RESEARCHREPORT
ANIMAL SCIENCE

Title: Correlation between physical characteristics of diets and absorption of energy by pigs – **NPB #** 15-115

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revised

Industry Summary

Distillers dried grains with solubles (**DDGS**), wheat middlings, and soybean hulls are cost-effective co-products that may replace some corn in swine diets. However, these co-products contain more dietary fiber and less starch compared with corn. The amount of energy obtained by pigs consuming dietary fiber is less compared with pigs consuming starch. The digestibility of dietary fiber varies among sources of dietary fiber and, therefore, energy absorbed also varies. Water binding capacity and bulk density are two physical characteristics of dietary fiber that were hypothesized to be related to digestibility of dietary fiber by pigs and, therefore, the energy obtained by the pig from consuming dietary fiber. Therefore, this experiment was conducted to test the hypothesis that dietary physical characteristics of dietary fiber are correlated with the digestibility of dietary fiber fractions and energy and may be used to predict the disappearance of dietary fiber fractions and energy along the gastrointestinal tract of the pig. Results indicated that water binding capacity and bulk density were not correlated with ileal or total tract digestibility of dietary fiber fractions or energy. However, bulk density was positively correlated with the apparent cecal digestibility of gross energy and this implies that as the bulk density of diets decreases; the apparent digestibility of gross energy in the cecum of pigs

but this does not contribute a great amount of energy supply to the pig because DDGS, wheat middlings, and soybean hulls contain only small quantities of soluble dietary fiber. Insoluble dietary fiber, on the other hand, is mostly fermented in the colon of pigs and contributes a significant amount of energy to pigs fed diets containing DDGS, wheat middlings, or soybean hulls because the concentration of insoluble dietary fiber is greater when these co-products are added to a corn-soybean meal diet. Wheat middlings contains more fermentable dietary fiber fractions compared with DDGS and soybean hulls, but the digestible energy (**DE**) in DDGS is similar to that of wheat middlings because of the greater concentration of fat in DDGS compared with wheat middlings. The DE in soybean hulls is mostly attributed to insoluble dietary fiber fermentation in the colon, and this is the reason the DE in soybean hulls is less than in DDGS or wheat middlings.

Key Findings:

- The physical characteristics of dietary fiber in experimental diets were not correlated with the digestibility of energy or dietary fiber fractions in experimental diets.
- Soluble dietary fiber is mostly fermented in the cecum of pigs, but this does not contribute a great amount of energy supply to the pig due to the low concentration of soluble dietary fiber in most swine diets.
- Insoluble dietary fiber is mostly fermented in the colon of pigs and contributes a significant energy supply to pigs fed diets containing DDGS, wheat middlings, or soybean hulls.
- Dietary fiber fractions in wheat middlings are more fermentable compared with the dietary fiber fractions in DDGS and soybean hulls.
- The digestible energy in soybean hulls is mostly attributed to insoluble dietary fiber fermentation in the colon, and this is the reason the DE in soybean hulls is less than in DDGS or wheat middlings.

Keywords: cecum, co-products, dietary fiber, digestibility, pigs

Scientific Abstract

Disappearance of nutrients and energy in the stomach and small intestine, cecum, and colon of pigs fed diets containing distillers dried grains with solubles (DDGS), wheat middlings, or soybean hulls was determined. A second objective was to test the hypothesis that physical characteristics of dietary fiber in diets are correlated with the digestibility of nutrients and energy by pigs fed experimental diets. Eight barrows (initial BW = 37.3 ± 1.0 kg) were surgically equipped with a T-cannula in the distal ileum and a T-cannula in the colon approximately 10 cm distal to the cecocolic junction. Pigs were randomly allotted to a replicated 4 × 4 Latin square design with 4 diets and 4 periods in each square. The basal diet was a corn-soybean meal diet and 3 additional diets were formulated by substituting 30% of the nutrients and energy from corn, soybean meal, and L-Lys HCl with DDGS, wheat middlings, or soybean hulls. Titanium dioxide was included as an indigestible marker. Each period lasted 14 d. The initial 8 d were considered an adaptation to the diet. On d 9 and 10, fecal samples were collected. Colon digesta were collected for 8 h on d 11 and 12, whereas ileal digesta were collected for 8 h on d 13 and 14. Values for apparent ileal digestibility (AID), apparent cecal digestibility (ACD), and apparent total tract digestibility (ATTD) of nutrients and energy by pigs fed experimental diets were calculated. Nutrient and energy flow along the gastrointestinal tract was calculated, and disappearance of nutrients and energy was calculated using digestibility values and flow. Results indicated that ACD and ATTD of soluble dietary fiber by pigs fed experimental diets was not different. Pigs fed basal or wheat middlings diets had greater ($P \leq 0.05$) ACD of insoluble dietary fiber compared with pigs fed diets containing DDGS or soybean hulls. Insoluble dietary fiber disappearance in the colon of pigs fed the soybean hulls diet was greater ($P \leq 0.05$) compared with other diets. Wheat middlings had greater ($P \leq 0.05$) disappearance of dietary fiber fractions compared with DDGS and soybean hulls. Water binding capacity, bulk density, and viscosity of dietary fiber in experimental diets were not correlated with digestibility of nutrients and energy by pigs. In conclusion, disappearance in the colon of most dietary fiber fractions and energy was greater in diets containing soybean hulls or DDGS compared with basal or wheat middlings diets.

Introduction

The U.S. swine feed industry has increased interest in co-product utilization because of the potential to reduce diet costs by inclusion of less expensive ingredients in the diets. Distillers dried grains with solubles (**DDGS**), wheat middlings, and soybean hulls are cost-effective co-products that contain more dietary fiber and less starch compared with corn (Burkhalter et al., 2001; Urriola et al., 2010; Jaworski et al., 2015). Feeding diets containing more dietary fiber results in pigs obtaining a greater proportion of dietary energy from VFA produced via microbial fermentation of dietary fiber compared with pigs fed high-starch and low-fiber diets (Bach Knudsen, 2011). Microbial fermentation of dietary fiber varies among sources of dietary fiber and, therefore, VFA absorption and utilization also varies (Urriola et al., 2010).

It is believed that the majority of microbial fermentation of dietary fiber occurs in the cecum of pigs; however, the extent and degradation of specific dietary fiber fractions fermented in the cecum and large intestine are unknown. Analyzed dietary fiber fractions, as well as the physicochemical characteristics of diets, may be related to the amount of dietary fiber degraded in specific sites of the gastrointestinal tract of pigs. Therefore, an experiment was conducted to test the hypothesis that dietary physical characteristics of dietary fiber are correlated with the digestibility of dietary fiber fractions and energy and may be used to predict the disappearance of dietary fiber fractions and energy along the gastrointestinal tract of the pig. The first objective of this experiment, therefore, was to quantify the disappearance of dietary fiber fractions in the stomach and small intestine, cecum, and colon of pigs. The second objective was to determine the correlation coefficients between physical dietary characteristics and the disappearance of dietary fiber fractions along the gastrointestinal tract of the pig.

Objectives

- To quantify the degradation of fiber fractions from diets based on corn and soybean meal, and corn, soybean meal and DDGS, wheat middlings, or soybean hulls along the intestinal tract of pigs and to relate this information to the amount of digestible energy (**DE**) supplied by each diet.

- To determine if physical characteristics of diets are correlated with the amount of energy obtained by pigs from diets or ingredients and therefore can be used to predict energy digestibility.

Materials & Methods

The protocol for this experiment was reviewed and approved by the Institutional Animal Care and Use Committee at the University of Illinois at Urbana-Champaign.

Animals, Housing, and Diets. Eight barrows (initial BW = 37.3 ± 1.0 kg) that were the offspring of PIC359 boars and F-46 sows (Pig Improvement Company, Hendersonville, TN) were surgically equipped with two T-cannulas. One cannula was placed in the distal ileum according to Stein et al. (1998) and a second cannula was placed in the proximal colon approximately 10 cm distal to the cecocolic junction. After surgery, pigs were housed in individual pens and allowed to recover for 8 d. Each pen had a fully slatted tri-bar floor and was equipped with a feeder and a nipple drinker. Cannulated pigs (initial BW = 41.0 ± 1.5 kg) were randomly allotted to a replicated 4 × 4 Latin square design with 4 diets and 4 periods in each square.

The DDGS was procured from One Earth Energy, Gibson City, IL (Table 1). Wheat middlings were procured from Siemers Milling, Teutopolis, IL. Soybean hulls were procured from Archer Daniels Midland Company, Decatur, IL.

Four experimental diets were prepared. The basal diet was a corn-soybean meal diet (Table 2). Three additional diets were formulated by substituting 30% of the nutrients and energy from corn, soybean meal, and L-Lys HCl with DDGS, wheat middlings, or soybean hulls. Vitamins and minerals were included in all diets at 0.2% to meet current requirements (NRC, 2012) and titanium dioxide was included in all diets at 0.4% as an indigestible marker.

Feeding and Sample Collection. Pigs were provided feed in an amount equivalent to 3 times the estimated requirement for maintenance energy (i.e., 197 kcal ME / $kg^{0.60}$; NRC, 2012) and daily feed allotments were divided into two daily meals that were provided at 0700 and 1600 h. Water was available at all times. The BW of each pig was recorded at the beginning of the experiment and at the end of each period. Each diet was fed during one 14-d period. The initial 8 d were considered the diet adaptation period. On d 9 and 10, fecal samples were collected and stored at – 20°C immediately after collection. Colon digesta were collected for 8 h on d 11 and 12, whereas ileal digesta were collected for 8 h on d 13 and 14. Digesta were stored at -20°C immediately after collection. The final BW of pigs was 84.7 ± 6.4 kg.

Chemical Analysis. Diets, ingredients, freeze-dried samples of ileal and colon digesta, and feces dried at 65°C were ground through a 1 mm screen in a Wiley mill (model 4; Thomas Scientific, Swedesboro, NJ). All samples were analyzed for DM (Method 930.15; AOAC Int., 2007). Diets and ingredients were analyzed for ash (Method 942.05; AOAC Int., 2007) and acid hydrolyzed ether extract (**AEE**) was determined by acid hydrolysis using 3*N* HCl (Ankom^{HCl}, Ankom Technology, Macedon, NY) followed by crude fat extraction using petroleum ether (Ankom^{XT15}, Ankom Technology, Macedon, NY). The concentration of GE in all samples was determined using an isoperibol bomb calorimeter (model 6300, Parr Instruments, Moline, IL). Benzoic acid was the standard for calibration. All diets and ingredients were analyzed for AA on a Hitachi AA Analyzer, Model No. L8800 (Hitachi High Technologies America, Inc, Pleasanton, CA) using ninhydrin for postcolum derivatization and norleucine as the internal standard. Prior to analysis, samples were hydrolyzed with 6*N* HCl for 24 h at 110°C [Method 982.30 E(a); AOAC Int., 2007]. Titanium concentration in all diets, ileal digesta samples, colon digesta samples, and fecal samples were determined using an ICP procedure (Method 990.08; AOAC Int., 2007). Samples were prepared using nitric acid-perchloric acid (Method 968.08 D(b); AOAC Int., 2007). Total starch was analyzed in all diets and ingredients by the glucoamylase procedure (Method 979.10; AOAC Int., 2007). All samples were analyzed for ADF and NDF using Ankom Technology method 12 and 13, respectively (Ankom^{2000} Fiber Analyzer, Ankom Technology, Macedon, NY), and ADL was analyzed in ingredients and diets using Ankom Technology method 9 (Ankom Daisy^{II} Incubator, Ankom Technology, Macedon, NY). Insoluble and soluble dietary fiber was analyzed in all samples according to method 991.43 (AOAC Int., 2007) using the Ankom^{TDF} Dietary Fiber Analyzer (Ankom Technology, Macedon, NY).

Physicochemical Analysis. All samples of ingredients and diets were analyzed for water binding capacity (Robertson et al., 2000) and bulk density (Cromwell et al., 2000). Values for water binding capacity were expressed as the amount of water retained by the pellet (g / g; Urriola and Stein, 2010). Viscosity was measured in ileal and colon digesta that was not freeze dried using a Brookfield LV-DV-II+ Viscometer (Brookfield Eng. Lab. Inc., Middleboro, MA) as described by Dikeman and Fahey (2006) using V-72, V-73, and V-75 spindles over a range of speeds (0.5 to 6 rpm).

Calculations and Statistical Analysis. The concentration of total dietary fiber (insoluble dietary fiber + soluble dietary fiber), cellulose (ADF – ADL), insoluble hemicelluloses (NDF – ADF), non-starch polysaccharides (**NSP**; total dietary fiber – ADL), insoluble NSP (NSP – soluble NSP), and non-cellulosic NSP (NSP – cellulose) were calculated for all samples. Total nutrient concentration, on an as-fed basis, was calculated as the sum of ash, AEE, total AA, starch, sugars, oligosaccharides, and total dietary fiber. Values for apparent ileal digestibility (**AID**), apparent cecal digestibility (**ACD**), and apparent total tract digestibility (**ATTD**) of nutrients and energy by pigs fed experimental diets were calculated according to Stein et al. (2007). Values for AID, ACD, and ATTD of nutrients and energy in DDGS, wheat middlings, and soybean hulls were calculated by multiplying the AID, ACD, or ATTD of nutrients and energy in the corn-basal diet by 70.9% to calculate the contribution from the basal diet to the AID, ACD, or ATTD of nutrients and energy in the DDGS, wheat middlings, or soybean hulls test diets.

The ileal, cecal, and total tract flow of nutrients and energy (g or kcal / kg DMI) by pigs fed experimental diets was calculated according to Urriola and Stein (2010). The disappearance of nutrients and energy (g or kcal / kg DMI) in the stomach and small intestine of pigs was calculated by subtracting the flow of nutrients and energy at the ileum from the nutrients and energy in the experimental diets. Cecum disappearance of nutrients and energy was calculated by subtracting the flow of nutrients and energy at the cecum from the flow of nutrients or energy at the ileum. Disappearance of nutrients and energy by pigs in the colon was calculated by subtracting the flow of nutrients and energy at the total tract from the flow of nutrients and energy at the cecum. The disappearance of nutrients and energy in the stomach, small intestine, cecum, and colon from DDGS, wheat middlings, and soybean hulls was calculated as the difference between the flow of nutrients and energy from 70.9% of the basal corn-soybean meal diet and the 3 diets containing DDGS, wheat middlings, or soybean hulls.

Viscosity of ileal and cecal digesta was calculated using the Rheocalc software (Brookfield Eng. Lab. Inc., Middleboro, MA). The NLREG statistical software (NLREG, Brentwood, TN) was used to report viscosity measurements in terms of the power law equation (Cervantes-Pahm et al., 2013).

Homogeneity of the variance among treatments was confirmed using the UNIVARIATE procedure of SAS. The BOXPLOT procedure of SAS (SAS Inst. Inc., Cary, NC) was used to check for outliers. However, no outliers were identified. Data were analyzed using the MIXED procedure (SAS Inst. Inc., Cary, NC) using pig and period as the random effects and diet or ingredient as the fixed effect. Means were calculated using the LSMEANS statement in SAS. Differences were evaluated using the PDIFF option. Correlation coefficients among physicochemical characteristics of diets and the AID, ACD, and ATTD of nutrients and energy by pigs fed experimental diets were determined using the CORR procedure (SAS Inst. Inc., Cary, NC). The pig was the experimental unit for all analyses, except that dietary treatment was the experimental unit for correlation analysis. A P-value ≤ 0.05 was used to determine significance among dietary treatments for all outcomes.

Results

All pigs were successfully cannulated at the distal ileum and in the proximal colon at approximately 10 cm distal to the cecocolic junction. Pigs recovered from surgery without complications and digesta were successfully collected from the cannula in the ileum and in the colon. One pig fed the corn-soybean meal plus soybean hulls diet died in the middle of the adaptation of period 3. Therefore, there were only 7 observations for the corn-soybean meal plus soybean hulls diet.

Apparent Ileal, Cecal, and Total Tract Digestibility

The AID of DM and GE was least ($P \leq 0.05$) in the diet containing soybean hulls and greatest ($P \leq 0.05$) in the basal corn-soybean meal diet, and the diet containing wheat middlings had greater ($P \leq 0.05$) AID of DM and GE than the DDGS diet (Table 3). The AID of ADF was greater ($P \leq 0.05$) in the basal diet and the diet containing wheat middlings compared with the diet containing soybean hulls. The AID of NDF was least ($P \leq 0.05$) in the diet containing soybean hulls and greatest ($P \leq 0.05$) in the wheat middlings diet. The AID of soluble dietary fiber was greater ($P \leq 0.05$) in the basal diet compared with diets containing soybean hulls or

DDGS. The AID of insoluble dietary fiber, total dietary fiber, NSP, insoluble NSP, and non-cellulosic NSP was greater ($P \leq 0.05$) in basal and wheat middlings diets compared with DDGS and soybean hulls diets, but the AID of cellulose was less ($P \leq 0.05$) in the soybean hulls diet compared with the basal diet. The diet containing wheat middlings had the highest ($P \leq 0.05$) AID of insoluble hemicelluloses compared with the other 3 dietary treatments.

The ACD of DM and GE was least ($P \leq 0.05$) in the diet containing soybean hulls and greatest ($P \leq 0.05$) in the basal corn-soybean meal diet, but the diet containing wheat middlings had greater ($P \leq 0.05$) ACD of DM and GE than the DDGS diet. The ACD of ADF in the basal diet was greater ($P \leq 0.05$) compared with diets containing DDGS or soybean hulls, and the ACD of ADF in the wheat middlings diet was greater ($P \leq 0.05$) compared with the diet containing soybean hulls. The ACD of NDF was greater ($P \leq 0.05$) in the wheat middlings diet than in all other diets, but the soybean hull diet had less ($P \leq 0.05$) ACD of NDF than all other diets. The basal diet and the wheat middlings diet had the greatest ($P \leq 0.05$) ACD of insoluble dietary fiber, total dietary fiber, NSP, and insoluble NSP, followed by the diet containing DDGS, whereas the soybean hulls diet had the least ($P \leq 0.05$) ACD of these fractions. The basal diet had greater ($P \leq 0.05$) ACD of cellulose than diets containing DDGS or wheat middlings, whereas the ACD of cellulose in the soybean hulls diet was less ($P \leq 0.05$) than in all other diets.

The basal corn-soybean meal diet had the greatest ($P \leq 0.05$) ATTD of DM and GE, and diets containing DDGS or wheat middlings had greater ATTD of DM and GE ($P \leq 0.05$) than the soybean hull diet. With the exception of insoluble hemicelluloses and cellulose, the basal diet had greater ($P \leq 0.05$) ATTD of all dietary fiber components than the other diets but, with a few exceptions, no differences among the other diets were observed. The DE was different ($P \leq 0.05$) among diets and was 3,430, 3,299, 3,218, and 2,948 kcal/kg in the basal diet, the DDGS diet, the wheat middlings diet, and the soybean hull diet, respectively.

Wheat middlings had the greatest ($P \leq 0.05$) AID of DM and GE followed by DDGS and soybean hulls (Table 4). The AID of NDF, insoluble dietary fiber, total dietary fiber, insoluble hemicelluloses, NSP, insoluble

NSP, and non-cellulosic NSP also was greater ($P \leq 0.05$) in wheat middlings compared with DDGS and soybean hulls.

Wheat middlings also had the greatest ($P \leq 0.05$) ACD of DM, GE, NDF, insoluble dietary fiber, and total dietary fiber, and soybean hulls had the least ($P \leq 0.05$) ACD of these components. The ACD of ADF was greater ($P \leq 0.05$) in DDGS compared with soybean hulls, and the ACD of soluble dietary fiber, insoluble hemicelluloses, NSP, insoluble NSP, and non-cellulosic NSP were greater ($P \leq 0.05$) in wheat middlings compared with DDGS and soybean hulls.

The ATTD of DM and GE were greater ($P \leq 0.05$) in DDGS and wheat middlings compared with soybean hulls, but wheat middlings had the least ($P \leq 0.05$) ATTD of ADF and cellulose compared with DDGS and soybean hulls. The ATTD of soluble dietary fiber was greater ($P \leq 0.05$) in wheat middlings than in soybean hulls, but DDGS had the least ATTD of soluble dietary fiber. Wheat middlings had the greatest ($P \leq 0.05$) ATTD of total dietary fiber, NSP, insoluble NSP, and non-cellulosic NSP compared with DDGS and soybean hulls. The DE was different ($P \leq 0.05$) among ingredients and was 2,975, 2,697, and 1,763 kcal/kg in DDGS, wheat middlings, and soybean hulls, respectively.

Disappearance of Nutrients and Energy in the Stomach and Small intestine, Cecum, and Colon

Disappearance of GE and DM before the end of the ileum was greater ($P \leq 0.05$) in pigs fed the corn-soybean meal basal diet than in pigs fed the other diets, and pigs fed the soybean hull diet had the least ($P \leq 0.05$) disappearance of GE and DM in the stomach and small intestine (Table 5). Disappearance of dietary fiber components before the end of the ileum was greater ($P \leq 0.05$) in pigs fed the diet containing wheat middlings, whereas the basal diet had less disappearance of dietary fiber components in the stomach and small intestine compared with the diets containing DDGS or soybean hulls.

The disappearance of soluble dietary fiber in the cecum was greater ($P \leq 0.05$) in the diet containing soybean hulls compared with the basal and the wheat middlings diets, but for all other measured components, no differences in cecal disappearance among diets were observed. The degradation of DM and most dietary fiber components in the colon was greater ($P \leq 0.05$) in the diet containing soybean hulls compared with the other diets, with the exception that pigs fed the diet containing DDGS had the greatest ($P \leq 0.05$) degradation of insoluble hemicelluloses. The degradation of GE in the large intestine of pigs fed diets containing DDGS or soybean hulls was greater ($P \leq 0.05$) compared with the degradation in the basal diet and the diet containing wheat middlings.

The disappearance of DM and all dietary fiber components before the end of the ileum was greater ($P \leq 0.05$) from wheat middlings compared with DDGS and soybean hulls (Table 6). Disappearance of GE in the stomach and small intestine was greater for wheat middlings compared with soybean hulls.

There were no differences among DDGS, wheat middlings, or soybean hulls in the disappearance of DM, GE, or dietary fiber components in the cecum of pigs. However, disappearance of DM and most dietary fiber components in the colon was greater ($P \leq 0.05$) from soybean hulls than from DDGS and wheat middlings, and wheat middlings had the least ($P \leq 0.05$) disappearance of dietary fiber components in the colon. The disappearance of GE in the large intestine of pigs was also less ($P \leq 0.05$) for wheat middlings compared with DDGS and soybean hulls.

Physical Characteristics of Ileal and Cecal Digesta and Feces

The water binding capacity of ileal digesta from pigs fed the diet containing soybean hulls was greater ($P \leq 0.05$) compared with the other 3 diets (Table 7). Ileal digesta viscosity was less ($P \leq 0.05$) in pigs fed the diet containing wheat middlings than in digesta from pigs fed diets containing DDGS or soybean hulls. The water binding capacity of cecal digesta from pigs fed the diet containing soybean hulls was greater ($P \leq 0.05$) than in digesta from all other diets, and water binding capacity of cecal digesta from pigs fed the wheat middlings or DDGS diets was greater ($P \leq 0.05$) than in digesta from pigs fed the basal diet. The water binding capacity of feces from pigs fed the wheat middlings diet was greater ($P \leq 0.05$) than that of all other diets, but pigs fed the basal diet or the soybean hull diets had water binding capacity in feces that was less ($P \leq 0.05$) than in the other diets.

Correlations between Physical Characteristics and Digestibility

A positive correlation between bulk density of experimental diets and ACD of GE (r = 0.88; $P \leq 0.05$) was observed; however, no other correlations between physical characteristics of experimental diets and digestibility were significant. Therefore, only the correlation coefficients between physical characteristics of diets and ACD of nutrients and energy are presented in Table 8.

Discussion

Ingredients used in this experiment contained similar concentrations of nutrients and energy as reported by NRC (2012). Oil was not removed from DDGS used in this experiment because DDGS contained 9.89% AEE which is approximately 3 times greater compared with corn (3.27%). Corn contained 13.41% total dietary fiber and DDGS contained 38.72% total dietary fiber, once again, approximately 3 times greater compared with corn. Soybean meal, wheat middlings, and soybean hulls contained 18.80, 37.11, and 67.46% total dietary fiber, respectively.

The ATTD of DM and GE in the corn-soybean meal basal diet and the diet containing DDGS used in the current experiment are in agreement with previous research that used similar corn-soybean meal diets (Urriola and Stein, 2010). The ATTD of DM, GE, insoluble dietary fiber, total dietary fiber, and insoluble NSP for the corn-soybean meal basal diet compared with the other 3 diets is likely the reason for the greater DE that was observed in the corn-soybean meal basal diet compared with the other 3 diets. The DE obtained for experimental diets in the current experiment are in agreement with calculated values (NRC, 2012). The ATTD of soluble dietary fiber in experimental diets was, on average, 86.5% and this was in agreement with Urriola and Stein (2010). The average ATTD of soluble dietary fiber was 20 percentage units greater compared with the ATTD of insoluble dietary fiber among experimental diets, thus confirming results indicating that soluble dietary fiber is more fermentable by pigs compared with insoluble dietary fiber (Urriola et al., 2010). Due to the differentiation of components of dietary fiber, it was possible to distinguish the digestibility of the different dietary fiber fractions. The ATTD of cellulose by pigs fed the basal diet or the DDGS diet was greater compared with the ATTD of insoluble hemicelluloses, whereas diets containing wheat middlings and soybean hulls had greater ATTD of insoluble hemicelluloses, NSP, insoluble NSP, and non-cellulosic NSP compared with cellulose. It may be speculated that cellulolytic enzymes and bacteria are utilized in ethanol production, and this may render the cellulose in DDGS more susceptible for fermentation in the pig.

The AID, ACD, and ATTD of DM and GE are less in DDGS, wheat middlings, and soybean hulls than in the experimental diets because these ingredients contain more dietary fiber and less starch. The ATTD of total dietary fiber from DDGS was 54.69% in the current experiment, which is in agreement with the average ATTD of total dietary fiber from 8 DDGS sources (49.5%) obtained by Urriola et al. (2010). The ATTD of most dietary fiber fractions were greater in wheat middlings compared with DDGS and soybean hulls; however, the ATTD of GE was not different between wheat middlings and DDGS. This may be explained by the greater concentration of fat in DDGS compared with wheat middlings.

The AID of dietary fiber fractions in diets and ingredients are relatively low and in agreement with data from Bach Knudsen et al. (2013), indicating that the AID of NSP by pigs range from -7 to 40%. The ACD of soluble dietary fiber in diets and ingredients was greater than the AID of soluble dietary fiber, whereas values for the ACD of insoluble dietary fiber were close to values observed for the AID of insoluble dietary fiber. This observation indicates that mainly soluble dietary fiber is fermented in the cecum. However, the ACD of GE was close to the AID of GE in diets and ingredients, which indicates that fermentation of soluble dietary fiber in the cecum has a low energy contribution. This is likely mostly because the concentration of soluble dietary fiber is low in the diets and ingredients used in the current experiment.

The colon of pigs is the main site for insoluble dietary fiber fermentation as indicated by the greater disappearance of insoluble dietary fiber fractions in the colon compared with the stomach and small intestine, and the cecum. To our knowledge, this is the first time dietary fiber fermentation has been estimated separately in the cecum and in the colon of pigs. The structure of insoluble dietary fiber fractions is much more hydrophobic and crystalline and, therefore, microbial fermentation of insoluble dietary fiber fractions occurs more slowly and requires longer retention time in the colon of pigs compared with soluble dietary fiber (Bach Knudsen and Hansen, 1991; Wilfart et al., 2007). Differences in size and microbial populations of the cecum and the colon also may influence dietary fiber fermentation. The cecum and colon have been reported to be 0.3

and 1.75% of the empty BW of pigs, respectively, and this difference in size indicates the importance of the colon to dietary fiber fermentation (Agyekum et al., 2012). Total viable counts of anaerobic bacteria increase from 10^9 viable counts in the distal ileum to 10^{12} viable counts in pig feces and it is expected that viable counts in the cecum is between the values in the ileum and the colon (Jensen and Jørgensen, 1994).

Antithetical to our hypothesis, water binding capacity and bulk density of experimental diets were not correlated with ileal, cecal, or total tract digestibility of nutrients and energy, with the exception that bulk density was positively correlated with ACD of GE. Serena et al. (2008) also were unable to correlate physicochemical properties of dietary fiber and digestibility of energy in sows.

Overall, ATTD of insoluble dietary fiber in wheat middlings was greater than in DDGS and soybean hulls, but the ATTD of cellulose was less in wheat middlings. However, the energy contribution from cellulose fermentation in wheat middlings is relatively low because wheat middlings has a low concentration of cellulose. Soybean hulls had the greatest concentration of total dietary fiber and the least concentrations of starch and fat and, as a result, fermentation of dietary fiber contributes the majority of the DE in soybean hulls. The energy contribution from dietary fiber fermentation is much less compared with the energy contribution from enzymatic digestion of starch and fat, which is the reason soybean hulls had the least DE compared with DDGS and wheat middlings (Nelson and Cox, 2008). The ATTD of soluble dietary fiber in DDGS in the current experiment was less compared with the ATTD of soluble dietary fiber in 8 sources of DDGS determined by Urriola et al. (2010). The ATTD of soluble dietary fiber was also less than the ATTD of insoluble dietary fiber in DDGS and these differences may be attributed to the low concentration of soluble dietary fiber in DDGS as well as differences in ethanol production today compared with several years ago. A greater variety of cellulolytic enzymes and bacteria are utilized in ethanol plants today and it is also likely that the efficacy of cellulose degradation by ethanol plants has been improved; therefore, the dietary fiber fractions remaining in DDGS may be different.

In conclusion, the physical characteristics of dietary fiber in experimental diets were not correlated with the digestibility of energy or dietary fiber fractions in experimental diets. Soluble dietary fiber is mostly fermented in the cecum of pigs, but this does not contribute a great amount of energy supply to the pig due to the low concentration of soluble dietary fiber in most swine diets. Insoluble dietary fiber is mostly fermented in the colon of pigs and contributes a significant energy supply to pigs fed diets containing DDGS, wheat middlings, or soybean hulls because the concentration of insoluble dietary fiber is greater when these co-products are added to a corn-soybean meal diet. Dietary fiber fractions in wheat middlings are more fermentable compared with the dietary fiber fractions in DDGS and soybean hulls; however, the DE in DDGS is similar to that of wheat middlings because of the greater concentration of fat in DDGS compared with wheat middlings. The DE in soybean hulls is mostly attributed to insoluble dietary fiber fermentation in the colon, and this is the reason the DE in soybean hulls is less than in DDGS or wheat middlings.

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Table 1. Chemical and physical composition of feed ingredients

Item	Corn	Soybean meal	DDGS[1]	Wheat middlings	Soybean hulls
GE, kcal/kg	3,822	4,204	4,518	4,034	3,692
DM, %	85.89	88.76	85.18	87.38	87.68
Ash, %	1.06	6.54	5.13	4.81	4.18
AEE[1], %	3.27	1.75	9.89	4.24	1.87
Indispensable AA, %					
Arg	0.34	3.47	1.21	1.08	0.37
His	0.21	1.23	0.71	0.44	0.23
Ile	0.27	2.32	1.08	0.55	0.34
Leu	0.86	3.69	2.94	1.02	0.58
Lys	0.27	3.01	0.92	0.71	0.62
Met	0.15	0.66	0.49	0.23	0.10
Phe	0.35	2.40	1.28	0.66	0.32
Thr	0.25	1.74	0.98	0.49	0.29
Trp	0.05	0.74	0.23	0.20	0.06
Val	0.35	2.43	1.37	0.79	0.41
Dispensable AA, %					
Ala	0.53	2.04	1.76	0.75	0.39
Asp	0.48	5.24	1.65	1.10	0.74
Cys	0.15	0.61	0.45	0.32	0.15
Glu	1.29	8.45	3.29	3.08	0.93
Gly	0.30	2.05	1.17	0.85	0.79
Pro	0.58	2.41	1.92	1.04	0.50
Ser	0.31	1.88	1.08	0.56	0.42
Tyr	0.20	1.68	0.95	0.39	0.32
Total AA, %	7.05	46.18	23.62	14.39	8.24
Carbohydrates, %					
Fructose	0.16	0.10	0.08	0.67	0.24
Glucose	0.36	0.08	0.39	0.91	0.26
Sucrose	1.09	6.33	0.04	1.38	0.28
Maltose	0.31	0.01	0.30	0.11	0.07
Raffinose	0.13	0.94	0.03	1.06	0.08
Stachyose	0.01	4.10	0.02	0.02	0.23
Verbascose	N.D.[2]	0.12	N.D.	N.D.	0.01
Starch	53.93	2.01	2.74	22.20	7.49
ADF	2.53	7.38	17.78	9.76	40.28
NDF	8.07	7.51	36.99	33.16	55.37
ADL	0.47	0.39	4.83	3.14	1.94
Soluble dietary fiber	1.57	1.83	1.74	2.64	5.31
Insoluble dietary fiber	11.84	16.97	36.98	34.47	62.15
Total dietary fiber[3]	13.41	18.80	38.72	37.11	67.46
Cellulose[4]	2.06	6.99	12.95	6.62	38.34
Insoluble hemicelluloses[5]	5.54	0.13	19.21	23.40	15.09
Non-starch polysaccharides[6]	12.94	18.41	33.89	33.97	65.52
Insoluble non-starch polysaccharides[7]	11.37	16.58	32.15	31.33	60.21

Non-cellulosic non-starch polysaccharides[8]	10.88	11.42	20.94	27.35	27.18
Total[9], %	80.78	86.96	80.96	86.90	90.41
DE[10], kcal/kg	3,484	3,590	2,635	2,470	1,334
Bulk density, g/L	559.75	644.93	442.65	356.57	435.63
Water binding capacity, g/g	1.07	2.81	2.02	2.99	4.22

[1]DDGS = distillers dried grains with solublesAEE = acid hydrolyzed ether extract.
[2]N.D. = not detectable.
[3]Total dietary fiber = soluble dietary fiber + insoluble dietary fiber.
[4]Cellulose = ADF – ADL.
[5]Insoluble hemicelluloses = NDF – ADF.
[6]Non-starch polysaccharides = total dietary fiber – ADL.
[7]Insoluble non-starch polysaccharides = non-starch polysaccharides – soluble dietary fiber.
[8]Non-cellulosic non-starch polysaccharides = non-starch polysaccharides – cellulose.
[9]Total = ash + AEE + total AA + starch + sugars + oligosaccharides + total dietary fiber.
[10]DE (kcal / kg of DM) = 1,161 + (0.749 × GE) – (4.3 × ash) – (4.1 × NDF) (Noblet and Perez, 1993).

Table 2. Ingredient composition, analyzed nutrients and energy, and physical characteristics of experimental diets

Item	Basal	Basal + DDGS[1]	Basal + wheat middlings	Basal + soybean hulls
Ingredient, %				
Corn	64.50	45.15	45.15	45.15
Soybean meal	32.25	22.58	22.58	22.58
DDGS	-	29.10	-	-
Wheat middlings	-	-	29.10	-
Soybean hulls	-	-	-	29.10
Limestone	0.85	0.85	0.85	0.85
Dicalcium P	1.15	1.15	1.15	1.15
Lysine HCl	0.25	0.18	0.18	0.18
Titanium dioxide	0.40	0.40	0.40	0.40
Salt	0.40	0.40	0.40	0.40
Vitamin-mineral premix[2]	0.20	0.20	0.20	0.20
Analyzed composition				
GE, kcal/kg	3,831	3,968	3,862	3,745
DM, %	87.22	87.04	87.44	87.59
Ash, %	5.76	6.01	6.07	6.12
AEE[3], %	3.15	4.97	3.33	2.52
Indispensable AA, %				
Arg	1.38	1.24	1.24	1.01
His	0.55	0.57	0.50	0.43
Ile	0.94	0.91	0.80	0.73
Leu	1.81	2.05	1.54	1.39
Lys	1.37	1.15	1.21	1.13
Met	0.29	0.33	0.27	0.22
Phe	1.03	1.06	0.89	0.78
Thr	0.76	0.78	0.65	0.58
Trp	0.28	0.26	0.25	0.21
Val	1.04	1.07	0.93	0.81
Dispensable AA, %				
Ala	1.02	1.20	0.93	0.81
Asp	2.09	1.87	1.74	1.61
Cys	0.30	0.33	0.29	0.25
Glu	3.67	3.50	3.45	2.77
Gly	0.86	0.90	0.84	0.83
Pro	1.23	1.38	1.13	0.98
Ser	0.85	0.88	0.74	0.69
Tyr	0.68	0.71	0.57	0.54
Total AA, %	20.33	20.34	18.14	16.11
Carbohydrates, %				

Fructose	0.20	0.12	0.37	0.35
Glucose	0.26	0.37	0.60	0.40
Sucrose	2.69	1.80	2.22	1.78
Maltose	0.16	0.18	0.23	0.33
Raffinose	0.39	0.26	0.59	0.28
Stachyose	1.29	0.77	0.91	0.90
Verbascose	0.03	0.02	0.02	0.02
Starch	35.09	27.64	32.51	28.83
ADF	3.93	6.43	5.18	15.00
NDF	7.68	16.30	15.01	21.72
ADL	0.45	1.11	1.21	0.88
Soluble dietary fiber	1.49	1.37	2.02	2.21
Insoluble dietary fiber	12.14	19.00	19.06	26.35
Total dietary fiber[4]	13.63	20.37	21.08	28.56
Cellulose[5]	3.48	5.32	3.97	14.12
Insoluble hemicelluloses[6]	3.75	9.87	9.83	6.72
Non-starch polysaccharides[7]	13.18	19.26	19.87	27.68
Insoluble non-starch polysaccharides[8]	11.69	17.89	18.66	26.80
Non-cellulosic non-starch polysaccharides[9]	9.70	13.94	15.90	13.56
Total[10], %	82.98	82.85	86.07	86.20
DE[11], kcal/kg	3,393	3,429	3,270	2,959
Bulk density, g/L	638.68	584.13	533.40	574.07
Water binding capacity, g/g	1.47	1.58	1.84	2.21

[1]DDGS = distillers dried grains with solubles.

[2]The vitamin-micromineral premix provided the following quantities of vitamins and micro-minerals per kilogram of complete diet: Vitamin A as retinyl acetate, 11,136 IU; vitamin D3 as cholecalciferol, 2,208 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B12, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper sulfate; Fe, 126 mg as iron sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganous sulfate; Se, 0.25 mg as sodium selenite and selenium yeast; and Zn, 124.9 mg as zinc sulfate.

[3]AEE = acid hydrolyzed ether extract.

[4]Total dietary fiber = soluble dietary fiber + insoluble dietary fiber.

[5]Cellulose = ADF – ADL.

[6]Insoluble hemicelluloses = NDF – ADF.

[7]Non-starch polysaccharides = total dietary fiber – ADL.

[8]Insoluble non-starch polysaccharides = non-starch polysaccharides – soluble dietary fiber.

[9]Non-cellulosic non-starch polysaccharides = non-starch polysaccharides – cellulose.

[10]Total = ash + AEE + total AA + starch + sugars + oligosaccharides + total dietary fiber.

[11]DE calculated from NRC (2012).

Table 3. Apparent ileal, cecal, and total tract digestibility of dry matter, energy, and nutrients in experimental diets

Item	Basal	Basal + DDGS	Basal + wheat middlings	Basal + soybean hulls	SEM	*P*-value
Apparent ileal digestibility, %						
DM	72.6[a]	56.0[c]	62.8[b]	48.9[d]	1.4	< 0.001
GE	74.6[a]	60.8[c]	65.5[b]	54.7[d]	1.3	< 0.001
ADF	29.5[a]	20.6[ab]	24.5[a]	10.7[b]	4.9	0.014
NDF	26.0[b]	24.1[b]	38.5[a]	15.0[c]	4.2	< 0.001
Soluble dietary fiber	43.9[a]	5.3[c]	33.7[ab]	17.8[bc]	7.6	0.002
Insoluble dietary fiber	41.2[a]	23.3[b]	43.0[a]	17.6[b]	3.6	< 0.001
Total dietary fiber	41.5[a]	22.1[b]	42.0[a]	17.6[b]	3.5	< 0.001
Cellulose	30.2[a]	17.4[bc]	24.9[ab]	9.9[c]	5.1	0.009
Insoluble hemicelluloses	22.5[b]	26.4[b]	46.0[a]	25.4[b]	4.0	< 0.001
Non-starch polysaccharides	42.0[a]	21.4[b]	43.2[a]	17.5[b]	3.6	< 0.001
Insoluble non-starch polysaccharides	41.9[a]	22.6[b]	44.3[a]	17.4[b]	3.7	< 0.001
Non-cellulosic non-starch polysaccharides	46.5[a]	22.8[b]	47.9[a]	24.9[b]	4.0	< 0.001
Apparent cecal digestibility, %						
DM	75.7[a]	61.3[c]	68.0[b]	53.3[d]	1.4	< 0.001
GE	74.6[a]	61.2[c]	67.6[b]	55.7[d]	1.5	< 0.001
ADF	27.0[a]	21.9[ab]	19.3[b]	8.6[c]	3.1	< 0.001
NDF	26.6[b]	23.3[b]	37.6[a]	16.0[c]	2.7	< 0.001
Soluble dietary fiber	67.6	62.1	66.7	67.5	4.5	0.637
Insoluble dietary fiber	48.7[a]	31.9[b]	47.6[a]	22.7[c]	2.2	< 0.001
Total dietary fiber	50.7[a]	33.9[b]	49.4[a]	26.1[c]	2.3	< 0.001
Cellulose	30.4[a]	20.0[b]	21.5[b]	7.8[c]	3.2	< 0.001
Insoluble hemicelluloses	26.1[bc]	24.3[c]	47.4[a]	32.2[b]	2.9	< 0.001
Non-starch polysaccharides	52.5[a]	34.1[b]	51.7[a]	26.4[c]	2.3	< 0.001
Insoluble non-starch polysaccharides	50.6[a]	32.0[b]	50.1[a]	22.9[c]	2.2	< 0.001
Non-cellulosic non-starch polysaccharides	60.4[a]	39.5[c]	59.4[a]	45.3[b]	2.5	< 0.001
Apparent total tract digestibility, %						
DM	89.1[a]	82.8[b]	82.9[b]	78.3[c]	0.7	< 0.001
GE	89.5[a]	83.1[b]	83.3[b]	78.7[c]	0.7	< 0.001
ADF	66.3[a]	67.2[a]	40.3[c]	56.9[b]	3.7	< 0.001
NDF	63.9	66.2	61.9	63.5	2.1	0.345
Soluble dietary fiber	86.6	84.1	90.1	85.4	3.8	0.122
Insoluble dietary fiber	71.2[a]	64.1[b]	64.7[b]	64.0[b]	1.9	0.001
Total dietary fiber	72.9[a]	65.5[b]	67.1[b]	65.7[b]	1.8	< 0.001

Cellulose	72.2[a]	69.8[a]	52.7[c]	60.1[b]	3.3	< 0.001
Insoluble hemicelluloses	61.3[b]	65.6[b]	73.3[a]	78.0[a]	2.1	< 0.001
Non-starch polysaccharides	74.7[a]	66.1[c]	71.3[ab]	67.6[bc]	1.9	< 0.001
Insoluble non-starch polysaccharides	73.1[a]	64.7[c]	69.1[b]	66.0[bc]	1.9	0.001
Non-cellulosic non-starch polysaccharides	75.5[a]	64.7[b]	75.9[a]	75.3[a]	1.7	< 0.001
DE, kcal/kg	3,430[a]	3,299[b]	3,218[c]	2,948[d]	27	< 0.001

[a-d]Values within a row lacking a common superscript letter are different ($P < 0.05$).

Table 4. Apparent ileal, cecal, and total tract digestibility of dry matter, energy, and nutrients in distillers dried grains with solubles (**DDGS**), wheat middlings, and soybean hulls

Item	DDGS	Wheat middlings	Soybean hulls	SEM	*P*-value
Apparent ileal digestibility, %					
DM	15.7[b]	39.0[a]	-8.1[c]	5.4	< 0.001
GE	29.2[b]	42.4[a]	1.3[c]	4.7	< 0.001
ADF	9.3	15.6	6.7	8.7	0.657
NDF	22.7[b]	44.9[a]	11.0[b]	7.1	0.001
Soluble dietary fiber	-74.3[b]	28.4[a]	-3.1[a]	18.8	0.001
Insoluble dietary fiber	7.7[b]	45.9[a]	5.3[b]	7.0	< 0.001
Total dietary fiber	4.1[b]	44.6[a]	4.5[b]	7.0	< 0.001
Cellulose	4.5	12.2	5.5	10.3	0.752
Insoluble hemicelluloses	35.1[b]	57.2[a]	24.7[b]	7.1	0.001
Non-starch polysaccharides	1.5[b]	46.6[a]	3.8[b]	7.4	< 0.001
Insoluble non-starch polysaccharides	5.5[b]	48.2[a]	4.5[b]	7.4	< 0.001
Non-cellulosic non-starch polysaccharides	-0.5[b]	55.3[a]	2.1[b]	8.3	< 0.001
Apparent cecal digestibility, %					
DM	24.5[b]	47.7[a]	-2.3[c]	5.1	< 0.001
GE	28.0[b]	47.1[a]	2.1[c]	5.4	< 0.001
ADF	11.7[a]	7.2[ab]	3.2[b]	4.2	0.023
NDF	21.1[b]	42.4[a]	11.3[c]	3.3	< 0.001
Soluble dietary fiber	26.8[b]	81.8[a]	50.7[b]	10.7	0.001
Insoluble dietary fiber	17.1[b]	47.8[a]	9.3[c]	3.4	< 0.001
Total dietary fiber	17.6[b]	50.2[a]	13.0[b]	3.5	< 0.001
Cellulose	7.2	4.1	2.1	4.9	0.433
Insoluble hemicelluloses	29.9[b]	57.8[a]	32.5[b]	3.9	< 0.001
Non-starch polysaccharides	16.7[b]	53.5[a]	12.6[b]	3.6	< 0.001
Insoluble non-starch polysaccharides	16.0[b]	51.2[a]	9.0[b]	3.6	< 0.001
Non-cellulosic non-starch polysaccharides	22.0[b]	66.0[a]	24.9[b]	4.9	< 0.001
Apparent total tract digestibility, %					
DM	68.6[a]	68.4[a]	52.7[b]	2.8	< 0.001
GE	64.8[a]	66.3[a]	46.9[b]	3.0	< 0.001
ADF	46.7[a]	8.2[b]	56.6[a]	5.8	< 0.001
NDF	66.6	60.2	63.9	3.5	0.209
Soluble dietary fiber	46.4[c]	116.9[a]	63.5[b]	9.4	< 0.001
Insoluble dietary fiber	55.1	61.6	59.1	3.7	0.069
Total dietary fiber	54.7[b]	65.5[a]	59.4[b]	3.6	0.002
Cellulose	50.1[a]	15.9[b]	59.6[a]	5.7	< 0.001
Insoluble hemicelluloses	84.9	81.9	82.3	2.5	0.535

Non-starch polysaccharides	57.2^{b}	72.4^{a}	61.4^{b}	3.7	0.001
Insoluble non-starch polysaccharides	57.7^{b}	68.7^{a}	61.2^{b}	3.9	0.010
Non-cellulosic non-starch polysaccharides	61.6^{b}	86.1^{a}	63.3^{b}	3.6	< 0.001
DE, kcal/kg	$2{,}975^{a}$	$2{,}697^{b}$	$1{,}763^{c}$	116	< 0.001

[a-c]Values within a row lacking a common superscript letter are different ($P \leq 0.05$).

Table 5. Disappearance of dietary dry matter, energy, and nutrients (g or kcal/kg of DMI) in the stomach and small intestine, cecum, and colon of pigs fed experimental diets

Item	Basal	Basal + DDGS[1]	Basal + wheat middlings	Basal + soybean hulls	SEM	*P*-value
Stomach and small intestine						
DM	633.4[a]	487.6[c]	548.8[b]	428.0[d]	11.9	< 0.001
GE	3,276[a]	2,769[b]	2,894[b]	2,337[c]	57	< 0.001
ADF	13.1	15.2	14.4	19.4	3.2	0.328
NDF	22.1[c]	45.2[b]	66.0[a]	38.0[b]	7.2	< 0.001
Soluble dietary fiber	7.5[a]	0.9[b]	7.7[a]	4.5[ab]	1.5	0.002
Insoluble dietary fiber	57.2[b]	50.9[b]	93.9[a]	54.0[b]	7.7	< 0.001
Total dietary fiber	64.6[b]	51.8[b]	101.6[a]	58.4[b]	8.2	< 0.001
Cellulose	11.9	10.7	11.2	17.2	2.7	0.153
Insoluble hemicelluloses	9.2[d]	23.0[b]	51.8[a]	18.9[c]	4.2	< 0.001
Non-starch polysaccharides	63.4[b]	47.3[b]	98.3[a]	56.0[b]	7.9	< 0.001
Insoluble non-starch polysaccharides	55.9[b]	46.4[b]	90.6[a]	51.6[b]	7.4	< 0.001
Non-cellulosic non-starch polysaccharides	51.6[b]	36.5[c]	87.3[a]	38.7[bc]	6.2	< 0.001
Cecum						
DM	30.8	45.8	49.5	43.6	15.9	0.690
GE	26.4	18.5	116.5	72.2	73.8	0.548
ADF	-1.0	1.0	-3.0	-2.9	3.1	0.685
NDF	0.3	-1.3	-2.1	1.8	5.8	0.953
Soluble dietary fiber	4.0[c]	8.9[ab]	7.6[bc]	12.7[a]	2.0	0.012
Insoluble dietary fiber	10.6	18.9	10.3	16.4	8.0	0.720
Total dietary fiber	14.6	27.8	17.9	29.0	8.3	0.389
Cellulose	0.3	1.6	-1.3	-2.5	2.7	0.646
Insoluble hemicelluloses	1.5	-2.4	1.1	4.7	3.2	0.385
Non-starch polysaccharides	15.8	28.4	19.5	29.4	8.7	0.420
Insoluble non-starch polysaccharides	11.9	19.5	11.9	16.8	7.8	0.769
Non-cellulosic non-starch polysaccharides	15.2	26.9	20.5	31.8	6.9	0.095
Colon						
DM	114.8[c]	187.6[b]	128.8[c]	217.3[a]	11.4	< 0.001
GE	647[b]	999[a]	687[b]	977[a]	61	< 0.001
ADF	17.5[c]	33.5[b]	12.1[c]	80.7[a]	4.5	< 0.001
NDF	33.1[c]	80.2[b]	41.6[c]	116.6[a]	6.3	< 0.001
Soluble dietary fiber	3.3	3.5	5.4	4.5	1.0	0.106
Insoluble dietary fiber	31.3[c]	70.3[b]	36.9[c]	123.2[a]	6.7	< 0.001
Total dietary fiber	34.7[c]	73.9[b]	42.4[c]	128.0[a]	7.3	< 0.001
Cellulose	16.4[c]	30.4[b]	13.8[c]	81.9[a]	4.3	< 0.001

Insoluble hemicelluloses	15.3[c]	46.6[a]	29.3[b]	35.5[b]	3.1	< 0.001
Non-starch polysaccharides	33.6[c]	70.8[b]	44.1[c]	129.2[a]	7.1	< 0.001
Insoluble non-starch polysaccharides	30.2[c]	67.3[b]	38.6[c]	124.4[a]	6.6	< 0.001
Non-cellulosic non-starch polysaccharides	17.0[c]	40.3[a]	30.1[b]	46.8[a]	4.7	< 0.001

[1]DDGS = distillers dried grains with solubles.

[a-d]Values within a row lacking a common superscript letter are different ($P \leq 0.05$).

Table 6. Disappearance of dry matter, energy, and nutrients (g or kcal/kg of DMI) from distillers dried grains with solubles (**DDGS**), wheat middlings, and soybean hulls in the stomach and small intestine, cecum, and colon of pigs

Item	DDGS	Wheat middlings	Soybean hulls	SEM	*P*-value
Stomach and small intestine					
DM	430.8[b]	549.3[a]	428.0[b]	32.1	0.015
GE	2,472[ab]	2,896[a]	2,333[b]	164	0.050
ADF	14.0	14.4	19.6	3.3	0.289
NDF	43.2[b]	66.2[a]	38.3[b]	7.7	0.006
Soluble dietary fiber	0.3[b]	7.8[a]	4.6[a]	1.5	0.002
Insoluble dietary fiber	45.8[b]	94.2[a]	54.3[b]	7.9	< 0.001
Total dietary fiber	46.0[b]	101.9[a]	58.7[b]	8.3	< 0.001
Cellulose	9.6	11.2	17.3	2.8	0.071
Insoluble hemicelluloses	29.2[b]	51.9[a]	19.0[c]	4.7	< 0.001
Non-starch polysaccharides	41.6[b]	98.6[a]	56.4[b]	8.0	< 0.001
Insoluble non-starch polysaccharides	41.3[b]	90.9[a]	51.9[b]	7.5	< 0.001
Non-cellulosic non-starch polysaccharides	32.0[b]	87.5[a]	39.1[b]	6.5	< 0.001
Cecum					
DM	21.7	26.1	19.5	17.8	0.942
GE	-15.6	87.5	38.9	83.3	0.523
ADF	1.7	-2.2	-2.1	3.4	0.549
NDF	-1.4	-2.3	1.8	6.5	0.871
Soluble dietary fiber	6.0	4.7	9.7	2.1	0.141
Insoluble dietary fiber	11.7	3.0	9.1	9.0	0.699
Total dietary fiber	17.7	7.7	18.9	9.9	0.576
Cellulose	1.4	-1.5	-2.5	3.6	0.533
Insoluble hemicelluloses	-3.4	0.3	4.0	3.7	0.241
Non-starch polysaccharides	17.4	8.3	18.3	9.8	0.623
Insoluble non-starch polysaccharides	11.4	3.7	8.6	8.8	0.746
Non-cellulosic non-starch polysaccharides	16.1	9.6	20.9	7.7	0.361
Colon					
DM	108.5[b]	50.4[c]	137.0[a]	11.8	< 0.001
GE	563[a]	248[b]	530[a]	62	< 0.001
ADF	21.3[b]	-0.1[c]	68.3[a]	4.9	< 0.001
NDF	57.2[b]	18.4[c]	93.2[a]	6.9	< 0.001
Soluble dietary fiber	1.2	3.1	2.1	1.0	0.219
Insoluble dietary fiber	48.4[b]	15.0[c]	101.0[a]	7.4	< 0.001
Total dietary fiber	49.5[b]	18.1[c]	103.3[a]	8.0	< 0.001

Cellulose	19.1[b]	2.4[c]	70.4[a]	5.0	< 0.001
Insoluble hemicelluloses	36.0[a]	18.4[b]	24.6[b]	3.5	0.002
Non-starch polysaccharides	47.3[b]	20.6[c]	105.4[a]	8.0	< 0.001
Insoluble non-starch polysaccharides	46.1[b]	17.4[c]	103.0[a]	7.4	< 0.001
Non-cellulosic non-starch polysaccharides	27.9[a]	18.5[b]	35.0[a]	5.5	0.003

[a-c]Values within a row lacking a common superscript letter are different ($P \leq 0.05$).

Table 7. Viscosity of ileal and cecal digesta and water binding capacity of ileal and cecal digesta and feces from pigs fed experimental diets

Item	Basal	Basal + DDGS[1]	Basal + wheat middlings	Basal + soybean hulls	SEM	*P*-value
Ileal digesta						
Water binding capacity, g/g	2.95[b]	3.12[b]	2.81[b]	3.82[a]	0.32	< 0.001
Viscosity						
Constant, cP	15,675[ab]	19,164[a]	6,361[b]	20,516[a]	4,218	0.044
Exponent	-1.21	-1.38	-1.01	-1.40	0.14	0.125
R^2	0.92	0.99	0.91	0.96	-	-
Cecal digesta						
Water binding capacity, g/g	1.71[c]	2.03[b]	2.23[b]	2.73[a]	0.11	< 0.001
Viscosity						
Constant, cP	7,362	8,203	4,735	14,822	3,405	0.134
Exponent	-0.91	-0.98	-0.92	-1.19	0.14	0.232
R^2	0.96	0.98	0.96	0.99	-	-
Feces						
Water binding capacity, g/g	2.09[c]	2.65[b]	3.07[a]	2.21[c]	0.06	< 0.001

[a-c]Values within a row lacking a common superscript letter are different ($P \leq 0.05$).

Table 8. Correlation coefficients[1] between physical characteristics of experimental diets and apparent cecal digestibility (**ACD**) of dry matter, energy, and dietary fiber fractions and physical characteristics of cecal digesta from pigs fed experimental diets

	Correlation coefficient							
Cecal digesta measurement	ACD of DM, %	ACD of GE, %	ACD of soluble dietary fiber, %	ACD of insoluble dietary fiber, %	ACD of total dietary fiber, %	ACD of non-starch polysaccharides, %	Water binding capacity, g/g	Viscosity, cP
Physical characteristic								
Water binding capacity	-0.64	-0.61	-0.31	-0.70	-0.68	-0.66	0.37	0.38
Bulk density	0.87	0.88*	0.86	0.61	0.65	0.65	-0.86	0.48

[1]Correlation coefficients were determined between all variables, but the table has been reduced for brevity.
*$P \leq 0.050$ ** $P < 0.01$.