $[0,\sigma_e^2]$).

Studentized residuals were generated from Eq. [1] and used to test normality. Outliers were removed until the Shapiro-Wilk's test reached $P > 0.05$ and studentized residual fell within ±3σ. The effect of Ingred was tested including the Kenward-Roger degrees-of-freedom approximation. Least squares means for Ingred were estimated and compared using the Tukey-Kramer adjustment. The effect of Ingred and multiple comparison differences were deemed significant at $P \leq 0.05$.

***Analysis of Dietary Fiber Concentration in Ingredients.*** An alternative method was proposed by including the effect of DF concentration of the ingredient in the model. The 11 different DF components were evaluated using a modified version of Eq. [1]. In this alternative model the linear, quadratic, and cubic effects of DF concentration instead of Ingred were included, following the model

$$Y_{ijkl} = ¼ + {}^{2}{}_{1}X_i + {}^{2}{}_{2}X_i^2 + {}^{2}{}_{3}X_i^3 + P_j + A_k + e_{ij(k)l}\,, \quad [2]$$

in which $Y_{ijkl}$, μ, $P_j$, $A_k$, and $e_{ij(k)l}$ are the same as defined in Eq. [1] and $\beta_1$, $\beta_2$, and $\beta_3$ are the linear, quadratic, and cubic effects associated with the DF concentration terms $X_i$, $X_i^2$, and $X_i^3$, respectively.

***Comparison between Fiber Models and Ingredient.*** The goodness-of-fit of Eq. [2] was assessed for all DF components to identify the DF component that best fits the trait categories and then compared to the model fit using Ingred (Eq. [1]). The Akaike information criterion (**AIC**) was used to measure the goodness-of-fit of these models. The AIC values were calculated using maximum-likelihood estimation to compare models with different fixed effects (Bolker et al., 2009)

The best fitting DF component, that is, the DF model that resulted in the lowest AIC statistics within a trait category, was obtained by ranking the AIC values of each trait within category. The overall fit of the 11 DF components within category was assessed as the average ranking of the assays. The assay showing the best fit within category was then compared to the goodness-of-fit when using Ingred for each trait.

***Regression Equations of the Best Dietary Fiber Component and Loss of Predictability.*** The linear, quadratic, and cubic effects of DF concentration in Eq. [2] were tested for and kept in the model according to the significance of the highest order term. To assess the loss in predictability of the DF concentration models compared to the Ingred, the residuals obtained from Eq. [2] were further analyzed including only the fixed effect of Ingred in the model without the intercept. The variance explained by the DF concentration using the best fitting DF component in Eq. [2] was compared to the variance explained by Ingred using the $R^2$ for linear mixed models ($\boldsymbol{R^2}_{\mathbf{LMM}(\boldsymbol{m})}$; Nakagawa and Schielzeth, 2013) as

$$R^2_{\mathrm{LMM}(m)} = \sigma_f^2 \,/\, \sigma_f^2 + \sigma_p^2 + \sigma_a^2 + \sigma_e^2\,, \quad [3]$$

in which $\sigma_f^2$ is the variance calculated from the fixed effect (concentration of the best fitting DF component) components (Snijders and Bosker, 1999), whereas $\sigma_p^2$, $\sigma_a^2$, and $\sigma_e^2$ are the period, experimental unit, and residual variances. For simplicity, $R^2_{\mathrm{LMM}(m)}$ will hereafter be referred to as $\boldsymbol{R^2}_{\mathbf{fiber}}$. Similarly, the variance due to Ingred ($\sigma_i^2$) was calculated on the residuals of Eq. [2] and computed an $R^2$ using the same variance components as in Eq. [3] but $\sigma_f^2$ as

$$R^2_{Ingred} = \sigma_i^2 \,/\, \sigma_p^2 + \sigma_a^2 + \sigma_e^2\,. \quad [4]$$

The advantage of this sequential approach is that it measures the variance explained by Ingred on the portion of the variance not explained by the DF concentration, allowing the direct comparison of these 2 $R^2$. The loss in predictability of the DF concentration in place of the Ingred was computed as $R^2_{\mathrm{Ingred}}/(R^2_{\mathrm{Ingred}} + R^2_{\mathrm{fiber}})$. All statistical analyses were performed using SAS 9.3 (SAS Inst., Inc., Cary, NC).

## RESULTS AND DISCUSSION

### *Nutrient Composition of Corn Coproducts*

All pigs were successfully cannulated at the distal ileum and recovered from surgery without complications. Corn coproducts came from the same source but different batches, as in Anderson et al. (2012), and the analyzed composition was similar (Table 2). Extensive variation in nutrient composition was observed among ingredients, reflecting the diversity of the selected coproducts and the manufacturing processes used.

The NDF and TDF concentration of DDGS was close to values reported in the literature (Stein et al., 2006; Anderson et al., 2012; NRC, 2012) and was similar to the NDF and TDF concentration in HP-DDG. The concentration of NDF and TDF in HP-DDG was expected to be less than in the 3 sources of DDGS, because the bran is separated from the corn kernel during HP-DDG production. However, the bran may have been added back to the HP-DDG after production, which is supported by the higher concentration of NSP glucose residue in HP-DDG than in the 3 sources of DDGS, because bran is rich in cellulose and therefore has a high concentration of NSP glucose. The NDF concentration in HP-DDG was similar to values reported in NRC (2012) but has been shown to range from

**Table 2.** Analyzed nutrient composition of ingredients (as-fed basis)

| | Ingredient[1] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Item | CB-S | CB | DDGS-CV | DDGS-RO | DDGS-BPX | HP-DDG | DDC | CGmM | CGnM |
| DM, % | 95.3 | 80.9 | 89.4 | 90.1 | 91.5 | 93.9 | 90.1 | 91.9 | 92.1 |
| GE, Mcal/kg | 4.58 | 3.68 | 4.77 | 4.72 | 4.74 | 4.88 | 3.86 | 4.33 | 5.06 |
| Ether extract, % | 7.9 | 1.2 | 9.9 | 8.8 | 8.3 | 3.2 | 1.1 | 3.1 | 1.5 |
| Starch, % | 19.0 | 21.1 | 2.8 | 2.9 | 5.2 | 8.2 | 68.5 | 16.4 | 12.0 |
| ADF, % | 5.1 | 10.5 | 9.2 | 14.3 | 7.9 | 11.8 | 0.4 | 11.5 | 7.0 |
| NDF, % | 22.7 | 40.6 | 34.5 | 38.7 | 30.8 | 31.1 | 3.8 | 46.2 | 12.1 |
| Hemicellulose,[2] % | 17.6 | 30.1 | 25.3 | 24.4 | 22.9 | 19.3 | 3.4 | 34.7 | 5.1 |
| TDF,[3] % | 25.3 | 42.5 | 32.6 | 32.9 | 29.1 | 28.9 | 2.3 | 44.1 | 8.8 |
| I-NSP,[4] % | | | | | | | | | |
| Arabinose | 3.4 | 8 | 4.7 | 4.1 | 4.4 | 3.8 | 0.5 | 10.4 | 0.8 |
| Xylose | 5.9 | 14.4 | 5.9 | 6.1 | 6.3 | 4.9 | 0.4 | 9.9 | 0.7 |
| Mannose | 0.1 | 0.3 | 0.6 | 0.5 | 0.7 | 1.3 | – | 0.3 | – |
| Glucose | 5.3 | 11.7 | 6.9 | 6.6 | 7.3 | 8.6 | 0.2 | 10.8 | 1.4 |
| Galactose | 1.1 | 2.4 | 1.3 | 1 | 1.2 | 0.8 | – | 2 | 0.6 |
| Total insoluble | 15.7 | 36.8 | 19.2 | 18.2 | 19.9 | 19.3 | 1.1 | 33.5 | 3.5 |
| S-NSP,[5] % | | | | | | | | | |
| Arabinose | 0.1 | –0.1 | 0.2 | 2.2 | 0.5 | 0.3 | –0.1 | 5.4 | 0.3 |
| Xylose | 0.1 | –0.2 | – | 1.9 | 0.1 | 0.2 | – | 3.5 | 0.2 |
| Mannose | 0.6 | 0.1 | 0.3 | 0.4 | 0.5 | 0.6 | – | –0.3 | – |
| Glucose | 0.4 | 0.5 | 0.5 | 1.7 | 0.8 | 1.1 | 0.1 | 1.5 | 0.4 |
| Galactose | 0.1 | – | – | 0.5 | 0.2 | 0.2 | – | 0.8 | 0.5 |
| Total soluble | 1.4 | 0.2 | 1.2 | 6.8 | 2.1 | 2.6 | – | 10.9 | 1.4 |
| T-NSP,[6] % | | | | | | | | | |
| Arabinose | 3.5 | 7.9 | 4.9 | 6.3 | 4.9 | 4.1 | 0.4 | 15.8 | 1.1 |
| Xylose | 6 | 14.2 | 5.9 | 8 | 6.4 | 5.1 | 0.4 | 13.4 | 0.9 |
| Mannose | 0.7 | 0.4 | 0.9 | 0.9 | 1.2 | 1.9 | 0 | 0 | 0.1 |
| Glucose | 5.7 | 12.2 | 7.4 | 8.3 | 8.1 | 9.7 | 0.3 | 12.3 | 1.8 |
| Galactose | 1.2 | 2.4 | 1.3 | 1.5 | 1.4 | 1 | 0 | 2.8 | 1.1 |
| Total NSP,[7] % | 17.1 | 37.0 | 20.4 | 25.0 | 22.0 | 21.9 | 1.1 | 44.4 | 4.9 |
| Total arabinoxylan,[8] % | 9.5 | 22.1 | 10.8 | 14.3 | 11.3 | 9.2 | 0.8 | 29.2 | 2.0 |

[1]CB-S = corn bran with solubles; CB = corn bran; DDGS-CV = cooked corn distillers dried grains with solubles (DDGS); DDGS-RO = reduced oil DDGS; DDGS-BPX = uncooked DDGS; HP-DDG = high protein distillers dried grains; DDC = dehulled, degermed corn; CGmM = corn germ meal; CGnM = corn gluten meal.

[2]Hemicelluose = NDF – ADF.

[3]TDF = total dietary fiber.

[4]I-NSP = insoluble monosaccharide residues nonstarch polysaccharides (NSP), as percent of the ingredient.

[5]S-NSP = soluble monosaccharide residues in NSP, as percent of the ingredient. S-NSP = T-NSP – I-NSP.

[6]T-NSP = total monosaccharide residues in NSP, as percent of the ingredient.

[7]Total NSP = sum of T-NSP monosaccharide residues.

[8]Total arabinoxylan = $\text{T-NSP}_{arabinose} + \text{T-NSP}_{xylose}$.



16 to 41% depending on the manufacturing process used (Widmer et al., 2007; Robinson et al., 2008; Kim et al., 2009). The DF concentration varied among similar coproducts such as CB-S and CB. In CB-S, solubles remaining from the corn-ethanol distillation process were added to the corn bran and the NDF and TDF concentration were half of previously reported values for corn bran without solubles (Sauvant et al., 2004; Anderson et al., 2012). The NDF concentration of CGmM (46.2%) and CGnM (12.1%) was similar to previously reported values (Almeida et al., 2011; Anderson et al., 2012; NRC, 2012). The NDF concentration in CGnM was, however, greater than values reported by Sauvant et al. (2004) and NRC (2012).

In theory, TDF should be higher than NDF because soluble DF components are lost in NDF due to solubilization with the neutral detergents. The TDF to NDF ratio in CB, CB-S, and DDGS-CV was 1.05, 1.11, and 1.03, respectively, but in the remaining 6 ingredients ranged from 0.61 in DDC to 0.95 in CGmM. Urriola et al. (2010) reported lesser TDF than NDF values in 8 sources of corn DDGS, with TDF to NDF ratios ranging from 0.79 to 0.91. In corn and coproducts, however, most of the DF is insoluble and a reasonable relative agreement between NDF and TDF is expected as they are supposed to measure the same chemical entities. Although only 3 ingredients showed greater TDF than

NDF concentrations, values of TDF and NDF were similar overall in the present study, with the exception of DDC. Comparable differences between TDF and NDF values have been previously documented. The TDF to NDF ratios reported by Anderson et al. (2012) for CB (0.94), CB-S (1.06), DDGS (0.79 to 1.07), HP-DDG (0.66 to 0.98), CGnM (0.75), and DDC (0.61) agree with the TDF and NDF values and variation reported in the present study. Likewise, Campbell et al. (1997) reported differences between TDF and NDF concentrations in feed ingredients with high concentration of insoluble DF such as corn bran (0.90), rice bran (0.94), peanut hulls (0.97), and solka floc (1.07).

Total NSP values were lower but followed the same concentration pattern as NDF and TDF values, with the exception of CGmM. The NSP to TDF ratio ranged from 0.48 in DDC to 0.87 in CB but was 1.01 for CGmM. Total NSP values were expected to be lower than TDF values because lignin is included in the latter. However, similar variation in NSP to TDF ratios was observed in feed ingredients rich in insoluble DF content, with NSP to TDF ratios of 0.52, 0.55, 0.61, and 0.75 for solka floc, peanut hulls, corn bran, and rice bran, respectively (Campbell et al., 1997).

The inconsistency between expected and observed NDF, TDF, and NSP ratios reported in the literature and in the present study may be caused by differences in the nature of the analytical procedures used (acid and neutral detergents, enzymatic–gravimetric, enzymatic–chemical etc.). For example, TDF values determined in feed ingredients rich in insoluble DF by Prosky-TDF (enzymatic–gravimetric; Prosky et al., 1985) or Uppsala-TDF (enzymatic–chemical; Theander et al., 1995) showed differences between the 2 TDF values in corn bran (53.5 vs. 42.8), rice bran (17.2 vs. 21.3), peanut hulls (76 vs. 73.4), or solka floc (96.2 vs. 43; Campbell et al., 1997). Discrepancies may be exacerbated by low DF concentration in the feed ingredient, as observed in DDC.

The analysis of monosaccharide residues of NSP indicated that glucose was the most prevalent residue followed by xylose, arabinose, galactose, and mannose. Insoluble monosaccharide residues composed the majority of total NSP in all 9 corn coproducts. In DDGS-RO, CGmM, and CGnM, however, about a third of total NSP were soluble. The total NSP, monosaccharide residues of NSP, and insoluble NSP observed for DDGS in the present study agree with the concentrations reported by Widyaratne and Zijlstra (2007). The monosaccharide composition relates structurally to the polysaccharides forming the NSP of corn coproducts, such as arabinoxylans, cellulose, and galactomannans (Bach Knudsen, 1997; Choct, 2002).

The CP (7.5 to 59.5%) and AA concentrations varied among corn coproducts, with CGnM exhibiting the greatest values for CP and each AA, contrasting with CB-S, CB, and DDC (Table 3). As expected, the AA concentrations in HP-DDG were greater than in DDGS and in agreement with data published for HP-DDG (Widmer et al., 2007; Kim et al., 2009; NRC, 2012). The range in AA composition noted for DDGS was also similar to data published in the literature (Spiehs et al., 2002; Almeida et al., 2011; NRC, 2012). In CGmM and CGnM, the CP (20.6 and 59.5%, respectively) and AA concentrations were close to expected values (Almeida et al., 2011; NRC, 2012).

### *Apparent Ileal Digestibility of Traits and Energy Concentrations*

The AID and ATTD of GE and DM differed ($P < 0.05$) among ingredients (Table 4). Because most of the DM in DDC and in CGnM is starch and protein, respectively, the AID of GE and DM were the greatest ($P < 0.05$) among all ingredients. The AID of GE and DM were similar ($P > 0.05$) in the 4 sources of DDGS and both corn brans.

As expected, the ATTD of GE in both DDC (99.6%) and CGnM (91.6%) were the greatest ($P < 0.05$). In contrast, the ATTD of GE and DM in CB-S and CB were the lowest but similar to the observed AID values, meaning that both ingredients were highly resistant to hindgut fermentation. The observed ATTD of GE and DM of DDGS, CGmM, and CGnM are in agreement with values reported previously (Stein et al., 2006; Rojas and Stein, 2013). The ATTD of GE and DM of HP-DDG were, however, less than values obtained previously for HP-DDG (Widmer et al., 2007; Kim et al., 2009), which may be explained by the greater DF concentration caused by the added bran in the HP-DDG used in this study.

The apparent digestibility of NDF, on the other hand, did not differ at the ileal level ($P = 0.11$) but differed ($P < 0.05$) at the total tract level among ingredients. The difference between AID and ATTD of NDF values observed for the 3 DDGS sources indicated that approximately 18% of the NDF was fermented in the hindgut, which is in agreement with data reported by Urriola et al. (2010). In CB-S and CB, however, values of ATTD of NDF were lower than AID values. Unreliable values of AID of DF have been previously reported in wheat bran (Graham et al., 1986; Jorgensen et al., 1996) and in low and medium fiber diets (Wilfart et al., 2007), which was attributed to a combination of sampling or analytical errors and the relatively high variability of results. Partial separation of DF components and $Cr_2O_3$ as they flow through the digestive tract may also negatively affect the reliability of estimation of DF digestibility (Graham and Åman, 1986). Additionally, the ATTD of NDF in DDC (136.8%) largely surpassed 100%. It is very difficult

**Table 3.** Analyzed AA concentration (%) of ingredients (as-fed basis)

| | Ingredient[1] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Item, % | CB-S | CB | DDGS-CV | DDGS-RO | DDGS-BPX | HP-DDG | DDC | CGmM | CGnM |
| CP | 13.0 | 7.5 | 25.4 | 24. 5 | 25.5 | 36.5 | 7.6 | 20.6 | 59.5 |
| Indispensable AA | | | | | | | | | |
| Arg | 0.7 | 0.5 | 1.3 | 1.3 | 1.3 | 1.5 | 0.3 | 1.5 | 2.2 |
| His | 0.4 | 0.3 | 0.7 | 0.8 | 0.8 | 1.1 | 0.2 | 0.7 | 1.3 |
| Ile | 0.5 | 0.3 | 1.0 | 1.1 | 1.0 | 1.8 | 0.3 | 0.8 | 2.6 |
| Leu | 1.2 | 0.9 | 3.1 | 3.7 | 3.1 | 6.0 | 1.1 | 1.8 | 9.8 |
| Lys | 0.6 | 0.5 | 1.1 | 0.9 | 1.0 | 1.3 | 0.2 | 1.1 | 1.3 |
| Met | 0.2 | 0.2 | 0.5 | 0.6 | 0.5 | 0.9 | 0.1 | 0.4 | 1.3 |
| Phe | 0.5 | 0.4 | 1.4 | 1.4 | 1.2 | 2.2 | 0.4 | 0.9 | 3.8 |
| Thr | 0.6 | 0.4 | 1.0 | 1.1 | 1.0 | 1.5 | 0.2 | 0.8 | 2.0 |
| Trp | 0.1 | 0.1 | 0.2 | 0.2 | 0.2 | 0.1 | 0.1 | 0.2 | 0.2 |
| Val | 0.7 | 0.5 | 1.4 | 1.6 | 1.4 | 2.2 | 0.3 | 1.3 | 2.9 |
| Dispensable AA[2] | 6.9 | 4.8 | 13.6 | 15.8 | 13.9 | 22.8 | 4.3 | 10.0 | 35.0 |
| -9*All AA[3] | 12.5 | 8.6 | 25.2 | 28.4 | 25.3 | 41.2 | 7.4 | 19.4 | 62.4 |

[1]CB-S = corn bran with solubles; CB = corn bran; DDGS-CV = cooked corn distillers dried grains with solubles (DDGS); DDGS-RO = reduced oil DDGS; DDGS-BPX = uncooked DDGS; HP-DDG = high protein distillers dried grains; DDC = dehulled, degermed corn; CGmM = corn germ meal; CGnM = corn gluten meal.

[2]Sum of all dispensable AA.

[3]Sum of all indispensable and dispensable AA.



**Table 4.** Apparent ileal digestibility (AID) and apparent total tract digestibility (ATTD) traits of ingredients[1]

| | Ingredient[2] | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Item | CB-S | CB | DDGS-CV | DDGS-RO | DDGS-BPX | HP-DDG | DDC | CGmM | CGnM | Pooled SEM | *P*-value |
| AID, % | | | | | | | | | | | |
| GE | 52.1[b] | 46.7[bc] | 55.1[b] | 48.5[bc] | 53.9[b] | 52.8[b] | 84.4[a] | 30.9[c] | 75.8[a] | 4.00 | <0.01 |
| DM | 46.5[b] | 41.5[b] | 47.0[b] | 40.7[b] | 45.8[b] | 48.4[b] | 87.8[a] | 29.5[c] | 74.7[a] | 4.45 | <0.01 |
| NDF | 19.8 | 19.5 | 32.4 | 42.0 | 28.8 | 38.7 | 20.4 | 28.0 | 61.0 | 11.12 | 0.11 |
| ATTD, % | | | | | | | | | | | |
| GE | 53.4[d] | 40.3[e] | 72.1[b] | 64.8[bc] | 67.6[bc] | 70.7[bc] | 99.6[a] | 63.2[c] | 91.6[a] | 1.99 | <0.01 |
| DM | 52.3[e] | 39.9[f] | 68.6[cd] | 61.9[d] | 64.9[cd] | 71.9[c] | 101.7[a] | 67.0[cd] | 91.5[b] | 2.01 | <0.01 |
| NDF | 8.5[d] | 6.0[d] | 58.2[c] | 50.7[c] | 49.4[c] | 67.7[c] | 136.8[a] | 73.0[bc] | 94.3[b] | 6.19 | <0.01 |
| AID of AA, % | | | | | | | | | | | |
| Arg | 74.4[ab] | 65.6[ab] | 80.0[ab] | 82.4[ab] | 71.5[ab] | 59.6[b] | 67.2[ab] | 79.0[ab] | 86.5[a] | 5.98 | 0.03 |
| His | 61.3[bc] | 56.2[c] | 73.7[ab] | 71.8[abc] | 65.5[abc] | 63.9[bc] | 74.6[ab] | 62.1[bc] | 81.2[a] | 3.74 | <0.01 |
| Ile | 56.7[bc] | 49.6[c] | 67.7[bc] | 73.2[ab] | 60.4[bc] | 62.9[bc] | 71.1[ab] | 60.9[bc] | 86.6[a] | 4.14 | <0.01 |
| Leu | 66.7[cde] | 60.8[e] | 80.9[ab] | 79.2[ab] | 77.1[bc] | 75.9[bcd] | 84.6[ab] | 63.2[de] | 90.4[a] | 2.81 | <0.01 |
| Lys | 35.9[ab] | 35.9[ab] | 51.7[ab] | 51.3[ab] | 40.0[ab] | 44.5[ab] | 20.2[b] | 54.4[ab] | 65.5[a] | 4.46 | <0.01 |
| Met | 68.8[cd] | 61.7[d] | 78.3[bc] | 81.4[ab] | 75.2[bc] | 73.3[bcd] | 80.1[bc] | 70.5[bcd] | 92.4[a] | 2.55 | <0.01 |
| Phe | 59.0[d] | 55.6[d] | 75.2[abc] | 76.2[abc] | 68.2[cd] | 70.3[bcd] | 84.0[ab] | 66.0[cd] | 88.5[a] | 3.49 | <0.01 |
| Thr | 50.3[bc] | 33.3[c] | 66.0[ab] | 66.3[ab] | 54.4[bc] | 54.6[bc] | 62.0[ab] | 46.1[bc] | 79.3[a] | 5.42 | <0.01 |
| Trp | 35.0[bc] | 16.9[c] | 55.1[ab] | 58.5[ab] | 51.8[abc] | 37.9[bc] | 46.0[bc] | 58.6[ab] | 76.2[a] | 5.67 | <0.01 |
| Val | 52.1[bc] | 42.2[c] | 67.7[ab] | 70.3[ab] | 60.5[bc] | 60.4[bc] | 67.1[ab] | 61.8[bc] | 85.6[a] | 4.96 | <0.01 |
| Indispensable[3] | 58.4[cd] | 50.6[d] | 72.4[abc] | 73.4[abc] | 65.3[bcd] | 65.9[bcd] | 74.7[ab] | 63.3[bcd] | 86.6[a] | 3.54 | <0.01 |
| Dispensable[4] | 58.5[bc] | 44.4[c] | 69.0[ab] | 69.9[ab] | 68.1[ab] | 64.2[abc] | 53.9[bc] | 52.4[bc] | 82.0[a] | 6.08 | <0.01 |
| All AA[5] | 57.8[bc] | 47.2[c] | 70.6[ab] | 71.6[ab] | 66.9[b] | 65.0[b] | 60.2[bc] | 57.6[bc] | 84.1[a] | 4.39 | <0.01 |

[a,b]Means within a row lacking a common superscript letter are different ($P < 0.05$).

[1]Least squares means of 8 pigs per ingredient.

[2]CB-S = corn bran with solubles; CB = corn bran; DDGS-CV = cooked corn distillers dried grains with solubles (DDGS); DDGS-RO = reduced oil DDGS; DDGS-BPX = uncooked DDGS; HP-DDG = high protein distillers dried grains; DDC = dehulled, degermed corn; CGmM = corn germ meal; CGnM = corn gluten meal.

[3]Average AID for all indispensable AA.

[4]Average AID for all dispensable AA.

[5]Average AID for all AA (indispensable and dispensable).

**Table 5.** Digestible and metabolizable energy value of ingredients[1]

| Item | Ingredient[2] | | | | | | | | | Pooled | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | CB-S | CB | DDGS-CV | DDGS-RO | DDGS-BPX | HP-DDG | DDC | CGmM | CGnM | SEM | *P*-value |
| As-fed basis, Mcal/kg | | | | | | | | | | | |
| DE | 2.45[e] | 1.48[f] | 3.58[bc] | 3.19[d] | 3.34[cd] | 3.59[bc] | 3.84[b] | 2.74[e] | 4.64[a] | 0.09 | <0.01 |
| ME | 2.39[d] | 1.46[e] | 3.40[b] | 3,03[c] | 3,17[bc] | 3.33[bc] | 3.79[a] | 2,63[d] | 4.07[a] | 0.08 | <0.01 |

[a,b]Means within a row lacking a common superscript letter are different ($P < 0.05$).

[1]Least squares means of 8 pigs per ingredient.

[2]CB-S = corn bran with solubles; CB = corn bran; DDGS-CV = cooked corn distillers dried grains with solubles (DDGS); DDGS-RO = reduced oil DDGS; DDGS-BPX = uncooked DDGS; HP-DDG = high protein distillers dried grains; DDC = dehulled, degermed corn; CGmM = corn germ meal; CGnM = corn gluten meal.

to accurately estimate the AID and ATTD of a nutrient present in low concentrations in the tested ingredient, because the nutrient value is calculated by difference and the analytical methods may not be precise enough to determine small nutrient concentrations.

The observed AID of all indispensable AA differed ($P < 0.05$) among ingredients. Values of AID of indispensable AA in DDGS determined in the present experiment were close to previously published data (Stein et al., 2006; Urriola et al., 2009; NRC, 2012). For CGmM and CGnM, the AID of indispensable AA concurs with previously published values (Almeida et al., 2011; NRC, 2012) but is slightly less than European values (Sauvant et al., 2004). Additionally, the AID of indispensable AA in HP-DDG are less than values reported by Widmer et al. (2007) and Kim et al. (2009), which may be a consequence of the previously reported variability in nutrient composition of different sources of HP-DDG.

The observed DE and ME values differed ($P < 0.05$) among ingredients (Table 5). The DE and ME values were greatest ($P < 0.05$) for DDC and CGnM, because of their low DF and high concentrations of starch and CP, respectively. In contrast, the high DF concentration in CB, in addition to its low starch and EE, resulted in DE and ME to be less ($P < 0.05$) than the rest of corn coproducts. The high EE concentration in CB-S, on the other hand, caused its DE and ME content to be greater ($P < 0.05$) than in CB and similar to CGmM. The DE and ME of HP-DDG were similar to the values for DDGS-CV and DDGS-BPX. The lower EE in DDGS-RO resulted in DE and ME being less ($P < 0.05$) than in DDGS-CV. Anderson et al. (2012) determined the DE and ME content on different batches of the same corn coproduct sources, but values were greater for CB-S, CB, DDGS-RO, HP-DDG, and CGmM. The discrepancy in DE and ME may originate from the fact that values in Anderson et al. (2012) were obtained by total collection of urine and feces from finishing gilts, whereas values in the present study were obtained by grab sampling of feces from growing pigs fed diets formulated with $Cr_2O_3$ as an inert marker. Values of DE and ME observed in the present trial, however, agree with values available in the literature for CB (Sauvant et al., 2004), DDGS-CV (Stein et al., 2006; Pedersen et al., 2007), DDGS-BPX, DDC, and CGnM (Anderson et al., 2012), HP-DDG, and CGmM (NRC, 2012).

### *Best Fitting Fiber Component by Trait Categories*

A best fitting DF component that better explains variation due to DF concentration was determined for each trait. The goodness-of-fit of the 11 selected fiber components for each trait was assessed and ranked, showing that the variation in AID and ATTD traits, DE, and ME of corn coproducts was best explained by the concentration of monosaccharide residues in NSP, predominantly xylose and arabinose and their polymer arabinoxylan (Table 6). This finding suggests that the monosaccharide composition of DF in corn coproducts, which is ultimately defined by the polysaccharides they form, is a better predictor of the nutrient value of the ingredient than commonly used DF assays such as ADF, NDF, and TDF.

In corn and its coproducts, polymers of glucose and xylose are the most abundant NSP, organized mainly in the form of cellulose and arabinoxylans, respectively (Bach Knudsen, 1997, 2001). Cellulose is a glucose polymer and is the most abundant polysaccharide in corn cell walls. In spite of its high concentration in NSP, glucose was the best model fit for ATTD of NDF only. The effect of glucose concentration on ATTD of NDF may be related to the highly organized structure of the cellulose polymer, which is inaccessible to water. Therefore, cellulose is usually less degraded than arabinoxylans in cereals but with a wide variability of degradability between structural components of the corn kernel (e.g., cellulose present in the bran vs. endosperm). Xylose is the backbone residue in arabinoxylan and to a varying degree substituted with arabinose. Xylose was a better fit than glucose or hemicellulose for most of the traits, implying that the xylose content in DF may relate to the nutrient value of corn coproducts better than cellulose or hemicellulose. Cellulose and hemicellulose have been previously used to predict the ME of ingredients in pigs (Anderson et al., 2012) and chickens (Rochell et al., 2011). The microbial degradation of arabinoxylans varies substantially in different components of the corn

**Table 6.** Goodness-of-fit ranking of dietary fiber assays by trait

| | Ranking of chemical analyses[1] | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Trait[2] | Best fit | Second | Third | Fourth | Fifth | Sixth | Seventh | Eighth | Ninth | 10th | Worst fit |
| AID | | | | | | | | | | | |
| GE | AraXyl | Ara | Hemi | NSP | NDF | Xyl | TDF | Glc | Gal | ADF | Man |
| DM | AraXyl | Ara | Hemi | NSP | TDF | Xyl | NDF | Glc | Gal | ADF | Man |
| NDF | TDF | Gal | ADF | NDF | NSP | Xyl | Glc | Hemi | AraXyl | Man | Ara |
| ATTD | | | | | | | | | | | |
| GE | Xyl | AraXyl | Glc | NSP | Ara | TDF | Hemi | Gal | NDF | ADF | Man |
| DM | AraXyl | Xyl | Ara | NSP | Glc | TDF | Hemi | Gal | NDF | Man | ADF |
| NDF | Glc | Xyl | AraXyl | TDF | Ara | Gal | NDF | Hemi | NSP | Man | ADF |
| AID of AA | | | | | | | | | | | |
| Lys | Gal | ADF | NDF | TDF | NSP | AraXyl | Ara | Glc | Hemi | Xyl | Man |
| Thr | Xyl | Glc | NSP | AraXyl | TDF | Gal | Ara | Hemi | NDF | ADF | Man |
| Met | Xyl | NSP | Glc | AraXyl | TDF | Ara | Hemi | Gal | NDF | ADF | Man |
| Met + Cys | Xyl | Glc | NSP | AraXyl | TDF | Hemi | Ara | Gal | NDF | ADF | Man |
| Trp | NSP | Xyl | AraXyl | Ara | TDF | Man | NDF | Glc | Hemi | Gal | ADF |
| Indispensable AA | Xyl | AraXyl | NSP | Glc | TDF | Ara | Hemi | Gal | NDF | Man | ADF |
| Dispensable AA | Gal | TDF | NSP | Xyl | Glc | AraXyl | Ara | NDF | Hemi | ADF | Man |
| Energy concentration, as-fed basis | | | | | | | | | | | |
| DE | Xyl | AraXyl | NSP | Ara | Gal | TDF | Glc | Hemi | NDF | Man | ADF |
| ME | Xyl | AraXyl | NSP | Ara | Gal | Glc | TDF | Hemi | NDF | Man | ADF |

[1]Monosaccharide residues in nonstarch polysaccharides (NSP): Ara = NSP arabinose; AraXyl = arabinoxylan; Gal = NSP galactose; Glc = NSP glucose; Hemi = hemicellulose. Man = NSP mannose; TDF = total dietary fiber; Xyl = NSP xylose. NSP is the total NSP.

[2]AID = apparent ileal digestibility; ATTD = apparent total tract digestibility.

kernel—from hardly anything in the pericarp and testa to almost 85 to 90% in the endosperm (Bach Knudsen, 1997)—and may also encapsulate lipids and proteins in the aleurone layer of corn (Benamrouche et al., 2002), which may explain why NSP xylose and arabinoxylan were the best fit for the digestibility and energy value traits in the tested ingredients. Galactose was the best fitting NSP monosaccharide for AID of Lys and the average of dispensable AA but ranked below NSP xylose for the rest of the AA. Mannose, on the other hand, forms the backbone of mannans, but they are rarely present in cereal grains (Choct, 1997) and hence its low concentration in corn coproducts. The lesser ranking of NSP galactose and NSP mannose, compared to the other monosaccharides, may be related to the low concentration and functionality of the polysaccharides they form.

To simplify the estimation of the effect of DF concentration and its adequacy to predict the nutrient value of the ingredient, a single best fitting DF component was selected for each category (Table 7). The arabinoxylan concentration was the best fitting DF component for AID of GE, DM, and NDF. The NSP xylose residue was, on the other hand, the best fitting DF component for the remaining 3 categories, including ATTD of GE, DM, and NDF, AID of AA, and DE and ME. Zijlstra et al. (1999) reported xylan to be a better predictor than NDF for differences among wheat samples (Zijlstra et al., 1999). The comparison of the goodness-of-fit between the DF concentration and Ingred models showed that Ingred was better than DF concentration for explaining variation in most traits. Dietary fiber concentration, however, showed a better fit when used in the model for AID of GE (550.3) and DM (562.2), when compared to the models using Ingred (555.4 and 570.1, respectively). The effect of Ingred in the model includes the combined effects of other analytical components such as CP, EE, starch, minerals, and DF concentrations, which together can describe the variation in traits better than DF concentration alone. In prediction equations of DE and ME values of feed ingredients fed to swine, Noblet and Perez (1993) reported that the DE and ME values increased with the concentration CP and EE and decreased with the concentrations of minerals, crude fiber, NDF, or hemicellulose. Predictability usually increased as more chemical components were added to the model. Other prediction models of digestible nutrients and energy values have also been developed for feed ingredients based on their chemical composition (Anderson et al., 2012; Urriola et al., 2013).

Although the effect of DF concentration is not as good as the effect of Ingred to explain the variation, the DF concentration showed significant effect on most traits (Table 8). The arabinoxylan concentration, for example, showed a cubic effect on AID of GE ($P = 0.02$) and DM ($P = 0.04$). Similarly, the NSP xylose concentration showed a cubic effect ($P < 0.01$) on the ATTD of GE and DM; on the AID ($P < 0.05$) of Met, Met + Cys, Trp, and average of indispensable AA; and on the ME value ($P < 0.01$). Additionally, the DE was

**Table 7.** Goodness-of-fit for the best dietary fiber (DF) within category and feed ingredient models across traits

| Trait[2] | Chemical assay | AIC[1] | |
|---|---|---|---|
| | | DF | Ingredient |
| AID | | | |
| GE | AraXyl[3] | 546.9 | 555.4 |
| DM | AraXyl | 561.0 | 570.1 |
| NDF | AraXyl | 666.1 | 663.0 |
| ATTD | | | |
| GE | Xylose | 504.2 | 448.9 |
| DM | Xylose | 513.7 | 450.1 |
| NDF | Xylose | 649.8 | 593.2 |
| AID of AA | | | |
| Lys | Xylose | 569.5 | 556.1 |
| Thr | Xylose | 592.8 | 585.9 |
| Met | Xylose | 504.1 | 482.9 |
| Met + Cys | Xylose | 553.4 | 551.0 |
| Trp | Xylose | 578.7 | 561.1 |
| Indispensable AA | Xylose | 548.7 | 537.6 |
| Dispensable AA | Xylose | 574.7 | 564.4 |
| Energy concentration, as-fed basis | | | |
| DE | Xylose | 1,093.4 | 987.5 |
| ME | Xylose | 1,065.2 | 981.7 |

[1]AIC = Akaike information criterion. Smaller is better.

[2]AID = apparent ileal digestibility; ATTD = apparent total tract digestibility.

[3]AraXyl = arabinoxylan.

linearly affected ($P = 0.02$) by the NSP xylose concentration. This finding agrees with previous data where the ATTD of energy, DM, and CP of complete diets decreased linearly with dietary increase of insoluble DF (Huisman et al., 1985; Noblet and Perez, 1993; Le Goff and Noblet, 2001). The AID of Lys and Thr in the present trial, however, was not affected ($P > 0.05$) by the NSP xylose concentration. The NSP xylose concentration affected the AID and ATTD of NDF differently. The AID of NDF was not affected ($P > 0.05$), but a cubic effect ($P < 0.01$) was observed for ATTD of NDF with NSP xylose concentration.

Interestingly, the $R^2_{\text{fiber}}$ showed a moderate to high predictability of GE and DM digestibility and of DE and ME values, from arabinoxylan or NSP xylose residue concentrations in the feed ingredient. The arabinoxylan concentration explained approximately 66% of the variance in AID of GE and DM, and the NSP xylose residue explained 80, 78, and 63% of the variance in ATTD of GE, DM, and NDF, respectively. The NSP xylose residue was able to explain 66 and 71% of the variability in DE and ME values, respectively. The increase in insoluble and low-fermentable DF concentration in the ingredient, at the expense of a highly digestible source of carbohydrates, may explain why NSP and xylose concentration are good predictors of these traits. Predictability of AID of AA from the NSP xylose residue concentration was poorer, ranging from 0.11 in AID of Trp to 0.44 in AID of Met + Cys. These observations coincide with the lack of correlation ($r \approx 0.33$) between the NDF content and the SID of Lys, Met, Thr, or Trp in DDGS reported by Urriola et al. (2013). The lower predictability of AID of AA maybe caused by the high insoluble to soluble DF concentration ratio in ingredients, because insoluble DF may have a lesser impact on the availability of AA than the soluble DF concentration (Urriola et al., 2013). Another contributing factor may be that some of the ingredients have been processed, therefore reducing the encapsulation of AA in intact cell structures, for example, aleurone cells.

### *Assessment of Loss of Predictability*

The $R^2_{\text{fiber}}$ demonstrated that the DF concentration in corn coproducts is an acceptable predictor for most traits. However, a portion (model residuals) of the total predictable variance could not be explained by DF concentration but can be explained by the effect of Ingred. For the traits with significant effects of DF concentration (Table 8), the residuals of these models were tested for the effect of Ingred and the portion of the variance explained by Ingred ($R^2_{\text{Ingred}}$) was determined (Table 9). The loss of predictability is the proportion of variance from the residuals of DF models that is explained by the effect of Ingred ($R^2_{\text{Ingred}}$) out of the total explainable variance ($R^2_{\text{fiber}} + R^2_{\text{Ingred}}$).

Ingredient did not affect ($P > 0.05$) the residuals of DF concentration models for AID of GE, DM, and Met + Cys, and therefore low $R^2_{\text{Ingred}}$ (0.01, 0.01, and 0.07, respectively) and minimum loss of predictability (0.02, 0.01, and 0.13, respectively) values were observed. The effect of Ingred on these 3 traits did not account for more variation, because the concentration of arabinoxylan and NSP xylose residue explained the overwhelming majority of the variation in AID of GE and DM and AID of Met + Cys, respectively.

In the remaining traits, however, Ingred affected ($P < 0.05$) the residuals of DF concentration models. Therefore, an additional portion of the variance not explained by DF concentration was accounted by the effect of Ingred ($R^2_{\text{Ingred}}$). In the case of AID of Trp, for instance, the $R^2_{\text{Ingred}}$ was greater than the $R^2_{\text{fiber}}$ and DF concentration showed the highest loss of predictability (0.59), indicating that DF concentration is not sufficient to explain the variation in this trait. The loss of predictability, however, revealed that the share of the variance explained by Ingred after accounting for the effect of DF concentration was lower overall for the remaining traits, ranging from 0.14 in ATTD of GE to 0.27 in DE value. The fact that the loss of predictability was overall low, except for AID of Trp, indicates that the concentra-

**Table 8.** Regression coefficients and model fit of the best fitting dietary fiber (DF) across traits

| Trait[1] | DF | Regression components: Intercept | Linear | Quadratic | Cubic | $R^2_{fiber}$ | *P*-value[2] |
|---|---|---|---|---|---|---|---|
| AID, % | | | | | | | |
| GE | AraXyl[3] | 88.618 | –6.559 | 0.380 | –0.008 | 0.65 | <0.01 |
| DM | AraXyl | 92.280 | –8.336 | 0.463 | –0.009 | 0.67 | <0.01 |
| NDF | AraXyl | – | – | – | – | n/a[4] | >0.05 |
| ATTD, % | | | | | | | |
| GE | Xylose | 106.455 | –18.346 | 2.596 | –0.113 | 0.80 | <0.01 |
| DM | Xylose | 108.411 | –19.661 | 2.721 | –0.115 | 0.78 | <0.01 |
| NDF | Xylose | 147.595 | –52.227 | 7.844 | –0.337 | 0.63 | <0.01 |
| AID of AA, % | | | | | | | |
| Lys | Xylose | – | – | – | – | n/a | >0.05 |
| Thr | Xylose | – | – | – | – | n/a | >0.05 |
| Met | Xylose | 90.469 | –9.020 | 1.514 | –0.072 | 0.40 | 0.02 |
| Met + Cys | Xylose | 87.475 | –10.333 | 1.610 | –0.076 | 0.44 | 0.04 |
| Trp | Xylose | 71.795 | –20.447 | 3.874 | –0.185 | 0.11 | 0.04 |
| Indispensable AA | Xylose | 86.045 | –11.075 | 1.831 | –0.086 | 0.35 | 0.02 |
| Dispensable AA | Xylose | – | – | – | – | n/a | >0.05 |
| Energy concentration, Mcal/kg (as-fed basis) | | | | | | | |
| DE | Xylose | 4.464 | –0.457 | – | – | 0.66 | 0.02 |
| ME | Xylose | 4.215 | –0.520 | 0.078 | –0.004 | 0.71 | 0.01 |

[1]AID = apparent ileal digestibility; ATTD = apparent total tract digestibility.
[2]*P*-value of the highest order regression component.
[3]AraXyl = arabinoxylan.
[4]n/a = not applicable.

tion of arabinoxylan or NSP xylose residue explained the majority of the predictable variance and can be used to predict the AID of GE, DM, Met, and indispensable AA; the ATTD of GE, DM, and NDF; and DE and ME values without substantial loss of predictability.

In conclusion, extensive variation was observed in digestibility of energy, DF, and indispensable AA and on DE and ME in a wide variety of corn coproducts. Part of the variation is explained by differences in the DF concentration in these ingredients. The arabinoxylan and NSP xylose residue were the DF components that best explained variation due to DF concentration and can therefore be used to explain digestibility of energy, DM, and NDF and of DE and ME values in corn coproducts without substantial loss of predictability. The AID of Lys and most AA was not predictable from the DF concentration in corn coproducts.

**Table 9.** Comparison of model adequacy and effect of ingredient on the residuals from the dietary fiber (DF) models

| Trait[1] | DF | $R^2_{fiber}$[2] | $R^2_{Ingred}$[3] | *P*-value[4] | Loss of predictability[5] |
|---|---|---|---|---|---|
| AID | | | | | |
| GE | AraXyl[6] | 0.65 | 0.01 | >0.05 | 0.02 |
| DM | AraXyl | 0.67 | 0.01 | >0.05 | 0.01 |
| ATTD | | | | | |
| GE | Xylose | 0.80 | 0.13 | <0.01 | 0.14 |
| DM | Xylose | 0.78 | 0.15 | <0.01 | 0.16 |
| NDF | Xylose | 0.63 | 0.23 | <0.01 | 0.27 |
| AID of AA | | | | | |
| Met | Xylose | 0.40 | 0.12 | <0.01 | 0.24 |
| Met + Cys | Xylose | 0.44 | 0.07 | >0.05 | 0.13 |
| Trp | Xylose | 0.11 | 0.17 | <0.01 | 0.59 |
| Indispensable AA | Xylose | 0.35 | 0.13 | <0.01 | 0.27 |
| Energy concentration, as-fed basis | | | | | |
| DE | Xylose | 0.66 | 0.26 | <0.01 | 0.28 |
| ME | Xylose | 0.71 | 0.21 | <0.01 | 0.23 |

[1]AID = apparent ileal digestibility; ATTD = apparent total tract digestibility.
[2]$R^2_{fiber} = R^2$ of DF on the observed values (Eq. [3]).
[3]$R^2_{Ingred} = R^2$ of ingredient on the residuals of the DF model (Eq. [4]).
[4]*P*-value of Ingred on the residuals of the DF model.
[5]Loss of predictability = $R^2_{Ingred} / (R^2_{Ingred} + R^2_{fiber})$.
[6]AraXyl = arabinoxylan.

## LITERATURE CITED


Adeola, O. 2001. Digestion and balance techniques in pigs. In: A. J. Lewis and L. L. Southern, editors, Swine nutrition. 2nd ed. CRC Press, Boca Raton, FL. p. 903–916.

Almeida, F. N., G. I. Petersen, and H. H. Stein. 2011. Digestibility of amino acids in corn, corn coproducts, and bakery meal fed to growing pigs. J. Anim. Sci. 89:4109–4115.

Anderson, P. V., B. J. Kerr, T. E. Weber, C. J. Ziemer, and G. C. Shurson. 2012. Determination and prediction of digestible and metabolizable energy from chemical analysis of corn coproducts fed to finishing pigs. J. Anim. Sci. 90:1242–1254.

AOAC. 2007. Official methods of analysis of AOAC Int. 18th ed. AOAC Int., Gaithersburg, MD.

Association of Official Analytical Chemists (AOAC). 1990. Official methods of analysis. 15th ed. AOAC, Arlington, VA.

Bach Knudsen, K. E. 1997. Carbohydrate and lignin contents of plant materials used in animal feeding. Anim. Feed Sci. Technol. 67:319–338.

Bach Knudsen, K. E. 2001. The nutritional significance of “dietary fibre” analysis. Anim. Feed Sci. Technol. 90:3–20.

Benamrouche, S., D. Cronier, P. Debeire, and B. Chabbert. 2002. A chemical and histological study on the effect of (1→4)-β-endo-xylanase treatment on wheat bran. J. Cereal Sci. 36:253–260.

Bolker, B. M., M. E. Brooks, C. J. Clark, S. W. Geange, J. R. Poulsen, M. Henry, H. Stevens, and J. S. White. 2009. Generalized linear mixed models: A practical guide for ecology and evolution. Trends Ecol. Evol. 24:127–135.

Campbell, J. M., E. A. Flickinger, and G. C. Fahey Jr. 1997. A comparative study of dietary fiber methodologies using pulsed electrochemical detection of monosaccharide constituents. Semin. Food Anal. 2:43–53.

Choct, M. 1997. Feed non-starch polysaccharides: Chemical structures and nutritional significance. Feed Milling Int. 6:13–26.

Choct, M. 2002. Non-starch polysaccharides: Effect on nutritive value. In: J. M. McNab and K. N. Boorman, editors, Poultry feedstuffs: Supply, composition, and nutritive value. Poult. Sci. Symp. Series. Vol. 26. CABI Publishing, New York. p. 221–235.

Englyst, H. N., and G. J. Hudson. 1987. Colorimetric method for routine measurement of dietary fibre as non-starch polysaccharides. A comparison with gas-liquid chromatography. Food Chem. 24:63–76.

Fairbairn, S. L., J. F. Patience, H. L. Classen, and R. T. Zijlstra. 1999. The energy content of barley fed to growing pigs: Characterizing the nature of its variability and developing prediction equations for its estimation. J. Anim. Sci. 77:1502–1512.

Farrell, D. J. 1973. Digestibility by pigs of the major chemical components of diets high in plant cell-wall constituents. Anim. Prod. 16:43–47.

Fenton, T. W., and M. Fenton. 1979. An improved procedure for the determination of chromic oxide in feed and feces. Can. J. Anim. Sci. 59:631–634.

Goering, H. K., and P. J. Van Soest. 1970. Forage fiber analyses (apparatus, reagents, procedures, and some applications). In: Handbook no. 379. USDA-ARS, Washington, DC.

Graham, H., and P. Åman. 1986. Circadian variation in composition of duodenal and ileal digesta from pigs fitted with T-cannulas. Anim. Prod. 43:133–140.

Graham, H., K. Hesselman, and J. Lindberg. 1986. The influence of wheat bran and sugar-beet pulp on the digestibility of dietary components in a cereal-based pig diet. J. Nutr. 116:242–251.

Huisman, J., L. A. den Hartog, H. Boer, E. J. van Weerden, and W. J. G. Thielen. 1985. The effect of various carbohydrate sources on the ileal and faecal digestibility of protein and amino acids in pigs. In: Proceedings of the 3rd International Seminar on Digestive Physiology in the Pigs. Copenhagen. p. 207-210.

Jacobs, B. M., J. F. Patience, W. A. Dozier III, K. J. Stalder, and B. J. Kerr. 2011. Effects of drying methods on nitrogen and energy concentrations in pig feces and urine, and poultry excreta. J. Anim. Sci. 89:2624–2630.

Jaworski, N. 2012. Carbohydrate composition, in vitro digestion, and effects of xylanase and phytase on nutrient and energy digestibility by pigs in grains and grain coproducts. M.S. Thesis. Univ. of Illinois, Urbana-Champaign, IL.

Jorgensen, H., X. Q. Zaho, and B. Eggum. 1996. The influence of dietary fibre and environmental temperature on the development of the gastrointestinal tract, digestibility, degree of fermentation in the hind-gut and energy metabolism in pigs. Br. J. Nutr. 75:365–378.

Kim, B. G., G. I. Petersen, R. B. Hinson, G. L. Allee, and H. H. Stein. 2009. Amino acid digestibility and energy concentration in a novel source of high-protein distillers dried grains and their effects on growth performance of pigs. J. Anim. Sci. 87:4013-4021.

Le Goff, G., and J. Noblet. 2001. Comparative total tract digestibility of dietary energy and nutrients in growing pigs and adult sows. J. Anim. Sci. 79:2418-2427.

Nakagawa, S., and H. Schielzeth. 2013. A general and simple method for obtaining $R^2$ from generalized linear mixed-effects models. Methods Ecol. Evol. 4:133–142.

Noblet, J., and J. M. Perez. 1993. Prediction of digestibility of nutrients and energy values of pig diets from chemical analysis. J. Anim. Sci. 71:3389–3398.

NRC. 1998. Nutrient requirements of swine. 10th rev. ed. Natl. Acad. Press, Washington, DC.

NRC. 2012. Nutrient requirements of swine. 11th rev. ed. Natl. Acad. Press, Washington, DC.

Oresanya, T. F., A. D. Beaulieu, and J. F. Patience. 2008. Investigations of energy metabolism in weanling barrows: The interaction of dietary energy concentration and daily feed (energy) intake. J. Anim. Sci. 86:348–363.

Pedersen, C., M. G. Boersma, and H. H. Stein. 2007. Digestibility of energy and phosphorus in ten samples of distillers dried grains with solubles fed to growing pigs. J. Anim. Sci. 85:1168–1176.

Prosky, L., N. G. Asp, I. Furda, J. W. DeVries, T. F. Schweizer, and B. F. Harland. 1985. Determination of total dietary fiber in foods and food products: Collaborative study. J. Assoc. Off. Anal. Chem. 68:677–679.

Robinson, P. H., K. Karges, and G. C. Gibson. 2008. Nutritional evaluation of four co-product feedstuffs from the motor fuel ethanol distillation industry in the Midwestern USA. Anim. Feed Sci. Technol. 146:345–352.

Rochell, S. J., B. J. Kerr, and W. A. Dozier. 2011. Energy determination of corn co-products fed to broiler chicks from 15 to 24 days of age, and use of composition analysis to predict nitrogen-corrected apparent metabolizable energy. Poult. Sci. 90:1999–2007.

Rojas, O. J., and H. H. Stein. 2013. Phosphorus digestibility and concentration of digestible and metabolizable energy in corn, corn co-products, and bakery meal fed to pigs. J. Anim. Sci. 91(Suppl.2):122 (Abstr.).

Sauvant, D., J. M. Perez, and G. Tran. 2004. Tables of composition and nutritional value of feed materials: Pig, poultry, sheep, goats, rabbits, horses, fish. Wageningen Academic Publishers, Wageningen, The Netherlands, and INRA Editions, Paris.

Snijders, T., and R. Bosker. 1999. Multilevel analysis: An introduction to basic and advanced multilevel modeling. Sage, London.

Souffrant, W. B. 2001. Effect of dietary fiber on ileal digestibility and endogenous nitrogen losses in the pig. Anim. Feed Sci. Technol. 90:93–102.

Spiehs, M. J., M. H. Whitney, and G. C. Shurson. 2002. Nutrient database for distillers dried grains with solubles produced from new plants in Minnesota and South Dakota. J. Anim. Sci. 80:2639–2645.

Stein, H. H., M. L. Gibson, C. Pedersen, and M. G. Boersma. 2006. Amino acid and energy digestibility in ten samples of distillers dried grain with solubles fed to growing pigs. J. Anim. Sci. 84:853–860.

Stein, H. H., C. F. Shipley, and R. A. Easter. 1998. Technical note: A technique for inserting a T-cannula into the distal ileum of pregnant sows. J. Anim. Sci. 76:1433–1436.

Theander, O., P. Åman, E. Westerlund, R. Andersson, and D. Petersson. 1995. Total dietary fiber determined as neutral sugar residues, uronic acid residues, and klason lignin (The uppsala method): collaborative study. J. AOAC Int. 78:1030-1044.

Urriola, P. E., D. Hoehler, C. Pedersen, H. H. Stein, and G. C. Shurson. 2009. Amino acid digestibility of distillers dried grains with solubles, produced from sorghum, a sorghum-corn blend, and corn fed to growing pigs. J. Anim. Sci. 87:2574–2580.

Urriola, P. E., L. J. Johnston, H. H. Stein, and G. C. Shurson. 2013. Prediction of the concentration of standardized ileal digestible amino acids in distillers dried grains with solubles. J. Anim. Sci. 91:4389–4396.

Urriola, P. E., G. C. Shurson, and H. H. Stein. 2010. Digestibility of dietary fiber in distillers coproducts fed to growing pigs. J. Anim. Sci. 88:2373–2381.

Van Soest, P. J., and J. B. Robertson. 1980. Systems of analysis for evaluating fibrous feeds. In: Workshop Standardization of Analytical Methodology for Feeds, Int. Dev. Res. Center, Ottawa, ON, Canada. p. 49–60.

Widmer, M. R., L. M. McGinnis, and H. H. Stein. 2007. Energy, phosphorus, and amino acid digestibility of high-protein distillers dried grains and corn germ fed to growing pigs. J. Anim. Sci. 85:2994–3003.

Widyaratne, G. P., and R. T. Zijlstra. 2007. Nutritional value of wheat and corn distiller's dried grains with solubles: Digestibility and digestible contents of energy, amino acids and phosphorus, nutrient excretion and growth performance of grower-finisher pigs. Can. J. Anim. Sci. 87:103–114.

Wilfart, A., L. Montagne, P. H. Simmins, J. van Milgen, and J. Noblet. 2007. Sites of nutrient digestion in growing pigs: Effect of dietary fiber. J. Anim. Sci. 85:976–983.

Zijlstra, R. T., C. F. M. de Lange, and J. F. Patience. 1999. Nutritional value of wheat for growing pigs: Chemical composition and digestible energy content. Can. J. Anim. Sci. 79:187–194.