Effects of physicochemical characteristics of feed ingredients on the apparent total tract digestibility of energy, DM, and nutrients by growing pigs¹

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ABSTRACT: Effects of physicochemical characteristics of feed ingredients on DE and ME and apparent total tract digestibility (ATTD) of GE, DM, and nutrients were determined in growing pigs using ingredients with different ratios between insoluble dietary fiber (IDF) and soluble dietary fiber (SDF). Eighty growing barrows (BW: 48.41 ± 1.50 kg) were allotted to a randomized complete block design with 10 diets and eight replicate pigs per diet. Dietary treatments included a corn-based diet, a wheat-based diet, a corn–soybean meal (SBM) diet, and seven diets based on a mixture of the corn–SBM diet and canola meal, distillers dried grains with solubles (DDGS), corn germ meal (CGM), copra expellers, sugar beet pulp (SBP), synthetic cellulose, or pectin. Values for the ATTD of DM and nutrients were also compared with the in vitro digestibility of GE, DM, and nutrients. Results indicated that the ATTD of GE was greater ($P < 0.05$) in wheat than in canola meal, DDGS, CGM, copra expellers, SBP, and synthetic cellulose, but not different from corn, SBM, or pectin. SBM had greater ($P < 0.05$) DE and ME (DM basis) compared with all other ingredients. The concentration of ME (DM basis) was greater ($P < 0.05$) in wheat than in canola meal, DDGS,

CGM, copra expellers, SBP, synthetic cellulose, and pectin, but not different from corn. Stronger correlations between total dietary fiber (TDF) and DE and ME than between ADF or NDF and DE and ME were observed, indicating that TDF can be used to more accurately predict DE and ME than values for NDF or ADF. The DE, ME, and the ATTD of DM in ingredients were positively correlated ($P < 0.05$) with in vitro ATTD of DM, indicating that the in vitro procedure may be used to estimate DE and ME in feed ingredients. Swelling and water-binding capacity were positively correlated ($P < 0.05$) with the ATTD of IDF, TDF, non-starch polysaccharides (NSP), and insoluble NSP, and viscosity was positively correlated ($P < 0.05$) with the ATTD of NDF, IDF, and insoluble NSP, indicating that some physical characteristics may influence digestibility of fiber. However, physical characteristics of feed ingredients were not correlated with the concentration of DE and ME, which indicates that these parameters do not influence in vivo energy digestibility in feed ingredients. It is concluded that the DE and ME in feed ingredients may be predicted from some chemical constituents and from in vitro digestibility of DM, but not from physical characteristics.

Key words: correlation, digestibility, energy, physicochemical characteristics, pigs, total dietary fiber

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INTRODUCTION

Feed costs represent approximately 70% of the total cost of swine production and energy is the most expensive component in diets for pigs

Table 1. Analyzed nutrient composition of corn, wheat, SBM, canola meal, DDGS, CGM, CE, SBP, SF, and pectin, as-fed basis

Item	Ingredient ¹									
	Corn	Wheat	SBM	CM	DDGS	CGM	CE	SBP	SF	Pectin
GE, kcal/kg	3,722	3,797	4,109	4,267	4,537	4,179	4,713	3,740	3,957	3,384
DM, %	85.42	86.81	88.80	88.90	88.77	89.28	96.54	92.48	98.35	91.50
CP, %	6.56	10.80	46.90	40.52	25.52	23.91	21.65	7.27	0.71	1.68
AEE ² , %	3.06	1.86	1.55	4.06	9.58	2.97	11.17	2.00	0.38	0.14
NDF, %	8.51	11.36	6.30	23.63	32.29	39.60	48.14	45.47	30.49	0.78
ADF, %	2.40	3.06	5.00	17.33	12.97	14.70	23.79	21.54	16.43	0.15
Lignin, %	0.47	0.69	0.16	7.39	2.29	4.29	5.14	2.46	ND	ND
Ash, %	1.05	1.61	6.78	7.14	5.91	2.61	5.63	6.96	0.04	1.62
OM, %	84.37	85.20	82.02	81.76	82.86	86.67	90.91	85.52	98.31	89.88
TDF ³ , %	10.76	11.40	17.84	26.42	34.66	39.78	43.84	48.54	93.31	51.69
IDF ³ , %	10.71	10.93	16.70	25.44	34.38	38.47	42.05	44.57	93.16	0.09
SDF ³ , %	0.06	0.47	1.14	0.98	0.29	1.31	1.79	3.97	0.15	51.60
Cellulose ⁴	1.93	2.37	4.84	9.94	10.68	10.41	18.65	19.08	16.43	0.15
Insoluble hemicelluloses ⁵	6.11	8.30	1.30	6.30	19.32	24.90	24.35	23.93	14.06	0.63
NSP ⁶	10.29	10.71	17.68	19.03	32.37	35.49	38.70	46.08	93.31	51.69
Insoluble NSP ⁷	10.24	10.24	16.54	18.05	32.09	34.18	36.91	42.11	93.16	0.09
Noncellulosic NSP ⁸	8.36	8.34	12.84	9.09	21.69	25.08	20.05	27.00	76.88	51.54

¹SBM = soybean meal; CM = canola meal; DDGS = distillers dried grains with solubles; CGM = corn germ meal; CE = copra expellers; SBP = sugar beet pulp; SF = synthetic cellulose.

²AEE = acid hydrolyzed ether extract.

³TDF = total dietary fiber; IDF = insoluble dietary fiber; SDF = soluble dietary fiber.

⁴Cellulose = ADF – Lignin.

⁵Insoluble hemicelluloses = NDF – ADF.

⁶NSP = nonstarch polysaccharides, TDF – Lignin.

⁷Insoluble NSP = NSP – SDF.

⁸Noncellulosic NSP = NSP – Cellulose.

(Noblet and van Milgen, 2013). Increasing concentrations of alternative feed ingredients and coproducts from the ethanol and biofuel industries are included in diets fed to pigs to reduce diet costs (Zijlstra and Beltranena, 2013). However, these coproducts contain more dietary fiber than corn and other cereal grains, which may negatively affect the digestibility of energy and nutrients and thus growth performance of pigs (Urriola et al., 2013). Dietary fiber is not digested in the small intestine, but may be hydrolyzed in the large intestine via microbial fermentation, which results in synthesis and absorption of VFA that may contribute to the energy status of the pig (Urriola et al., 2013). The chemical and physical characteristics of dietary fiber determine the extent to which it is fermented, and thus, the rate of fermentation and the amount of VFA absorbed may vary among different sources of fibrous ingredients. There is, however, a lack of information about how the physicochemical characteristics of feed ingredients influence fermentation of fiber and the apparent total tract digestibility (ATTD) of energy and nutrients in feed ingredients fed to pigs. Therefore, the

objective of this experiment was to test the hypothesis that the physicochemical characteristics of feed ingredients are correlated with concentrations of DE and ME and the ATTD of energy, DM, and nutrients in corn, wheat, soybean meal (SBM), canola meal, distillers dried grains with solubles (DDGS), corn germ meal (CGM), copra meal, sugar beet pulp (SBP), synthetic cellulose, and pectin. The second objective was to test the hypothesis that ATTD of DM and energy and the concentration of DE and ME are correlated with in vitro digestibility of DM and energy in feed ingredients.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocol for this experiment. Pigs used were the offspring of Line 359 boars mated to Camborough females (Pig Improvement Company, Hendersonville, TN). Ten feed ingredients varying in concentrations of insoluble and soluble dietary fiber were procured (Table 1).

Diets, Animals, Housing, and Experimental Design

Eighty growing barrows (initial BW: 48.41 ± 1.50 kg) were allotted to a randomized complete block design with four blocks of 20 pigs, 10 diets, and two replicate pigs per diet in each block for a total of eight replicate pigs per diet. Dietary treatments included a corn-based diet, a wheat-based diet, a corn–SBM diet, and seven diets based on a mixture of the corn–SBM diet and one of seven fiber sources (i.e., canola meal, DDGS, CGM, copra expellers, SBP, synthetic cellulose, or pectin; [Table 2](#)). The ingredients were chosen to represent a range of different ratios between insoluble dietary fiber (IDF) and soluble dietary fiber (SDF). The ratio between corn and SBM was the same in the basal corn–SBM diet and in the seven corn–SBM diets that also contained a fiber source so the contribution of corn and SBM to those diets could be calculated. Vitamins and minerals were included in all diets to meet or exceed the estimated nutrient requirements for growing pigs ([NRC, 2012](#)).

Experimental diets were fed for 26 d. Pigs were housed in individual pens in an environmentally controlled room with slatted floors, a self-feeder, and a nipple waterer for 14 d to adapt to the diets. Pigs were allowed ad libitum access to feed and water during this period. On day 15, pigs were moved to metabolism crates where they were housed individually for the remaining 12 d of the experiment. Metabolism crates were equipped with a feeder, a nipple waterer, fully slatted floors, a screen floor, and urine trays that allowed for the total, but separate, collection of urine and fecal materials from each pig. All diets were fed in a meal form. Days 15 to 19 were considered the adaptation period to metabolism crates. Urine and feces were collected from the feed provided from days 20 to 25. While in the metabolism crates, pigs were provided feed corresponding to 3.2 times the energy requirement for maintenance (i.e., 197 kcal of ME/kg BW^{0.60}; [NRC, 2012](#)), which was provided each day in two equal meals at 0800 and 1700 h. Pigs had free access to water at all times.

Data Recording and Sample Collection

The BW of each pig was recorded at the beginning of the adaptation period and on day 15 and feed consumption was recorded daily during the 5-d collection period from days 20 to 25. Nondigestible fecal markers were included in the morning meal on day 20 (chromic oxide) and on day 25 (ferric oxide) to mark the beginning and the conclusion of fecal

collections, respectively ([Adeola, 2001](#)). Feces were collected twice daily and stored at -20°C immediately after collection. Urine buckets with a preservative of 50 mL of 3N HCl were placed under the metabolism crates for urine collection and buckets were emptied every morning from days 21 to 25. The collected urine was weighed and a 20% subsample was stored at -20°C . At the conclusion of the experiment, urine samples were thawed and mixed within animal and diet, and a subsample was lyophilized before analysis. Fecal samples were thawed and mixed within pig and diet, and dried in a 60°C forced air drying oven prior to analysis.

Chemical Analyses and Physical Characteristics of Diets and Ingredients

Diets, ingredients, and fecal samples were analyzed for DM, ash, GE, CP, acid hydrolyzed ether extract (AEE), ADF, NDF, ADL, IDF, and SDF using standard procedures described by [Navarro et al. \(2018\)](#). All analyses of physical characteristics were performed in triplicates with the exception of viscosity, which was analyzed in quadruplicates. The physical characteristics of diets and ingredients were determined by measuring the bulk density, swelling, water-binding capacity, and viscosity according to [Navarro et al. \(2018\)](#). Synthetic cellulose and pectin were used to represent purified sources of insoluble and SDF, respectively. The source of pectin used in this experiment contained approximate 50% sucrose as a carrier.

Calculations and Statistical Analysis

Concentrations of total dietary fiber (TDF; IDF + SDF), cellulose (ADF – lignin), insoluble hemicelluloses (NDF – ADF), nonstarch polysaccharides (NSP; TDF – lignin), insoluble NSP (NSP – SDF), and noncellulosic NSP (NSP – cellulose) were calculated for each ingredient and diet. The DE and ME for each diet were calculated by subtracting the GE excreted in the feces and in urine, respectively, from the intake of GE ([Adeola, 2001](#)). The DE and ME in the corn and wheat diets were divided by the inclusion rate of corn or wheat to calculate the DE and ME in corn or wheat. The DE and ME in the corn diet was used to calculate the contribution of corn to the corn–SBM diet and the DE and ME in SBM was calculated by difference. The DE and ME in the corn–SBM diet was used to calculate the contribution of corn and SBM to the diets containing corn, SBM, and each of the test ingredients and the DE and ME in each test ingredient was subsequently calculated

Table 2. Ingredient and chemical composition of experimental diets (as-fed basis)

Ingredient, %	Diet ¹									
	Corn	Wheat	SBM	CM	DDGS	CGM	CE	SBP	SF	Pectin
Corn	96.70	—	72.90	42.90	42.90	42.90	50.10	50.70	61.65	61.65
Wheat	—	97.10	—	—	—	—	—	—	—	—
SBM	—	—	24.30	14.30	14.30	14.30	16.70	16.90	20.55	20.55
Canola meal	—	—	—	40.90	—	—	—	—	—	—
DDGS	—	—	—	—	40.30	—	—	—	—	—
CGM	—	—	—	—	—	40.20	—	—	—	—
Copra expellers	—	—	—	—	—	—	30.60	—	—	—
SBP	—	—	—	—	—	—	—	30.20	—	—
Solka floc	—	—	—	—	—	—	—	—	15.00	—
Pectin	—	—	—	—	—	—	—	—	—	15.00
Monocalcium phosphate	1.20	0.60	0.70	0.20	0.10	0.25	1.25	0.79	0.75	0.75
Limestone	1.00	1.20	1.00	0.60	1.30	1.25	0.25	0.31	0.95	0.95
Salt	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin–mineral premix ²	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Titanium dioxide	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Analyzed composition										
GE, kcal/kg	3,592	3,670	3,779	3,912	3,983	3,872	3,981	3,714	3,780	3,624
CP, %	7.12	10.86	17.36	25.83	20.62	18.99	18.05	13.49	14.04	13.35
DM, %	87.08	88.75	87.45	87.91	87.77	89.31	90.32	89.42	89.89	88.35
Ash, %	4.34	4.22	4.86	6.12	5.81	5.29	6.06	5.83	4.70	4.63
AEE ³ , %	2.83	1.79	1.60	4.41	5.08	2.46	4.66	1.78	2.29	1.26
NDF, %	6.88	9.17	7.29	12.83	16.55	20.20	18.31	16.41	12.77	6.69
ADF, %	3.36	3.32	5.64	11.15	7.45	7.30	8.86	9.50	8.24	3.06
Lignin, %	0.84	0.98	1.27	4.20	1.52	1.70	1.73	1.04	0.30	0.44
TDF ⁴ , %	9.31	10.80	11.87	18.99	20.54	22.32	21.23	21.20	23.98	15.37
IDF ⁴ , %	8.82	10.32	9.71	17.62	20.25	21.32	19.64	19.68	22.90	7.46
SDF ⁴ , %	0.48	0.48	2.16	1.37	0.28	0.99	1.59	1.52	1.08	7.92
Cellulose ⁵ , %	2.52	2.34	4.37	6.94	5.93	5.61	7.13	8.46	7.93	2.61
Insoluble hemicelluloses ⁶ , %	3.52	5.85	1.65	1.68	9.10	12.89	9.44	6.91	4.54	3.63
NSP ⁷ , %	8.46	9.82	10.60	14.79	19.02	20.62	19.50	20.15	23.67	14.93
Insoluble NSP ⁸ , %	7.98	9.34	8.44	13.42	18.74	19.62	17.91	18.64	22.60	7.01
Noncellulosic NSP ⁹ , %	5.95	7.48	6.23	7.85	13.09	15.01	12.37	11.70	15.74	12.31

¹SBM = soybean meal; CM = canola meal; DDGS = distillers dried grains with solubles; CGM = corn germ meal; CE = copra expellers; SBP = sugar beet pulp; SF = synthetic cellulose.

²The 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 dimethylprimidol 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 and copper chloride; Fe, 126 mg as ferrous sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese sulfate; Se, 0.3 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc sulfate.

³AEE = acid hydrolyzed ether extract.

⁴TDF = total dietary fiber; IDF = insoluble dietary fiber; SDF = soluble dietary fiber.

⁵Cellulose = ADF – Lignin.

⁶Insoluble hemicelluloses = NDF – ADF.

⁷NSP = nonstarch polysaccharides, TDF – Lignin.

⁸Insoluble NSP = NSP – SDF.

⁹Noncellulosic NSP = NSP – Cellulose.

by difference (Widmer et al., 2007). The ATTD of DM, energy, and nutrients was calculated using the direct procedure for diets, corn, and wheat, whereas

the difference procedure was used for the other ingredients (Adeola, 2001). The ATTD of CP, AEE, and SDF in synthetic cellulose and the ATTD of CP,

AEE, NDF, ADF, IDF, cellulose, insoluble hemicellulose, and insoluble NSP in pectin were not analyzed because these nutrients are not present in synthetic cellulose and pectin, respectively. The *in vitro* apparent ileal digestibility (IVAID) and the apparent total tract digestibility (IVATTD) of DM were measured in three separate subsamples of each ingredient providing three replicates per ingredient following a procedure described by Navarro et al. (2018).

Data were analyzed as a randomized complete block design with the pig as the experimental unit. An analysis of variance was conducted using the MIXED procedure in SAS (SAS Institute Inc., Cary, NC). Homogeneity of the variances was confirmed using the UNIVARIATE procedure in PROC MIXED. Diet was the fixed effect and block and pig within block were the random effects. Least squares means were calculated using a Least Significant Difference test and means were separated using the PDIFF statement in PROC MIXED. Correlation coefficients among the physical characteristics of experimental diets or feed ingredients and concentration of DE and ME and ATTD of energy and nutrients were determined using the CORR procedure of SAS. Likewise, the results of this experiment were correlated with least square means of IVAID and IVATTD of DM in

ingredients from an experiment using the same ingredients (Navarro et al., 2018) using PROC CORR. Results were considered significant at $P < 0.05$ and considered a trend at $0.05 \leq P < 0.10$.

RESULTS

Bulk density ranged from 254 g/L in the synthetic cellulose diet to 787 g/L in the SBM diet and was greater ($P < 0.05$) in the wheat diet than in the DDGS, copra expellers, SBP, and synthetic cellulose diets, but not different from the canola meal and pectin diets (Table 3). Water-binding capacity ranged from 0.8 g/g in the wheat diet to 2.3 g/g in the pectin diet and was greater ($P < 0.05$) in the CGM diet than in the corn, wheat, SBM, canola meal, DDGS, and synthetic cellulose diets, but not different from the copra expellers diet. Swelling capacity ranged from 2.7 L/kg DM in the corn diet to 6.0 L/kg DM in the pectin diet and was greater ($P < 0.05$) in the copra expellers diet than in the corn, wheat, SBM, CGM, and synthetic cellulose diets, but not different from the canola meal and DDGS diets. Viscosity ranged from 1.0 cP in the CGM diet to 2.7 cP in the pectin diet and viscosity of the SBP diet was less ($P < 0.05$) than in the pectin diet, but not different from all other diets.

Table 3. Bulk density, swelling, water-binding capacity, and viscosity of experimental diets and test ingredients¹

	Diet or ingredient ²											
Item	Corn	Wheat	SBM	CM	DDGS	CGM	CE	SBP	SF	Pectin	SEM	<i>P</i> value
Ingredient												
Bulk density, g/L	729 ^c	676 ^{ef}	783 ^a	715 ^d	656 ^g	705 ^d	658 ^g	666 ^{fg}	681 ^e	768 ^b	3.79	<0.01
Swelling, L/kg DM	2.5 ⁱ	3.0 ^h	5.0 ^e	4.5 ^f	3.8 ^g	5.8 ^d	7.5 ^c	8.1 ^b	4.1 ^g	9.0 ^a	0.18	<0.01
Water-binding capacity, g/g	1.2 ⁱ	1.0 ^j	2.7 ^f	1.8 ^g	1.7 ^h	3.1 ^d	3.6 ^b	4.1 ^a	2.9 ^e	3.4 ^c	0.03	<0.01
Viscosity, centipoise	1.1 ^{cde}	1.3 ^{bc}	1.1 ^{cde}	1.0 ^{de}	1.1 ^{cde}	1.2 ^{cde}	1.3 ^{bcd}	1.5 ^b	0.9 ^e	7.0 ^a	0.11	<0.01
Diet												
Bulk density, g/L	668 ^b	625 ^d	787 ^a	624 ^d	533 ^g	654 ^c	572 ^f	612 ^e	254 ^h	619 ^{de}	4.04	<0.01
Swelling, L/kg DM	2.7 ^g	3.0 ^f	3.5 ^e	4.1 ^{cd}	4.1 ^{cd}	3.9 ^d	4.2 ^c	4.5 ^b	3.1 ^f	6.0 ^a	0.10	<0.01
Water-binding capacity, g/g	1.2 ^g	0.8 ^h	1.5 ^f	1.7 ^e	1.6 ^e	2.1 ^c	2.1 ^c	2.2 ^b	1.7 ^d	2.3 ^a	0.02	<0.01
Viscosity, centipoise	1.0 ^b	1.0 ^b	1.0 ^b	1.0 ^b	1.0 ^b	1.0 ^b	1.0 ^b	1.4 ^b	1.0 ^b	2.7 ^a	0.22	<0.01

^{a-h}Means within a row lacking a common superscript letter differ ($P < 0.05$).

¹Data are means of three observations per diet or ingredient except for viscosity where four observations were used.

²SBM = soybean meal; CM = canola meal; DDGS = distillers dried grains with solubles; CGM = corn germ meal; CE = copra expellers; SBP = sugar beet pulp; SF = synthetic cellulose.

Bulk density was greatest ($P < 0.01$) in SBM among ingredients. SBP had the greatest ($P < 0.01$) WBC capacity among ingredients. Pectin had the greatest ($P < 0.01$) swelling capacity and viscosity among ingredients.

Energy Digestibility and Concentration of DE and ME in Diets and Ingredients

Pigs fed the wheat diet had greater ($P < 0.05$) ATTD of GE compared with pigs fed the other diets (Table 4). The ATTD of GE was greater ($P < 0.05$) in pigs fed the corn diet compared with pigs fed the canola meal, DDGS, CGM, copra expellers, SBP, and synthetic cellulose diets, but not different from pigs fed the SBM or pectin diets. Among all diets, the concentration of DE was greatest ($P < 0.05$) in the copra expellers diet. The concentration of ME was greater ($P < 0.05$) in the copra expellers diet than in the corn, canola meal, DDGS, CGM, SBP, synthetic cellulose, and pectin diets, but not different from the wheat or SBM diets.

The ATTD of GE was greater ($P < 0.05$) in wheat than in canola meal, DDGS, CGM, copra expellers, SBP, and synthetic cellulose, but not different from corn, SBM, or pectin. The concentration of DE (DM basis) was greater ($P < 0.05$) in wheat than in canola meal, DDGS, CGM, SBP, synthetic cellulose, and pectin, but not different from corn or copra expellers. The concentration of ME (DM basis) was greater ($P < 0.05$) in wheat than in canola meal, DDGS, CGM, copra expellers, SBP, synthetic cellulose, and pectin, but not different from corn.

ATTD of DM, OM, and Nutrients in Diets

The ATTD of DM and OM was greater ($P < 0.05$) in pigs fed the wheat diet than in pigs fed the corn, canola meal, DDGS, CGM, copra expellers, SBP, and synthetic cellulose diets, but not different from pigs fed the SBM or pectin diets (Table 5). The ATTD of CP was greater ($P < 0.05$) in pigs fed the SBM diet than in pigs fed the corn, canola meal, DDGS, CGM, copra expellers, SBP,

Table 4. Concentration of digestible and metabolizable energy and apparent total tract digestibility (ATTD) of GE in corn, wheat, SBM, canola meal, DDGS, CGM, CE, SBP, SF, and pectin, as-fed basis¹

	Diet ²										Pooled SEM	P value
Item	Corn	Wheat	SBM	CM	DDGS	CGM	CE	SBP	SF	Pectin		
Diets												
GE intake, kcal/d	6,170 ^f	6,278 ^f	8,081 ^{cd}	8,591 ^b	8,358 ^{bc}	8,473 ^{bc}	8,327 ^{bc}	7,803 ^d	9,341 ^a	7,081 ^e	189	<0.01
GE in feces, kcal/d	814 ^f	568 ^g	1,025 ^e	1,872 ^a	1,712 ^b	1,533 ^c	1,296 ^d	1,251 ^d	1,999 ^a	934 ^{ef}	66	<0.01
GE in urine, kcal/d	100 ^e	99 ^e	146 ^{cd}	288 ^a	192 ^b	185 ^{bc}	170 ^{bcd}	132 ^{de}	148 ^{bcd}	155 ^{bcd}	17	<0.01
ATTD of GE, %	86.7 ^b	90.0 ^a	87.5 ^b	78.3 ^e	79.4 ^e	81.8 ^d	84.8 ^c	84.0 ^c	78.5 ^e	86.7 ^b	0.7	<0.01
DE, kcal/kg	3,117 ^{cd}	3,304 ^b	3,307 ^b	3,062 ^d	3,162 ^c	3,167 ^c	3,375 ^a	3,121 ^{cd}	2,967 ^e	3,144 ^c	28	<0.01
ME, kcal/kg	3,057 ^b	3,239 ^a	3,239 ^a	2,930 ^c	3,070 ^b	3,082 ^b	3,294 ^a	3,058 ^b	2,907 ^c	3,064 ^b	28	<0.01
Ingredients												
ATTD of GE, %	87.0 ^a	89.9 ^a	89.0 ^a	66.6 ^e	69.8 ^{de}	74.7 ^{cd}	79.0 ^{bc}	75.8 ^{bcd}	30.0 ^f	82.4 ^{ab}	3.0	<0.01
DE, kcal/kg	3,239 ^{cd}	3,395 ^{bc}	3,925 ^a	2,742 ^f	3,033 ^c	3,037 ^{de}	3,571 ^b	2,705 ^f	992 ^h	2,328 ^g	86	<0.01
DE, kcal/kg DM	3,786 ^b	3,910 ^b	4,409 ^a	3,091 ^d	3,419 ^c	3,395 ^c	3,687 ^b	2,928 ^d	1,469 ^f	2,563 ^e	101	<0.01
ME, kcal/kg	3,174 ^c	3,328 ^{bc}	3,828 ^a	2,517 ^e	2,902 ^d	2,923 ^d	3,464 ^b	2,657 ^e	963 ^g	2,179 ^f	86	<0.01
ME, kcal/kg DM	3,714 ^{bc}	3,835 ^b	4,312 ^a	2,830 ^e	3,267 ^d	3,273 ^d	3,589 ^c	2,874 ^e	978 ^g	2,381 ^f	93	<0.01

^{a-h}Means within a row lacking a common superscript letter differ ($P < 0.05$).

¹Data are means of 8 observations per treatment.

²SBM = soybean meal; CM = canola meal; DDGS = distillers dried grains with solubles; CGM = corn germ meal; CE = copra expellers; SBP = sugar beet pulp; SF = synthetic cellulose.

Table 5. Apparent total tract digestibility (ATTD) of DM, OM, CP, AEE, NDF, ADF, TDF, IDF, and SDF in experimental diets

Item, %	Diet ¹										Pooled SEM	P value
	Corn	Wheat	SBM	CM	DDGS	CGM	CE	SBP	SF	Pectin		
DM	88.6 ^b	90.4 ^a	89.0 ^{ab}	79.2 ^f	81.1 ^e	84.3 ^d	86.4 ^c	85.9 ^c	80.1 ^{ef}	89.0 ^{ab}	0.65	<0.01
OM	90.6 ^b	92.1 ^a	90.7 ^{ab}	81.9 ^e	82.5 ^e	86.0 ^d	87.9 ^c	88.0 ^c	81.3 ^e	90.7 ^{ab}	0.63	<0.01
CP	77.9 ^d	87.4 ^a	88.3 ^a	81.1 ^c	84.1 ^b	76.9 ^d	81.9 ^{bc}	75.4 ^d	81.3 ^c	81.9 ^{bc}	1.11	<0.01
AEE ²	32.3 ^d	59.3 ^a	23.7 ^e	39.9 ^{cd}	49.8 ^b	35.9 ^{cd}	64.0 ^a	32.3 ^{cd}	40.3 ^c	-40.8 ^f	3.01	<0.01
NDF	50.8 ^{bc}	71.8 ^a	57.8 ^b	44.6 ^c	69.1 ^a	75.7 ^a	76.4 ^a	74.9 ^a	52.3 ^{bc}	48.0 ^c	3.69	<0.01
ADF	59.8 ^{bc}	59.8 ^{bc}	76.4 ^a	73.1 ^{ab}	75.5 ^a	71.6 ^{ab}	78.0 ^a	81.3 ^a	70.6 ^{ab}	49.4 ^c	5.35	<0.01
TDF ³	55.8 ^{ef}	61.5 ^d	70.2 ^c	59.6 ^{de}	59.3 ^{de}	75.5 ^b	77.7 ^{ab}	80.3 ^a	53.1 ^f	77.6 ^{ab}	1.69	<0.01
IDF ³	53.5 ^{fg}	59.8 ^{cd}	64.2 ^c	57.0 ^{def}	58.9 ^{de}	74.6 ^b	76.1 ^{ab}	79.9 ^a	50.8 ^g	54.8 ^{efg}	1.84	<0.01
SDF ³	97.9	96.8	97.4	92.7	87.9	96.1	97.3	86.2	101.9	99.0	5.05	0.29
Cellulose	65.0 ^{de}	62.6 ^e	81.0 ^{ab}	71.5 ^{cd}	78.6 ^{abc}	75.7 ^{bc}	82.4 ^{ab}	86.1 ^a	77.5 ^{bc}	61.7 ^e	2.84	<0.01
Ins. Hemi ⁴	41.6 ^{bc}	73.4 ^{ab}	-6.0 ^d	-136.7 ^e	68.4 ^{ab}	77.5 ^a	75.3 ^{ab}	68.7 ^{ab}	20.1 ^{cd}	48.3 ^{abc}	13.69	<0.01
NSP ⁵	56.9 ^{cd}	62.1 ^c	71.1 ^b	55.8 ^d	60.5 ^{cd}	77.3 ^{ab}	78.9 ^a	83.1 ^a	55.4 ^d	81.1 ^a	2.41	<0.01
Ins. NSP ⁶	54.3 ^{cd}	60.3 ^{bc}	64.5 ^b	52.0 ^d	60.1 ^{bc}	76.4 ^a	77.4 ^a	82.8 ^a	53.1 ^d	60.5 ^{bc}	2.68	<0.01
NC NSP ⁷	53.5 ^{bc}	61.9 ^b	64.3 ^b	42.0 ^d	53.3 ^{bc}	77.7 ^a	77.0 ^a	81.0 ^a	44.3 ^{cd}	85.2 ^a	4.30	<0.01

^{a-g}Means within a row lacking a common superscript letter differ ($P < 0.05$).

¹SBM = soybean meal; CM = canola meal; DDGS = distillers dried grains with solubles; CGM = corn germ meal; CE = copra expellers; SBP = sugar beet pulp; SF = synthetic cellulose.

²AEE = acid hydrolyzed ether extract.

³TDF = total dietary fiber; IDF = insoluble dietary fiber; SDF = soluble dietary fiber.

⁴Ins. Hemi = insoluble hemicelluloses.

⁵NSP = nonstarch polysaccharides.

⁶Ins. NSP = insoluble nonstarch polysaccharides.

⁷NC NSP = noncellulosic nonstarch polysaccharides.

synthetic cellulose, and pectin diets, but not different from pigs fed the wheat diet. The ATTD of AEE was greater ($P < 0.05$) in pigs fed the copra expellers diet than in pigs fed the corn, SBM, canola meal, DDGS, CGM, SBP, synthetic cellulose, and pectin diets, but not different from pigs fed the wheat diet. The ATTD of NDF was less ($P < 0.05$) in pigs fed the canola meal diet than in pigs fed the wheat, SBM, DDGS, CGM, copra expellers, and SBP diets. The ATTD of ADF was less ($P < 0.05$) in pigs fed the pectin diet than in pigs fed the SBM, canola meal, DDGS, CGM, copra expellers, SBP, and synthetic cellulose diets. The ATTD of IDF was greater ($P < 0.05$) in pigs fed the SBP diet than in pigs fed the corn, wheat, SBM, canola meal, DDGS, CGM, synthetic cellulose, and pectin diets. The ATTD of TDF was greater ($P < 0.05$) in pigs fed the SBP diet than in pigs fed the corn, wheat, SBM, canola meal, DDGS, CGM, and synthetic cellulose diets. The ATTD of cellulose was greater ($P < 0.05$) in pigs fed the SBP diet than in pigs fed the corn, wheat, canola meal, CGM, synthetic cellulose, and pectin diets, but not different from pigs fed the SBM, DDGS, or copra expellers diets. The ATTD of NSP was greater ($P < 0.05$) in pigs fed the pectin diet than in pigs fed the corn, wheat, SBM, canola meal, DDGS, and synthetic cellulose diets.

The ATTD of insoluble NSP was greater ($P < 0.05$) in pigs fed the SBP diet than in pigs fed the corn, wheat, SBM, canola meal, DDGS, synthetic cellulose, and pectin diets. The ATTD of noncellulosic NSP was less ($P < 0.05$) in pigs fed the canola meal diet than in pigs fed the corn, wheat, SBM, DDGS, CGM, copra expellers, SBP, and pectin diets.

ATTD of DM, OM, and Nutrients in Ingredients

The ATTD of DM, OM, and TDF was less ($P < 0.05$) in synthetic cellulose than in all other ingredients (Table 6). The ATTD of CP was greater ($P < 0.05$) in SBM than in corn, canola meal, CGM, copra expellers, and SBP. The ATTD of AEE was greater ($P < 0.05$) in copra expellers than in all other ingredients. The ATTD of NDF was less ($P < 0.05$) in canola meal than in wheat, SBM, DDGS, CGM, copra expellers, and SBP and the ATTD of IDF was greater ($P < 0.05$) in SBP than in corn, wheat, canola meal, DDGS, CGM, and synthetic cellulose. SBM had the greatest ($P < 0.05$) ATTD of ADF and cellulose and the least ($P < 0.05$) ATTD of insoluble hemicelluloses among all other ingredients. The ATTD of NSP was greater ($P < 0.05$) in SBM than in corn, wheat, canola meal, DDGS, CGM, and synthetic cellulose and the ATTD of insoluble

Table 6. Apparent total tract digestibility (ATTD) of DM, OM, CP, AEE, NDF, ADF, TDF, IDF, and SDF in ingredients

Item, %	Ingredient ¹										Pooled SEM	P value
	Corn	Wheat	SBM	CM	DDGS	CGM	CE	SBP	SF	Pectin		
DM	88.8 ^a	90.3 ^a	89.9 ^a	65.5 ^c	70.0 ^c	78.0 ^b	80.7 ^b	79.0 ^b	35.7 ^d	89.6 ^a	2.69	<0.01
OM	90.7 ^a	92.0 ^a	90.8 ^a	69.2 ^c	70.7 ^c	79.7 ^b	81.8 ^b	81.9 ^b	37.1 ^d	91.2 ^a	2.69	<0.01
CP	78.6 ^{bcd}	89.4 ^{ab}	91.6 ^a	76.4 ^{cd}	81.1 ^{abc}	63.9 ^e	67.4 ^{de}	6.0 ^f	—	—	4.57	<0.01
AEE ²	32.3 ^c	59.3 ^b	−30.0 ^d	54.0 ^b	59.6 ^b	50.7 ^b	84.0 ^a	56.4 ^b	—	—	7.15	<0.01
NDF	50.8 ^{bc}	71.9 ^{ab}	81.2 ^a	38.7 ^c	72.8 ^a	80.5 ^a	82.7 ^a	81.2 ^a	45.0 ^c	—	8.04	<0.01
ADF	60.3 ^{cd}	60.2 ^{cd}	109.7 ^a	70.0 ^{bcd}	75.2 ^{bcd}	70.4 ^{bcd}	78.4 ^{bc}	85.9 ^b	57.8 ^d	—	7.72	<0.01
TDF ³	55.8 ^{de}	61.5 ^d	93.6 ^a	52.7 ^e	53.8 ^e	77.9 ^c	82.2 ^{bc}	86.0 ^b	40.8 ^f	87.1 ^{ab}	2.84	<0.01
IDF ³	53.5 ^c	59.8 ^c	81.8 ^{ab}	53.0 ^c	56.7 ^c	78.4 ^b	82.3 ^{ab}	87.7 ^a	42.9 ^d	—	2.99	<0.01
SDF ³	97.5	95.6	98.1	78.2	−16.6	94.4	99.9	70.4	—	97.8	53.05	0.77
Cellulose	65.2 ^e	62.7 ^e	107.0 ^a	64.9 ^e	77.0 ^{cd}	72.2 ^{de}	83.0 ^{bc}	89.3 ^b	71.9 ^{de}	—	4.16	<0.01
Ins. Hemi ⁴	41.8 ^a	74.4 ^a	−409.8 ^c	−183.9 ^b	76.0 ^a	88.9 ^a	82.8 ^a	77.5 ^a	39.4 ^a	—	47.08	<0.01
NSP ⁵	57.0 ^c	62.0 ^c	92.8 ^a	43.3 ^d	55.3 ^c	79.8 ^b	83.5 ^{ab}	89.1 ^{ab}	45.1 ^d	92.2 ^a	3.84	<0.01
Ins. NSP ⁶	54.4 ^{cd}	60.2 ^c	80.4 ^b	43.5 ^e	58.3 ^c	80.0 ^b	83.9 ^{ab}	91.2 ^a	47.2 ^{de}	—	4.07	<0.01
NC NSP ⁷	53.6 ^{cd}	61.7 ^{bc}	80.9 ^{ab}	19.9 ^e	48.6 ^{cd}	81.9 ^a	86.1 ^a	89.5 ^a	35.1 ^{de}	99.3 ^a	7.28	<0.01

^{a–f}Means within a row lacking a common superscript letter differ ($P < 0.05$).

¹SBM = soybean meal; CM = canola meal; DDGS = distillers dried grains with solubles; CGM = corn germ meal; CE = copra expellers; SBP = sugar beet pulp; SF = synthetic cellulose.

²AEE = acid hydrolyzed ether extract.

³TDF = total dietary fiber; IDF = insoluble dietary fiber; SDF = soluble dietary fiber.

⁴Ins. Hemi = insoluble hemicelluloses.

⁵NSP = nonstarch polysaccharides.

⁶Ins. NSP = insoluble nonstarch polysaccharides.

⁷NC NSP = noncellulosic nonstarch polysaccharides.

NSP and noncellulosic NSP was less ($P < 0.05$) in canola meal than in corn, wheat, SBM, DDGS, CGM, copra expellers, SBP, and pectin.

Correlation Coefficients

There was a positive correlation ($P < 0.01$) between DE and ME, and both DE and ME were positively correlated ($P < 0.05$) with ATTD of DM and GE (Table 7). There was also a positive correlation ($P < 0.05$) between ATTD of DM and GE. The concentrations of TDF, NSP, and noncellulosic NSP were negatively correlated ($P < 0.05$) with the concentration of DE and ME and ATTD of DM and GE. The concentrations of TDF and NSP were negatively correlated ($P < 0.05$) with ATTD of CP. The concentration of IDF was also negatively correlated ($P < 0.05$) with the concentration of DE and ATTD of DM, and had a tendency to be negatively correlated ($P < 0.10$) with the concentration of ME and ATTD of CP. The concentration of insoluble NSP was also negatively correlated ($P < 0.05$) with the concentration of DE ($r = -0.67$) and ME ($r = -0.64$), ATTD of DM ($r = -0.88$), and ATTD of CP ($r = -0.72$). However, no correlation was observed between concentration of NDF, ADF, SDF, cellulose, or

insoluble hemicelluloses with the concentration of DE and ME or ATTD of GE.

Swelling capacity and WBC of ingredients were positively correlated ($P < 0.05$) with ATTD of IDF, TDF, NSP, and insoluble NSP (Table 8). Swelling capacity and WBC of ingredients were positively correlated ($P < 0.05$) with ATTD of noncellulosic NSP ($r = 0.73$ and 0.64 , respectively). Swelling capacity and WBC of ingredients were also negatively correlated ($P < 0.05$) with ATTD of CP ($r = -0.74$ and -0.72 , respectively). Viscosity of ingredients was positively correlated ($P < 0.05$) with ATTD of NDF, IDF, and insoluble NSP. Bulk density of ingredients was negatively correlated ($P < 0.01$) with ATTD of AEE ($r = -0.91$) and ATTD of insoluble hemicelluloses ($r = -0.84$). There was a tendency for WBC of ingredients to be correlated ($P < 0.10$) with ATTD of cellulose ($r = 0.60$) and for viscosity of ingredients to be correlated ($P < 0.10$) with ATTD of CP ($r = -0.68$). However, no correlation was observed between bulk density, swelling, WBC, or viscosity of ingredients with ATTD of DM, OM, GE, ADF, and SDF or the concentration of DE and ME.

Bulk density of the diet was positively correlated ($P < 0.01$) with the ATTD of DM and GE and the concentration of DE and ME, but was

Table 7. Correlation coefficients between the concentration of fiber in ingredients, concentration of DE and ME, and apparent total tract digestibility (ATTD) of DM and nutrients in ingredients

Item	Correlation coefficient ¹									ATTD of CP
	ADF	IDF	TDF	NSP	NC-NSP	DE	ME	ATTD of DM	ATTD of GE	
NDF	0.94***	0.65**	0.42	0.34	0.09	-0.11	-0.10	-0.40	-0.22	-0.68*
ADF	1.00	0.69**	0.47	0.37	0.11	-0.17	-0.18	-0.51	-0.31	-0.64*
IDF	—	1.00	0.81***	0.78***	0.63*	-0.65**	-0.63*	-0.90***	-0.48	-0.67*
TDF	—	—	1.00	0.99***	0.93***	-0.86***	-0.85***	-0.79***	-0.80***	-0.72**
NSP	—	—	—	1.00	0.96***	-0.86***	-0.85***	-0.74**	-0.75**	-0.75**
NC-NSP	—	—	—	—	1.00	-0.88***	-0.87***	-0.65**	-0.75**	-0.69*
DE	—	—	—	—	—	1.00	1.00***	0.80***	0.81***	0.59
ME	—	—	—	—	—	—	1.00	0.80***	0.84***	0.52
ATTD of DM	—	—	—	—	—	—	—	1.00	0.69**	0.20
ATTD of GE	—	—	—	—	—	—	—	—	1.00	0.32

* $P < 0.10$; ** $P < 0.05$; *** $P < 0.01$.

¹IDF = insoluble dietary fiber; SDF = soluble dietary fiber; TDF = total dietary fiber.

Table 8. Correlation coefficients between the physical characteristics of ingredients, concentration of DE and ME, and apparent total tract digestibility (ATTD) of nutrients in ingredients

Item	Correlation coefficient ¹									ATTD of iNSP
	Swelling	WBC	Viscosity	DE	ME	ATTD of NDF	ATTD of IDF	ATTD of TDF	ATTD of NSP	
Bulk	0.11	-0.01	0.48	0.15	0.14	-0.13	0.07	0.40	0.35	-0.03
Swelling	1.00	0.89***	0.62*	-0.08	-0.09	0.57	0.80***	0.73**	0.75**	0.79**
WBC	—	1.00	0.30	-0.21	-0.20	0.48	0.69**	0.63**	0.68**	0.73**
Viscosity	—	—	1.00	-0.21	-0.23	0.68**	0.70**	0.39	0.45	0.72**
DE	—	—	—	1.00	1.00***	0.59*	0.57	0.51	0.41	0.47
ME	—	—	—	—	1.00	0.61*	0.58*	0.51	0.42	0.50
ATTD of NDF	—	—	—	—	—	1.00	0.86***	0.83***	0.88***	0.90***
ATTD of IDF	—	—	—	—	—	—	1.00	0.97***	0.97***	0.97***
ATTD of TDF	—	—	—	—	—	—	—	1.00	0.98***	0.93***
ATTD of NSP	—	—	—	—	—	—	—	—	1.00	0.97***

* $P < 0.10$; ** $P < 0.05$; *** $P < 0.01$.

¹Bulk = bulk density; WBC = water-binding capacity; AEE = acid hydrolyzed ether extract; IDF = insoluble dietary fiber; TDF = total dietary fiber.

negatively correlated ($P < 0.01$) with ATTD of AEE (Table 9). Viscosity of the diet was negatively correlated ($P < 0.01$) with ATTD of CP. There was a tendency for WBC of diets to be negatively correlated ($P < 0.10$) with ATTD of CP and GE. Swelling capacity, WBC, and viscosity of diets were not correlated with the concentration of DE and ME.

The concentration of DE and ATTD of CP in ingredients was positively correlated ($P < 0.05$) with IVAID of DM, whereas DE, ME, and ATTD of DM in ingredients were positively correlated ($P < 0.05$) with IVATTD of DM (Table 10). There was also a tendency for ME and ATTD of DM to be positively correlated ($P < 0.10$) with IVAID of DM, and a tendency for ATTD of CP, TDF, and SDF to be positively correlated ($P < 0.10$) with IVATTD of DM. However, no correlation was

observed between ATTD of GE, AEE, NDF, ADF, IDF, cellulose, insoluble hemicelluloses, NSP, insoluble NSP, or noncellulosic NSP with IVAID or IVATTD of DM.

DISCUSSION

Concentrations of DE and ME were generally within the range of published values for corn (Anderson et al., 2012; Rojas et al., 2013; Sulabo et al., 2013; Berrocoso et al., 2015), wheat (NRC, 2012; Bolarinwa and Adeola, 2016), and canola meal (NRC, 2012; Berrocoso et al., 2015; Maison et al., 2015; Liu et al., 2016). For SBM, values for DE and ME were also within the range of previous estimates (Rojas and Stein, 2013; Berrocoso et al., 2015; Liu et al., 2016) and results from this

Table 9. Correlation coefficients between the physical characteristics of diets, concentration of DE and ME, and apparent total tract digestibility (ATTD) of nutrients in ingredients

Item	Correlation coefficient ¹								
	Swelling	WBC	Viscosity	DE	ME	ATTD of DM	ATTD of CP	ATTD of GE	ATTD of AEE
Bulk	0.10	-0.10	0.07	0.85***	0.83***	0.88***	0.26	0.66**	-0.91***
Swelling	1.00	0.79***	0.83***	-0.13	-0.16	0.18	-0.61	-0.54	0.38
WBC	—	1.00	0.53	-0.27	-0.29	-0.11	-0.68*	-0.59*	0.26
Viscosity	—	—	1.00	-0.26	-0.28	0.27	-0.91***	-0.42	0.10
DE	—	—	—	1.00	1.00***	0.80***	0.59	0.81***	-0.52
ME	—	—	—	—	1.00	0.80***	0.52	0.84***	-0.51
ATTD of DM	—	—	—	—	—	1.00	0.20	0.69**	-0.45
ATTD of CP	—	—	—	—	—	—	1.00	0.32	-0.32
ATTD of GE	—	—	—	—	—	—	—	1.00	-0.46

* $P < 0.10$; ** $P < 0.05$; *** $P < 0.01$.¹Bulk = bulk density; WBC = water-binding capacity; AEE = acid hydrolyzed ether extract.**Table 10.** Correlation coefficients between in vitro apparent ileal digestibility (IVAID) and in vitro apparent total tract digestibility (IVATTD) of DM, concentration of DE and ME, and in vivo apparent total tract digestibility (ATTD) of DM and nutrients in ingredients

Item	Correlation coefficient ¹								
	IVAID of DM	IVATTD of DE	IVATTD of ME	ATTD of DM	ATTD of GE	ATTD of CP	ATTD of NDF	ATTD of TDF	ATTD of SDF
IVAID of DM	0.81***	0.64**	0.61*	0.63*	0.34	0.92***	0.33	0.49	0.24
IVATTD of DM	1.00	0.74**	0.72**	0.79***	0.54	0.60*	0.37	0.63*	0.65*
DE	—	1.00	1.00***	0.67**	0.81***	0.43	0.59*	0.36	0.19
ME	—	—	1.00	0.69**	0.84***	0.39	0.61	0.36	0.20
ATTD of DM	—	—	—	1.00	0.76**	0.51	0.57	0.56*	0.60*
ATTD of GE	—	—	—	—	1.00	0.18	0.45	0.13	0.39
ATTD of CP	—	—	—	—	—	1.00	-0.28	0.24	0.03
ATTD of NDF	—	—	—	—	—	—	1.00	0.83***	-0.00
ATTD of TDF	—	—	—	—	—	—	—	1.00	0.44

* $P < 0.10$; ** $P < 0.05$; *** $P < 0.01$.¹IVAID = in vitro apparent ileal digestibility; IVATTD = in vitro apparent total tract digestibility; AEE = acid hydrolyzed ether extract; TDF = total dietary fiber.

experiment confirm that SBM has a greater concentration of ME than corn (Sotak-Peper et al., 2015). Concentrations of DE and ME in DDGS and CGM were also within the range of published values (Pedersen et al., 2007; Anderson et al., 2012; Rojas et al., 2013; Gutierrez et al., 2014). Concentrations of DE and ME in copra expellers were greater than values reported by Kwon and Kim (2015) because of a higher concentration of AEE in the copra expellers used in this experiment and concentrations of DE and ME in SBP were less than published values (NRC, 2012). To our knowledge, concentrations of DE and ME in synthetic cellulose and pectin have never been reported. It is likely that the reason DE and ME of pectin was approximately two times greater than the DE and ME in synthetic cellulose is that pectin is highly fermentable in the large intestine, which results in

production of short chained fatty acids that are absorbed and utilized by the pig (Urriola et al., 2013). The source of pectin used in this experiment consisted of 50% citrus pectin and 50% sucrose, and because sucrose is highly digestible, this also contributed to the high energy value of the pectin source that was used.

Negative correlations between fiber fractions and concentrations of DE and ME indicate that digestibility of energy will decrease if pigs are fed high-fiber diets (Jaworski et al., 2015). Almost all the TDF in pectin is soluble fiber that is highly fermentable in the gastrointestinal tract of the pig, which likely contributed to the high energy in pectin (Urriola et al., 2010; Jaworski and Stein, 2017). The negative correlation between the concentration of TDF and NSP and ATTD of CP indicates that the presence of fiber in the diet reduces the digestibility

of CP by pigs (Yin et al., 2000; Wilfart et al., 2007; Le Gall et al., 2009). This may be explained by the shift in N excretion from the urine to the feces due to greater use of N for bacterial metabolism and growth and a decrease in the amount of N absorbed in the blood and excreted in the urine (Mroz et al., 2000; Zervas and Zijlstra, 2002). The ATTD of AEE was very low in some ingredients because of low-fat concentrations in the diet, which resulted in a greater impact of endogenous losses of fat on the calculated value for ATTD of AEE (Kil et al., 2010). The ATTD of SDF was generally greater compared with IDF, which is in agreement with Urriola et al. (2010). This indicates that the soluble fraction of fiber is better utilized by the pig than the insoluble fraction, presumably because of greater fermentability. However, values for ATTD of fiber may be influenced by endogenous secretions or microbial matter that may be analyzed as carbohydrates (Cervantes-Pahm et al., 2014; Montoya et al., 2015). Therefore, a more accurate estimate for fiber digestibility may be obtained if endogenous components in the feces that are analyzed as TDF are quantified, which allows for calculation of the standardized total tract digestibility of TDF rather than the ATTD of TDF (Montoya et al., 2016).

Swelling and WBC are indicators of the fiber fraction that may be solubilized and fermented by the pig because both were correlated with ATTD of TDF, IDF, NSP, insoluble NSP, and noncellulosic NSP. Swelling occurs as the fiber structure solubilizes and is dispersed by incoming water, and therefore, is dependent on the WBC of the fiber fraction (Bach Knudsen et al., 2013). This expansion and dispersion of the fiber matrix may allow more rapid access for microbial enzymes with a subsequent increase in fermentation.

The stronger correlation between TDF and DE and ME than the correlations between ADF and NDF and DE and ME indicates that TDF is a better measure for estimating the concentration of DE and ME in a feed ingredient. This is supported by the observation that greater SE and reduced R^2 result from using NDF or ADF instead of TDF in prediction equations for DE and ME (Anderson et al., 2012; Kerr et al., 2013). The likely reason is that detergent fiber analysis does not take into account the entire soluble fraction of hemicellulose that includes pectins, mucilages, gums, and β -glucans, and therefore, underestimates the concentration of soluble fiber (Urriola et al., 2013). Acid detergent fiber also contains a portion of the insoluble fraction of hemicellulose, creating an

overlap with the analyzed content of NDF. The relatively strong correlation between the IVAID or the IVATTD of DM and the concentration of DE and ME as well as the ATTD of DM indicates that the in vitro procedure may be used to estimate digestibility of DM and energy. However, IVATTD of DM is more appropriate than IVAID because of the stronger correlation between IVATTD of DM and DE, ME, and ATTD of DM.

The positive correlations between swelling capacity or WBC and ATTD of TDF, IDF, NSP, insoluble NSP, and noncellulosic NSP, and between viscosity and ATTD of NDF, IDF, and insoluble NSP, indicates that these physical characteristics may be used to evaluate the digestibility of fiber in vivo. This observation is in contrast with results from Jaworski and Stein (2017) who did not observe any correlations between physical characteristics and digestibility of fiber fractions. Swelling capacity and WBC indicate increased digestibility of fiber, which may subsequently result in the release of encapsulated protein in fiber matrices in the feed and increased access for proteolytic enzymes. However, the negative correlation between WBC of ingredients and ATTD of CP may be due to increased ileal endogenous losses of N induced by an increase in WBC (Leterme et al., 1998). The increased endogenous losses of N may outweigh the proposed protein-releasing effect of the swelling capacity or WBC of ingredients. However, it is also possible that the negative correlation between WBC and ATTD of CP may be a result of an increase in microbial N in the feces due to an increase in digestibility of different fiber fractions via microbial fermentation. The positive correlation between bulk density of the diet and ATTD of GE and the concentration of DE and ME is in agreement with previous data, which indicate that apparent cecal digestibility of GE was positively correlated with bulk density of the diet (Jaworski and Stein, 2017). This may be explained by the negative correlation between bulk density and fiber fractions (i.e., ADF, NDF, cellulose, insoluble hemicellulose; data not shown), indicating that an increase in bulk density may also imply less concentration of fiber in the diet (Jaworski et al., 2014), which has less available energy compared with protein, fat, and digestible carbohydrates. Dusel et al. (1997) observed a negative correlation between viscosity and apparent ME (AME) in 34 varieties of wheat fed to broilers, but no correlation between viscosity and AME in five varieties of wheat was observed by Svihus and Gullord (2002). It is likely that a lack of a correlation between viscosity and energy digestibility or

concentration of DE and ME in pigs, as opposed to poultry, is a result of pigs being less affected by viscosity because poultry cecal contents are more viscous than in pigs (Thacker et al., 2002; Takahashi et al., 2004). Viscosity measurements may also be different before ingestion and at different points along the gastrointestinal tract due to potential depolymerization or reduction in electrostatic repulsion between polysaccharides (Guillon and Champ, 2000; Capuano, 2017). Therefore, viscosity measurements of diets and ingredients may not be representative of digesta viscosity at any given point in the gastrointestinal tract.

In conclusion, TDF and IDF are more appropriate than ADF and NDF in estimating the concentration of DE and ME in feed ingredients but the IVATTD of DM may also be used to estimate DE and ME. However, physical characteristics of feed ingredients were not correlated with the concentration of DE and ME and measures for bulk density, viscosity, swelling, and water-binding capacity cannot be used to estimate energy digestibility in feed ingredients in vivo. However, swelling, WBC, and viscosity may be used to evaluate digestibility of fiber fractions. Furthermore, the bulk density of the diet was positively correlated with concentration of DE and ME likely because increased bulk density indicates less concentration of fiber.

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, New York, NY. p. 903–916.
- 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. doi:10.2527/jas.2010–3605
- Bach Knudsen, K. E., H. N. Lærke, and H. Jørgensen. 2013. Carbohydrate and carbohydrate utilization in swine. In: L. I. Chiba, editor, *Sustainable swine nutrition*. John Wiley & Sons, Inc., Ames, IA. p. 109–137. doi:10.1002/9781118491454.ch5
- Berrocso, J. D., O. J. Rojas, Y. Liu, J. Shoulders, J. C. González-Vega, and H. H. Stein. 2015. Energy concentration and amino acid digestibility in high-protein canola meal, conventional canola meal, and soybean meal fed to growing pigs. *J. Anim. Sci.* 93:2208–2217. doi:10.2527/jas.2014–8528
- Bolarinwa, O. A., and O. Adeola. 2016. Regression and direct methods do not give different estimates of digestible and metabolizable energy values of barley, sorghum, and wheat for pigs. *J. Anim. Sci.* 94:610–618. doi:10.2527/jas.2015–9766
- Capuano, E. 2017. The behavior of dietary fiber in the gastrointestinal tract determines its physiological effect. *Crit. Rev. Food Sci. Nutr.* 57:3543–3564. doi:10.1080/10408398.2016.1180501
- Cervantes-Pahm, S. K., Y. Liu, A. Evans, and H. H. Stein. 2014. Effect of novel fiber ingredients on ileal and total tract digestibility of energy and nutrients in semi-purified diets fed to growing pigs. *J. Sci. Food Agric.* 94:1284–1290. doi:10.1002/jsfa.6405
- Dusel, G., H. Kluge, K. Gläser, O. Simon, G. Hartmann, J. Lengerken, and H. Jeroch. 1997. An investigation into the variability of extract viscosity of wheat-relationship with the content of non-starch-polysaccharide fractions and metabolisable energy for broiler chickens. *Arch. Tierernähr.* 50:121–135. doi:10.1080/17450399709386125
- Guillon, F., and M. Champ. 2000. Structural and physical properties of dietary fibres, and consequences of processing on human physiology. *Food Res. Int.* 33:233–245. doi:10.1016/S0963-9969(00)00038-7
- Gutierrez, N. A., N. V. Serão, B. J. Kerr, R. T. Zijlstra, and J. F. Patience. 2014. 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. *J. Anim. Sci.* 92:4505–4517. doi:10.2527/jas.2013–7265
- Jaworski, N. W., H. N. Lærke, K. E. Bach Knudsen, and H. H. Stein. 2015. Carbohydrate composition and in vitro digestibility of dry matter and nonstarch polysaccharides in corn, sorghum, and wheat and coproducts from these grains. *J. Anim. Sci.* 93:1103–1113. doi:10.2527/jas.2014–8147
- Jaworski, N. W., J. Shoulders, J. C. González-Vega, and H. H. Stein. 2014. Effects of using copra meal, palm kernel expellers, or palm kernel meal in diets for weanling pigs. *Prof. Anim. Sci.* 30:243–251. doi:10.15232/S1080-7446(15)30108-X
- Jaworski, N. W., and H. H. Stein. 2017. Disappearance of nutrients and energy in the stomach and small intestine, cecum, and colon of pigs fed corn-soybean meal diets containing distillers dried grains with solubles, wheat middlings, or soybean hulls. *J. Anim. Sci.* 95:727–739. doi:10.2527/jas.2016.0752
- Kerr, B. J., W. A. Dozier, 3rd, and G. C. Shurson. 2013. Effects of reduced-oil corn distillers dried grains with solubles composition on digestible and metabolizable energy value and prediction in growing pigs. *J. Anim. Sci.* 91:3231–3243. doi:10.2527/jas.2013–6252
- Kil, D. Y., T. E. Sauber, D. B. Jones, and H. H. Stein. 2010. Effect of the form of dietary fat and the concentration of dietary neutral detergent fiber on ileal and total tract endogenous losses and apparent and true digestibility of fat by growing pigs. *J. Anim. Sci.* 88:2959–2967. doi:10.2527/jas.2009–2216
- Kwon, W. B., and B. G. Kim. 2015. Effects of supplemental beta-mannanase on digestible energy and metabolizable energy contents of copra expellers and palm kernel expellers fed to pigs. *Asian-Australas. J. Anim. Sci.* 28:1014–1019. doi:10.5713/ajas.15.0275
- Le Gall, M., M. Warpechowski, Y. Jaguelin-Peyraud, and J. Noblet. 2009. Influence of dietary fibre level and pelleting on the digestibility of energy and nutrients in growing pigs and adult sows. *Animal* 3:352–359. doi:10.1017/S1751731108003728
- Leterme, P., E. Froidmont, F. Rossi, and A. Théwis. 1998. The high water-holding capacity of pea inner fibers affects the ileal flow of endogenous amino acids in pigs. *J. Agric. Food Chem.* 46:1927–1934. doi:10.1021/jf970955+
- Liu, Y., N. W. Jaworski, O. J. Rojas, and H. H. Stein. 2016. Energy concentration and amino acid digestibility in

- high protein canola meal, conventional canola meal, and in soybean meal fed to growing pigs. *Anim. Feed Sci. Technol.* 212:52–62. doi:10.1016/j.anifeedsci.2015.11.017
- Maison, T., Y. Liu, and H. H. Stein. 2015. Digestibility of energy and detergent fiber and digestible and metabolizable energy values in canola meal, 00-rapeseed meal, and 00-rapeseed expellers fed to growing pigs. *J. Anim. Sci.* 93:652–660. doi:10.2527/jas.2014-7792
- Montoya, C. A., S. J. Henare, S. M. Rutherford, and P. J. Moughan. 2016. Potential misinterpretation of the nutritional value of dietary fiber: correcting fiber digestibility values for nondietary gut-interfering material. *Nutr. Rev.* 74:517–533. doi:10.1093/nutrit/nuw014
- Montoya, C. A., S. M. Rutherford, and P. J. Moughan. 2015. Nondietary gut materials interfere with the determination of dietary fiber digestibility in growing pigs when using the Prosky method. *J. Nutr.* 145:1966–1972. doi:10.3945/jn.115.212639
- Mroz, Z., A. J. Moeser, K. Vreman, J. T. M. van Diepen, T. van Kempen, T. T. Canh, and A. W. Jongbloed. 2000. Effects of dietary carbohydrates and buffering capacity on nutrient digestibility and manure characteristics in finishing pigs. *J. Anim. Sci.* 78:3096–3106. doi:10.2527/2000.78123096x
- Navarro, D. M. D. L., E. M. A. M. Bruininx, L. de Jong, and H. H. Stein. 2018. Analysis for low-molecular-weight carbohydrates is needed to account for all energy-contributing nutrients in some feed ingredients, but physical characteristics do not predict in vitro digestibility of dry matter. *J. Anim. Sci.* 96:532–544. doi:10.1093/jas/sky010
- Noblet, J., and J. van Milgen. 2013. Energy and energy metabolism in swine. In: L. I. Chiba, editor, *Sustainable swine nutrition*. John Wiley & Sons, Inc., Ames, IA. p. 23–57. doi:10.1002/9781118491454.ch2
- NRC. 2012. *Nutrient requirements of swine*. 11th rev. ed. Natl. Acad. Press, Washington, DC. doi:10.17226/13298
- 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. doi:10.2527/jas.2006-252
- Rojas, O. J., Y. Liu, and H. H. Stein. 2013. Phosphorus digestibility and concentration of digestible and metabolizable energy in corn, corn coproducts, and bakery meal fed to growing pigs. *J. Anim. Sci.* 91:5326–5335. doi:10.2527/jas.2013-6324
- Rojas, O. J., and H. H. Stein. 2013. Concentration of digestible, metabolizable, and net energy and digestibility of energy and nutrients in fermented soybean meal, conventional soybean meal, and fish meal fed to weanling pigs. *J. Anim. Sci.* 91:4397–4405. doi:10.2527/jas.2013-6409
- Sotak-Peper, K. M., J. C. Gonzalez-Vega, and H. H. Stein. 2015. Concentrations of digestible, metabolizable, and net energy in soybean meal produced in different areas of the United States and fed to pigs. *J. Anim. Sci.* 93:5694–5701. doi:10.2527/jas.2015-9281
- Sulabo, R. C., W. S. Ju, and H. H. Stein. 2013. Amino acid digestibility and concentration of digestible and metabolizable energy in copra meal, palm kernel expellers, and palm kernel meal fed to growing pigs. *J. Anim. Sci.* 91:1391–1399. doi:10.2527/jas.2012-5281
- Svihus, B., and M. Gullord. 2002. Effect of chemical content and physical characteristics on nutritional value of wheat, barley and oats for poultry. *Anim. Feed Sci. Technol.* 102:71–92. doi:10.1016/S0377-8401(02)00254-7
- Takahashi, T., M. Goto, and T. Sakata. 2004. Viscoelastic properties of the small intestinal and caecal contents of the chicken. *Br. J. Nutr.* 91:867–872. doi:10.1079/BJN20041129
- Thacker, P. A., J. G. McLeod, and G. L. Campbell. 2002. Performance of growing-finishing pigs fed diets based on normal or low viscosity rye fed with or without enzyme supplementation. *Arch. Anim. Nutr.* 56:361–370. doi:10.1080/00039420215631
- Urriola, P. E., S. K. Cervantes-Pahm, and H. H. Stein. 2013. Fiber in swine nutrition. In: L. I. Chiba, editor, *Sustainable swine nutrition*. John Wiley & Sons, Inc., Ames, IA. p. 255–276. doi:10.1002/9781118491454.ch11
- 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. doi:10.2527/jas.2009-2227
- 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. doi:10.2527/jas.2006-840
- 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. doi:10.2527/jas.2006-431
- Yin, Y.-L., J. D. G. McEvoy, H. Schulze, U. Hennig, W.-B. Souffrant, and K. J. McCracken. 2000. Apparent digestibility (ileal and overall) of nutrients and endogenous nitrogen losses in growing pigs fed wheat (var. Soissons) or its byproducts without or with xylanase supplementation. *Livest. Prod. Sci.* 62:119–132. doi:10.1016/S0301-6226(99)00129-3
- Zervas, S., and R. T. Zijlstra. 2002. Effects of dietary protein and fermentable fiber on nitrogen excretion patterns and plasma urea in grower pigs. *J. Anim. Sci.* 80:3247–3256. doi:10.2527/2002.80123247x
- Zijlstra, R. T., and E. Beltranena. 2013. Alternative feedstuffs in swine diets. In: L. I. Chiba, editor, *Sustainable swine nutrition*. John Wiley & Sons, Inc., Ames, IA. p. 229–253. doi:10.1002/9781118491454.ch10