The contribution of digestible and metabolizable energy from high-fiber dietary ingredients is not affected by inclusion rate in mixed diets fed to growing pigs

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ABSTRACT: Effects of inclusion rate of fiber-rich ingredients on apparent ileal digestibility (AID) and apparent total tract digestibility (ATTD) of GE and on the concentration of DE and ME in mixed diets fed to growing pigs were determined. The hypothesis was that increasing the inclusion rate of fiber decreases digestibility of GE, and thus, the contribution of DE and ME from hindgut fermentation because greater concentrations may reduce the ability of microbes to ferment fiber. Twenty ileal-cannulated pigs (BW: 30.64 ± 2.09 kg) were allotted to a replicated 10 × 4 incomplete Latin Square design with 10 diets and four 26-d periods. There were 2 pigs per diet in each period for a total of 8 replications per diet. A basal diet based on corn and soybean meal (SBM) and a corn-SBM diet with 30% corn starch were formulated. Six additional diets were formulated by replacing 15% or 30% corn starch by 15% or 30% corn germ meal, sugar beet pulp, or wheat middlings, and 2 diets were formulated by including 15% or 30% canola meal in a diet containing corn, SBM, and 30% corn starch. Effects of adding 15% or 30% of each fiber source to experimental diets were analyzed using orthogonal contrasts and *t*-tests were used to

compare inclusion rates within each ingredient. The AID and ATTD of GE and concentration of DE and ME in diets decreased (*P* < 0.05) with the addition of 15% or 30% canola meal, corn germ meal, sugar beet pulp, or wheat middlings compared with the corn starch diet. However, inclusion rate did not affect the calculated DE and ME or AID and ATTD of GE in any of the ingredients indicating that concentration of DE and ME in ingredients was independent of inclusion rate and utilization of energy from test ingredients was equally efficient between diets with 15% and 30% inclusion. Increased inclusion of fiber in the diet did not influence transit time in the small intestine, but reduced the time of first appearance of digesta in the feces indicating that transit time was reduced in the hindgut of pigs fed high-fiber diets. However, this had no impact on DE and ME or ATTD of GE in test ingredients. In conclusion, fiber reduced the DE and ME in the diet. However, inclusion rate of fiber-rich ingredients in diets did not affect calculated values for DE and ME in feed ingredients indicating that microbial capacity for fermentation of fiber in pigs is not overwhelmed by inclusion of 30% high-fiber ingredients in the diets.

Key words: digestibility, energy, fiber, inclusion rate, passage rate, pigs

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INTRODUCTION

The concentration of DE and ME in feed ingredients fed to pigs is usually determined using a single inclusion rate of a test ingredient in the diet and the difference procedure is used to calculate

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DE and ME in the ingredient if it is not possible to feed the test ingredient as the only source of energy in the diet (Adeola, 2001). However, it is not clear if different inclusion rates result in comparable DE and ME values if the difference procedure is used. Results of studies using wheat middlings or wheat bran indicated that different inclusion rates may result in variable DE and ME values (Huang et al., 2013; Zhao et al., 2017). However, the effect of substitution rate on the concentration of DE and ME in canola meal, corn germ meal, and sugar beet pulp is not known. It is also not clear if there is a saturation point in the fermentation capacity in the hindgut of growing pigs, which may influence the amount of energy obtained by the pig from hindgut fermentation of high-fiber ingredients. If that is the case, it may be hypothesized that the DE and ME obtained for a high-fiber ingredient may be reduced with increasing inclusion rate. Data to confirm this hypothesis have been conflicting (Huang et al., 2013; Zhao et al., 2017), and this may be due to different test ingredients or differences in experimental procedures. Therefore, the objective of this experiment was to determine effects of inclusion rate of 4 commonly used high-fiber dietary ingredients on calculated values for DE and ME by growing pigs. The hypothesis was that increasing the inclusion rate of fiber decreases the relative contribution to DE and ME from hindgut fermentation because greater concentrations of fiber may overwhelm the ability of microbes to ferment fiber and because increasing dietary fiber increases passage rate in the digestive tract and thus reduces the time available for fermentation.

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).

Diets, Animals, Housing, and Experimental Design

Twenty pigs (initial BW: 30.64 ± 2.09 kg) were surgically fitted with a T-cannula in the distal ileum using procedures adapted from Stein et al. (1998). After surgery, pigs were individually housed in metabolism crates that were equipped with a feeder and a nipple drinker, fully slatted floors, a screen floor, and urine trays, which allowed for the total, but separate, collection of feces and urine from each pig. Pigs were allotted to a replicated 10×4

incomplete Latin Square design with 10 diets and four 26-d periods. There were 2 pigs per diet in each period for a total of 8 replications per diet. Pigs were fed equal amounts of feed at 0800 and 1700 h every day. Daily feed allotments were calculated as 3 times the estimated requirement for maintenance energy (i.e., 197 kcal ME/kg BW^{0.6}; NRC, 2012). Water was available at all times.

A basal diet based on corn and soybean meal (SBM) was formulated (Table 1). A diet based on corn, SBM, and 30% corn starch was also formulated. Six diets were formulated by replacing 15 or 30% corn starch by 15 or 30% corn germ meal, sugar beet pulp, or wheat middlings. Two additional diets were formulated by including 15 or 30% canola meal in a diet containing corn, SBM, and 30% corn starch. The ratio between corn and SBM remained constant among all diets to allow for calculation of the contribution of energy from corn and SBM to diets containing test ingredients. Vitamins and minerals were included in all diets according to current requirements (NRC, 2012). Titanium dioxide was added at 0.40% to each diet as an indigestible marker.

Data Recording and Sample Collection

The BW of each pig was recorded at the beginning of the experiment and subsequently on d 15 and d 26 of each period. The initial 14 d of each period were considered an adaptation period to the diet. Color markers were included in the morning meal on d 15 (indigo carmine) and on d 20 (ferric oxide) to mark the beginning and the end of fecal collections (Adeola, 2001). Feed consumption was recorded during the 5-d collection period. 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 from d 15 to 20 and were emptied daily during this period. 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 (Kim et al., 2009). Ileal digesta were collected for 8 h on d 22 and 23. A 225-mL plastic bag was attached to the cannula barrel using a cable tie and digesta flowing into the bag were collected. Bags were removed every 30 min, or whenever full, and replaced with a new bag. Digesta were stored at -20°C immediately after collection.

Pigs were fed their respective diets until d 26 to measure the time it takes for digesta to appear

Table 1. Composition of experimental diets (as-fed basis)

Ingredient, %	Basal	CS ^a	Canola meal		Corn germ meal		Sugar beet pulp		Wheat middlings	
			15%	30%	15%	30%	15%	30%	15%	30%
Ground corn	57.00	39.40	30.75	22.10	39.40	39.40	39.60	39.60	39.40	39.40
Soybean meal	40.20	27.80	21.65	15.60	27.80	27.80	27.90	27.90	27.80	27.80
Corn starch	–	30.00	30.00	30.00	15.00	–	15.00	–	15.00	–
Test ingredient	–	–	15.00	30.00	15.00	30.00	15.00	30.00	15.00	30.00
Ground limestone	0.90	1.00	0.80	0.70	1.00	1.00	0.70	0.70	1.20	1.20
Monocalcium phosphate	0.80	0.70	0.70	0.50	0.70	0.70	0.70	0.70	0.50	0.50
Sodium chloride	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin-mineral premix ^b	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
Analyzed values										
GE, kcal/kg	3,870	3,798	3,821	3,881	3,861	3,920	3,811	3,795	3,825	3,878
DM, %	87.19	87.70	87.49	87.74	87.91	87.63	88.03	87.84	87.58	87.29
Ash, %	5.42	4.49	4.92	5.28	5.27	5.22	5.30	6.39	5.42	5.86
OM, %	81.77	83.21	82.56	82.46	82.64	82.41	82.73	81.45	82.16	81.43
CP, %	22.84	15.65	17.97	21.72	20.47	22.79	16.83	17.90	17.51	19.74
AEE ^c , %	2.41	1.83	2.06	2.20	1.76	2.40	1.75	1.92	2.03	2.59
NDF, %	6.87	4.46	7.39	9.45	10.19	15.62	9.76	15.16	9.88	14.57
ADF, %	3.41	2.15	4.38	6.29	4.38	6.43	5.95	9.71	3.38	4.79
Lignin, %	0.54	0.30	1.42	2.32	0.98	1.76	0.93	1.54	0.77	1.20
TDF ^d , %	11.14	8.25	11.34	12.74	13.17	19.29	15.77	26.70	13.36	19.79
IDF ^d , %	10.55	7.64	10.92	12.07	12.56	17.64	13.54	21.62	13.03	18.80
SDF ^d , %	0.59	0.60	0.42	0.67	0.61	1.64	2.23	5.08	0.32	0.99

^aCS = corn starch diet.

^bThe vitamin-micromineral premix provided the following quantities of vitamins and microminerals 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 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.

^cAEE = acid hydrolyzed ether extract.

^dTDF = total dietary fiber; IDF = insoluble dietary fiber; SDF = soluble dietary fiber.

at the end of the ileum and in the feces (Urriola and Stein, 2010). Briefly, on d 24, the morning meal was mixed with 5 g/kg of indigo carmine. Pigs were allowed to eat their meal and the start of eating was considered time zero. The ileal cannula of each pig was opened 1 h after the morning meal was fed to observe if blue digesta were present in the cannula. If no blue digesta were present, the cannula was reopened every 15 min thereafter until blue digesta were detected in the cannula and time of first appearance was recorded. During the following 48 h, feces were scored every 30 min from all pigs and the first time blue feces appeared was recorded.

Chemical Analysis

Diets, ingredients, ileal digesta samples, and fecal samples were analyzed for DM (Method 930.15; AOAC Int., 2007). Diets and ingredients were also analyzed for ash (Method 942.05; AOAC Int., 2007). Organic matter was determined as the

difference between DM and ash. Diet, ingredient, ileal digesta, urine, and fecal samples were analyzed for GE on an isoperibol bomb calorimeter (Model 6300, Parr Instruments, Moline, IL) using benzoic acid as the internal standard. The concentration of N in diets and ingredients was determined using the combustion procedure (Method 990.03; AOAC Int., 2007) on an Elementar Rapid N-cube protein/nitrogen apparatus (Elementar Americas Inc., Mt. Laurel, NJ). Aspartic acid was used as a calibration standard and CP was calculated as $N \times 6.25$. Diets and ingredients were analyzed for ADF and NDF via Ankom Technology methods 12 and 13, respectively, using the Ankom²⁰⁰⁰ Fiber Analyzer (Ankom Technology, Macedon, NY). After ADF analysis, lignin was determined using Ankom Technology method 9 (Ankom Daisy^{II} Incubator, Ankom Technology, Macedon, NY). Insoluble dietary fiber (IDF) and soluble dietary fiber (SDF) in diets and ingredients were determined using the Ankom^{TDF} Dietary Fiber Analyzer (AOAC 991.43,

Table 2. Analyzed nutrient composition of corn, soybean meal (SBM), canola meal, corn germ meal, sugar beet pulp, and wheat middlings, as-fed basis

Item	Corn	SBM	Canola meal	Corn germ meal	Sugar beet pulp	Wheat middlings
GE, kcal/kg	3,746	4,282	4,267	4,136	3,740	4,040
DM, %	84.52	90.19	88.90	88.24	92.48	87.53
Ash, %	1.03	6.41	7.14	3.29	6.96	4.90
OM, %	83.49	83.79	81.76	84.95	85.52	82.63
CP, %	4.78	49.33	40.52	23.70	7.27	14.30
AEE ^a , %	3.35	1.68	4.06	3.12	2.00	4.44
NDF, %	6.20	8.80	23.63	37.37	45.47	35.18
ADF, %	1.92	5.76	17.33	14.31	21.54	10.26
Lignin, %	0.39	0.21	7.39	4.50	2.46	3.39
TDF ^b , %	8.27	14.38	26.42	35.89	48.54	34.65
IDF ^b , %	7.86	12.98	25.44	33.41	44.57	33.68
SDF ^b , %	0.41	1.40	0.98	2.48	3.97	0.96

^aAEE = acid hydrolyzed ether extract.

^bTDF = total dietary fiber; IDF = insoluble dietary fiber; SDF = soluble dietary fiber.

AOAC Int., 2007; Ankom Technology, Macedon, NY). Total dietary fiber in diets and ingredients was determined as the sum of IDF and SDF. Acid hydrolyzed ether extract (AEE) in diets and ingredients was analyzed by acid hydrolysis using 3N HCl (Ankom^{HCl}, Ankom Technology, Macedon, NY) followed by crude fat extraction using petroleum ether (Ankom^{XT15}, Ankom Technology, Macedon, NY). The concentration of titanium in diet and ileal digesta samples was analyzed following the procedure of Myers et al. (2004). Nutrient composition of ingredients is summarized in Table 2.

Calculations and Statistical Analysis

Apparent ileal digestibility (AID) of GE in the diets was calculated as described by Stein et al. (2007) using Eq. [1]:

$$\text{AID} = [1 - \{(\text{GE}_d / \text{GE}_f) \times (\text{TiO}_{2f} / \text{TiO}_{2d})\}] \times 100 \quad (1)$$

where AID is the apparent ileal digestibility of gross energy (%), GE_d is the analyzed GE of the ileal digesta DM, GE_f is the analyzed GE of feed DM, TiO_{2f} is the concentration of titanium in the feed DM, and TiO_{2d} is the concentration of titanium in the ileal digesta DM. The apparent total tract digestibility (ATTD) of GE in each diet was also calculated (Adeola, 2001; NRC, 2012) using Eq. [2]:

$$\text{ATTD} = [(\text{GE}_i - \text{GE}_o) / \text{GE}_i] \times 100 \quad (2)$$

where ATTD is the apparent total tract digestibility of gross energy (%), GE_i is the total intake of GE in the feed (g), and GE_o is the total fecal output

of GE (g). The AID and ATTD of GE in ingredients were calculated using the difference procedure (Kong and Adeola, 2014) with the corn-SBM basal diet and the corn-SBM-corn starch basal diet, subsequently, using the Eq. [3]:

$$\text{D}_{\text{bd}} + [(\text{D}_{\text{td}} - \text{D}_{\text{bd}}) / \text{P}_{\text{ti}}] \quad (3)$$

where D_{bd} is the digestibility of GE in the basal diet, D_{td} is the digestibility of GE in the test diet, P_{ti} is the proportional contribution of the test ingredient to the test diet. Apparent hindgut digestibility (AHD) was calculated as the difference between ATTD and AID values.

The contribution of DE from corn and SBM to the corn-SBM-corn starch diet was calculated by difference (Widmer et al., 2007) and the contribution of corn starch to the DE of diets containing test ingredients and corn starch was calculated by multiplying the DE of corn starch by the inclusion rate of corn starch in the diet. The DE in the corn-SBM diet was used to calculate the contribution of corn and SBM to the DE of all other diets and the DE of test ingredients for each inclusion level was calculated by difference (Widmer et al., 2007). First appearance of digesta in the intestinal tract was calculated as the difference between the time the blue marker was fed and the time it appeared in ileal digesta or fecal samples (Urriola and Stein, 2010).

Data were analyzed using SAS with pig as the experimental unit (SAS Institute Inc., Cary, NC). Homogeneity of the variances was confirmed using the UNIVARIATE procedure in PROC MIXED. The BOXPLOT procedure of SAS was used to check for outliers. An analysis of variance was conducted using the MIXED procedure. Diet was the

Table 3. Apparent ileal digestibility (AID) of GE, apparent hindgut digestibility (AHD) of GE, apparent total tract digestibility (ATTD) of GE, and concentration of DE and ME in experimental diets, as-fed basis^a

Item	Diet										Pooled SEM
	Basal	CS ^b	Canola meal		Corn germ meal		Sugar beet pulp		Wheat middlings		
			15%	30%	15%	30%	15%	30%	15%	30%	
GE intake ^c , kcal/d	8,841	7,558	8,222	8,351	8,452	8,937	8,410	8,733	8,239	8,842	255
GE in feces ^c , kcal/d	822	527	794	987	968	1,376	874	1,293	897	1,261	135
GE in urine, kcal/d	298	220	207	233	271	218	235	256	223	243	42
AID of GE ^d , %	63.1	75.7	73.5	65.7	65.1	56.3	62.2	51.8	65.0	62.7	2.99
AHD of GE ^e , %	28.1	17.1	16.4	22.6	23.8	28.1	27.4	33.5	24.0	20.0	3.1
ATTD of GE ^d , %	90.9	93.0	90.0	88.0	88.5	84.5	89.8	85.4	89.1	85.5	0.74
DE ^d , kcal/kg	3,517	3,532	3,440	3,415	3,417	3,313	3,420	3,241	3,409	3,314	28
ME ^d , kcal/kg	3,392	3,420	3,348	3,305	3,290	3,221	3,316	3,125	3,310	3,213	28

^aData are means of 8 observations per treatment except for 15% sugar beet pulp diet where only 7 observations were used.

^bCS = corn starch diet.

^cLinear increase ($P < 0.001$) for inclusion of 15% or 30% canola meal, corn germ meal, sugar beet pulp, or wheat middlings.

^dLinear reduction ($P < 0.001$) for inclusion of 15% or 30% canola meal, corn germ meal, sugar beet pulp, or wheat middlings.

^eLinear increase ($P < 0.05$) for inclusion of 15% or 30% canola meal, corn germ meal, or sugar beet pulp.

fixed effect and period and replicate were random effects. Least squares means were calculated using the LS Means option in SAS and effects of adding 15 or 30% of each fiber source to the corn-SBM-corn starch basal diet were analyzed using orthogonal contrasts. Independent sample *t*-tests were conducted using the TTEST procedure to compare response variables between 15 and 30% inclusion rate within each ingredient. Results were considered significant at $P < 0.05$ and considered a trend at $0.05 \leq P < 0.10$.

RESULTS AND DISCUSSION

All pigs were successfully cannulated at the distal ileum and recovered without complications. One pig fed the diet containing 15% sugar beet pulp died during the adaptation to period 4 due to peritonitis and no samples were collected for this diet in period 4. Therefore, there were only 7 observations for the diet containing 15% sugar beet pulp.

The GE intake and GE lost in the feces increased (linear, $P < 0.05$) with addition of 15 or 30% canola meal, corn germ meal, sugar beet pulp, or wheat middlings in the diet (Table 3). The inclusion rate of test ingredients did not affect GE lost in urine. The AID of GE decreased (linear, $P < 0.05$) from 75.7% in the corn starch diet to 73.5 and 65.7%, 65.1 and 56.3%, 62.2 and 51.8%, and 65.0 and 62.7% as the inclusion rate of canola meal, corn

germ meal, sugar beet pulp, or wheat middlings in the diet increased from 15 to 30%. In contrast, the AHD of GE linearly increased ($P < 0.05$) from 17.1% in the corn starch diet to 16.4 and 22.6%, 23.8 and 28.1%, and 27.4 and 33.5% as 15 or 30% canola meal, corn germ meal, or sugar beet pulp was added to the diet, but no change in AHD of GE was observed if wheat middlings was included in the diet. The ATTD of GE linearly decreased ($P < 0.001$) from 93.0% in the corn starch diet to 90.0 and 88.0%, 88.5 and 84.5%, 89.8 and 85.4%, and 89.1 and 85.5% as 15 or 30% canola meal, corn germ meal, sugar beet pulp, or wheat middlings was added to the diet. The concentration of DE linearly decreased ($P < 0.001$) from 3,532 kcal/kg in the corn starch diet to 3,440 and 3,415; 3,417 and 3,313; 3,420 and 3,241; and 3,409 and 3,314 kcal/kg as 15 or 30% canola meal, corn germ meal, sugar beet pulp, or wheat middlings was added to the diet. The concentration of ME linearly decreased ($P < 0.001$) from 3,420 kcal/kg in the corn starch diet to 3,348 and 3,305; 3,290 and 3,221; 3,316 and 3,125; and 3,310 and 3,213 kcal/kg as 15 or 30% canola meal, corn germ meal, sugar beet pulp, or wheat middlings was added to the diet.

The negative effects of fiber on concentration of DE and ME in the diet are due to the replacement of starch or CP with fiber fractions that are less digestible and make less contribution to ME (Le Gall et al., 2009). The greater concentration of

Table 4. Apparent ileal digestibility (AID) of GE, apparent hindgut digestibility (AHD) of GE, apparent total tract digestibility (ATTD) of GE and concentration of DE and ME in canola meal, corn germ meal, sugar beet pulp, and wheat middlings at 15% or 30% inclusion rate^a

	Inclusion rate			
Item	15%	30%	SEM	<i>P</i> -value
Canola meal				
AID, GE, %	48.7	28.8	12.6	0.137
AHD, GE, %	19.5	44.9	15.2	0.118
ATTD, GE, %	68.2	73.7	4.1	0.218
DE, kcal/kg	2,895	3,127	176	0.218
DE, kcal/kg DM	3,257	3,517	198	0.218
ME, kcal/kg	2,876	3,002	149	0.410
ME, kcal/kg DM	3,235	3,377	167	0.410
Corn germ meal				
AID, GE, %	33.8	42.9	12.0	0.456
AHD, GE, %	35.6	27.8	11.9	0.520
ATTD, GE, %	69.4	70.7	3.5	0.722
DE, kcal/kg	2,871	2,924	146	0.722
DE, kcal/kg DM	3,254	3,314	165	0.722
ME, kcal/kg	2,668	2,903	160	0.165
ME, kcal/kg DM	3,024	3,290	182	0.165
Sugar beet pulp				
AID, GE, %	23.2	25.3	13.6	0.881
AHD, GE, %	51.6	44.9	15.1	0.664
ATTD, GE, %	74.9	70.2	4.9	0.357
DE, kcal/kg	2,800	2,626	182	0.357
DE, kcal/kg DM	3,027	2,839	197	0.357
ME, kcal/kg	2,804	2,523	176	0.136
ME, kcal/kg DM	3,032	2,729	190	0.136
Wheat middlings				
AID, GE, %	38.6	60.4	21.9	0.285
AHD, GE, %	30.3	9.7	24.9	0.368
ATTD, GE, %	68.9	71.9	4.3	0.495
DE, kcal/kg	2,784	2,905	173	0.495
DE, kcal/kg DM	3,181	3,319	198	0.495
ME, kcal/kg	2,799	2,840	174	0.817
ME, kcal/kg DM	3,197	3,244	198	0.817

^aData are means of 8 observations per treatment except for the diet with 15% sugar beet pulp where only 7 observations were used.

DE and ME in the corn starch diet compared with diets containing high-fiber test ingredients is likely the result of greater AID and ATTD of DM and nutrients, which has also been previously reported (Yin et al., 2000; Le Goff and Noblet 2001; Le Goff et al., 2002; Owusu-Asiedu et al., 2006; Le Gall et al., 2009).

Inclusion rate did not affect AID, AHD, or ATTD of GE or DE and ME in any of the ingredients (Table 4). The DE and ME in canola meal determined in this experiment are within the range of published values (NRC, 2012; Berrocoso et al.,

2015; Maison et al., 2015; Liu et al., 2016). The DE and ME in corn germ meal were slightly less than values reported by Anderson et al. (2012), but in close agreement with values reported by the NRC (2012), Rojas et al. (2013), and Gutierrez et al. (2014). The DE and ME in sugar beet pulp concur with published values (Sauvant et al., 2004; NRC, 2012) and DE and ME in wheat middlings are also within the range of published values (Sauvant et al., 2004; NRC, 2012; Huang et al., 2013, 2014). The ATTD of GE in wheat middlings is in close agreement with values by Huang et al. (2014), but slightly greater than values reported by Huang et al. (2013) and Jaworski and Stein (2017).

The observation that concentration of DE and ME in feed ingredients was independent of inclusion rates indicates that under the conditions of this experiment, utilization of energy from the test ingredients was equally efficient in diets with 30% inclusion compared with diets with 15% inclusion. The lack of a difference between the 2 inclusion levels indicates that there were no interactions between the basal diet and the test ingredients (Villamide, 1996) and that the microbial population in the hindgut was not overwhelmed by the increased inclusion of fiber in the diet or the increased flow of nutrients into the large intestine. This observation is in agreement with data indicating that inclusion of 22.2 or 33.6% SBM resulted in estimates for DE and ME that were not different (Huang et al., 2013), although SBM has less concentration of total dietary fiber compared with canola meal, corn germ meal, sugar beet pulp, or wheat middlings. The presence of dietary fiber increases digestive secretions of gastric, biliary, and pancreatic origin (Dierick et al., 1989), which may provide more enzymes to digest protein, fat, and carbohydrates in the digesta in pigs fed diets with 30% inclusion compared with 15% inclusion to compensate for the fiber-induced reduction in nutrient digestibility. It is also possible that populations of cellulolytic and hemicellulolytic bacteria increase in response to continuous feeding of high-fiber diets and become more efficient in utilizing fiber (Varel and Yen, 1997).

In contrast to the results of this experiment, the concentration of DE and ME in wheat middlings increased with increased inclusion rate (Huang et al., 2013), whereas DE and the ATTD of GE in wheat bran decreased as the inclusion level increased (Zhao et al., 2017). It is possible that the contradicting results among experiments may be attributed to differences in the basal diets used. In this experiment, corn starch was replaced by the test ingredient to ensure that added fiber was supplied only by the test

Table 5. First appearance of indigestible marker, minutes

Item	Diet										Pooled SEM
	Basal	Corn starch	Canola meal		Corn germ meal		Sugar beet pulp		Wheat middlings		
			15%	30%	15%	30%	15%	30%	15%	30%	
Ileal	99	97	105	98	97	84	86	88	82	85	8
Fecal ^a	1,849	2,670	2,057	1,755	2,329	1,844	1,812	1,210	1,914	1,686	221

^aLinear reduction ($P < 0.01$) for inclusion of 15% or 30% canola meal, corn germ meal, sugar beet pulp, or wheat middlings.

ingredient, whereas a portion of the basal diet may be replaced in a typical digestibility experiment (Adeola, 2001) as was the case in the studies by Huang et al. (2013) and Zhao et al. (2017). The contribution of dietary fiber from the basal diet changes if a portion of the basal diet is replaced by the test ingredient, but this is not the case if corn starch is replaced because corn starch does not contain dietary fiber.

The time from feed ingestion to first appearance of digesta at the end of the ileum was not different among pigs fed experimental diets (Table 5). In contrast, the time from feed ingestion to first appearance in the feces was linearly reduced ($P < 0.01$) from 2,670 min for the corn starch diet to 2,057 and 1,755 min; 2,329 and 1,844 min; 1,812 and 1,210 min; and 1,914 and 1,686 min. This may explain the reduction in ATTD of GE in diets that was observed as the fiber-rich ingredients were added because a decrease in transit time in the hindgut will result in less time for the digesta to be fermented (Morel et al., 2006; Wilfart et al., 2007). These observations are in agreement with data by van Leeuwen et al. (2006) and indicate that dietary fiber primarily affects passage rate in the hindgut of pigs and a similar observation was also reported for maize bran and wheat bran (Le Goff et al., 2002). Addition of wheat bran did not affect gastric emptying in growing pigs, but increasing concentrations of wheat bran in the diet reduced the transit time in the small and large intestines (Wilfart et al., 2007). The reason for these observations may be that feeding a high-fiber diet results in a greater flow of DM into the large intestine due to lower digestibility of nutrients in the upper gut (Owusu-Asiedu et al., 2006; Serena et al., 2008), and the reduced nutrient digestibility results in a greater bulk of indigestible material that may induce peristaltic action and propulsion along the gastrointestinal tract (Le Goff et al., 2002; Wilfart et al., 2007). However, there was no difference in the time it took for digesta to appear at the end of the ileum, cecum, and feces between pigs fed a control diet and a diet with 30% corn distillers dried grains with solubles (DDGS; Urriola and Stein, 2010), but this may have been a result of the fat in DDGS, which increases transit

time. Purified guar gum and cellulose increased retention time in the small intestine compared with a control diet containing less nonstarch polysaccharides when fed to growing pigs, but only guar gum increased total tract retention time (Owusu-Asiedu et al., 2006). In contrast, nonstarch polysaccharides provided by palm kernel expellers or soy hulls did not change passage rate of digesta in the small intestine, but reduced retention time over the entire gastrointestinal tract (van Leeuwen et al., 2006). Thus, it appears that the effect on transit time is dependent on the source of fiber and a reduction in retention time is more evident in the hindgut than in the small intestine of pigs.

CONCLUSION

Inclusion of high-fiber ingredients may have a negative effect on the concentration of DE and ME in diets fed to pigs. However, inclusion rate does not affect calculated values for DE and ME in feed ingredients with relatively high concentration of fiber indicating that microbial capacity for fermentation of fiber in pigs is not overwhelmed by inclusion of 30% high-fiber ingredients in the diets. The time of first appearance of digesta in the feces was reduced as inclusion of fiber in the diets increased indicating reduced retention time in the hindgut of pigs fed high-fiber diets, but this had no impact on values for DE and ME and ATTD of GE in test ingredients.

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