Viscous and fermentable nonstarch polysaccharides affect intestinal nutrient and energy flow and hindgut fermentation in growing pigs¹

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ABSTRACT: Two experiments were conducted to determine the effects of viscosity and fermentability of purified nonstarch polysaccharides (NSP) on intestinal nutrient and energy flow and hindgut fermentation in growing pigs. In Exp. 1, 15 ileal-cannulated pigs (50.5 ± 2.9 kg BW) were allotted to 5 diets in a 2-period incompletely randomized design. Pigs were provided a cornstarch N-free diet (CST) or a diet containing 5% inulin (INU), carboxymethylcellulose sodium (CMC), microcrystalline cellulose (MCC), or Solka-Floc (SFC). Apparent ileal digestibility (AID) of DM, ash, and GE were greater ($P < 0.05$) in the MCC and SFC diets than in the INU and CMC diets. Apparent total tract digestibility (ATTD) of DM, carbohydrates (CHO), and GE and the DE content in the CST and INU diets were greater ($P < 0.01$) than in the CMC, MCC, and SFC diets. Hindgut disappearance of DM, CHO, and GE in the INU diet was greater ($P < 0.05$) than in the other N-free diets. The ileal endogenous flow of His, Ile, Leu, Met, Thr, Val, and all dispensable AA in the CMC diet was greater ($P < 0.05$) than in the other diets. In Exp. 2, 6 ileal-cannulated pigs were allotted to 3 diets containing either a corn-soybean meal control diet or the control diet with 5%

INU or CMC in a replicated 3 × 3 Latin square design. Standardized ileal digestibility (SID) of Ala, Arg, Asp, Cys, Gly, His, Ile, Leu, Lys, Phe, Ser, Thr, and Val were greater ($P < 0.05$) in the CMC diet than in the control and INU diets. Incorporation of 5% INU or CMC in the control diet reduced ($P < 0.01$) the AID of arabinoxylan and insoluble and total NSP. The ATTD of NSP and cellulose and the hindgut disappearance of NSP, β -glucan, and cellulose in the CMC diet were less ($P < 0.01$) than in the control and INU diets. Inclusion of 5% INU in the diet increased ($P < 0.01$) hindgut fermentation of insoluble and total NSP compared with the control and CMC diets. In conclusion, depending on the viscosity and fermentability of the NSP, different sources will have different effects on nutrient digestibility and hindgut fermentation. Addition of 5% INU to a corn-soybean meal diet reduced digestibility of the NSP component in the ileum and increased hindgut fermentation of total NSP. In contrast, the inclusion of CMC increased the AID and SID of the diet and reduced total tract digestion and hindgut fermentation of NSP component. Carboxymethylcellulose sodium is not recommended as a source of synthetic fiber in a N-free diet to determine the SID of AA of diets.

Key words: amino acid, digestibility, fermentability, nonstarch polysaccharides, pig, viscosity

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J. Anim. Sci. 2017.95:5054–5063
doi:10.2527/jas2017.1662

INTRODUCTION

The effect of dietary nonstarch polysaccharides (NSP) on nutrient digestibility of feeds in growing pigs largely reflects the structural and functional characteristics of NSP, such as solubility, viscosity, and fermentability (Bach Knudsen et al., 1993; Renteria-Flores et al., 2008). Analyzing viscosity and fermentability of a diet can help improve our understanding of the physiological characteristics of dietary NSP (Dégen et al., 2007; Chen et al., 2013). The specific

¹The authors are grateful for the financial support from the Fundamental Research Funds for Chinese Academy of Agricultural Sciences (2017ywf-zd-18, 2017ywf-zd-23, and Y2017PT42) and Agricultural Science and Technology Innovation Program (ASTIP-IAS07) in P.R. China.

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Received April 24, 2017.

Accepted September 5, 2017.

effects of functional or structural properties of dietary fiber can be differentiated by purified fiber fractions with semipurified diets to study specific contributions of viscosity and fermentability and their possible interactions (Hooda et al., 2011; Gao et al., 2015). However, there is little information about the role of viscosity and fermentability of dietary NSP on the intestinal nutrient digestion and hindgut fermentation.

Standardized ileal digestibility (SID) of AA in pigs has been recommended as a measure of AA availability (NRC, 2012) because SID values are additive in mixtures of feed ingredients (Stein et al., 2007). The basal AA losses for calculation of SID values are mostly estimated using a N-free diet (de Lange et al., 1989; Mariscal-Landin et al., 1995; Stein et al., 2007). However, the use of dietary fiber source in a N-free diet can vary among inulin (INU), carboxymethylcellulose sodium (CMC), microcrystalline cellulose (MCC), and Solka-Floc (SFC; International Fiber Corporation, North Tonawanda, NY; Larsen et al., 1993; Mosenthin et al., 1994; Leterme et al., 1996; Kong et al., 2014), and this choice may influence the results.

The hypothesis of the present study was that viscosity and fermentability of dietary NSP affect the intestinal nutrient digestion and hindgut fermentation of pigs. The first objective of the experiment was to determine the effects of dietary NSP source in semipurified diets on endogenous AA flow. The second objective was to determine the effects of dietary NSP source in a corn-soybean meal diet on ileal AA digestibility and intestinal digestibility and hindgut fermentation of NSP component in growing pigs.

MATERIALS AND METHODS

The experimental protocol was reviewed and approved by the Institutional Animal Care and Use Committee of the State Key Laboratory of Animal Nutrition at the Chinese Academy of Agricultural Science for 2 experiments. Pigs used in both experiments were the offspring of Large White (one-fourth) × Landrace (three-fourths; Beijing Breeding Swine Center, Beijing, P.R. China).

Animals, Diets, and Feeding

In Exp. 1, 15 growing barrows (20.1 ± 0.9 kg initial BW) were equipped with a T-cannula with an inner diameter of 1.5 cm in the distal ileum. All pigs were successfully cannulated at the distal ileum and recovered from surgery without complications. The control diet based on corn and soybean meal was fed to ileal-cannulated pigs to 50.5 ± 2.9 kg BW. Pigs were randomly allotted to 5 diets in a 2-period incomplete

Table 1. Analyzed nutrient composition of nonstarch polysaccharide ingredients, DM basis

Item	Nonstarch polysaccharides ¹				
	Cornstarch	INU	CMC	MCC	SFC
DM, %	88.38	93.20	92.55	94.79	95.66
CP, %	0.54	0.08	0.09	0.09	0.21
Ether extract, %	0.49	0.18	0.13	0.43	0.52
Ash, %	0.33	0.23	23.34	1.70	0.40
Carbohydrate, ² %	98.36	99.51	76.44	97.79	98.87
Starch, %	97.80	11.02	2.23	5.77	2.95
GE, kcal/kg	17.21	17.62	14.13	16.41	16.69

¹CMC = carboxymethylcellulose sodium; INU = inulin; MCC = microcrystalline cellulose; SFC = Solka-Floc (International Fiber Corporation, North Tonawanda, NY).

²Calculated value.

block design. During each period, each diet was fed to 3 pigs. Therefore, each diet was fed to a total of 6 pigs during the experiment and no pig was given the same diet more than once. A cornstarch N-free diet (CST) and the 4 diets in which the N-free diet contained 5% INU, CMC, MCC, or SFC, which were added at the expense of cornstarch, were formulated (Tables 1 and 2). Following a 5-d recovery period between the 2 periods, pigs were fed a corn-soybean meal diet.

In Exp. 2, 6 pigs (21.3 ± 1.0 kg initial BW) were surgically fitted with a T-cannula with an inner diameter of 1.5 cm in the distal ileum (Gao et al., 2015). All pigs were successfully cannulated at the distal ileum and recovered from surgery without complications. The control diet based on corn and soybean meal was fed to ileal-cannulated pigs to 56.0 kg BW. Pigs were allotted to a double 3×3 Latin square design with 3 diets and 3 periods in each square and provided a corn-soybean meal control diet or the control diet in which corn and soybean meal were partly replaced with 5% INU or CMC to provide dietary fiber (Table 3).

Vitamins and minerals were included in the diets to meet or exceed nutritional requirements of growing pigs (NRC, 2012). Chromic oxide was included in all diets as an indigestible marker. The daily feed allowance was adjusted to 3 times the maintenance requirement for energy (i.e., 106 kcal ME/kg BW^{0.75}; NRC, 1998). The diets were offered to the pigs at 0800 and 1600 h. Feed allowance was adjusted at the beginning of each period when the BW of each pig was recorded. All pigs were housed in individual pens (1.2 by 1.5 m) and had free access to water through a nipple drinker. The room temperature was $25 \pm 2^\circ\text{C}$ for the duration of the experiment.

Sample Collection

Pigs were fed the experimental diets and weighed at the beginning and end of each period. All pigs were

Table 2. Ingredient and analyzed nutrient composition of experimental diets containing 4 nonstarch polysaccharide sources (Exp. 1; as-fed basis)

Item	Diet ¹				
	Cornstarch	INU	CMC	MCC	SFC
Ingredients, %					
Cornstarch	71.0	66.0	66.0	66.0	66.0
Sucrose	20.0	20.0	20.0	20.0	20.0
INU	—	5.0	—	—	—
CMC	—	—	5.0	—	—
MCC	—	—	—	5.0	—
SFC	—	—	—	—	5.0
Soybean oil	4.0	4.0	4.0	4.0	4.0
Dicalcium phosphate	3.0	3.0	3.0	3.0	3.0
NaCl	0.4	0.4	0.4	0.4	0.4
Magnesium oxide	0.1	0.1	0.1	0.1	0.1
Potassium carbonate	0.4	0.4	0.4	0.4	0.4
Vitamin and mineral premix ²	0.3	0.3	0.3	0.3	0.3
Celite	0.8	0.8	0.8	0.8	0.8
Nutrient composition					
DM, %	90.66	90.80	90.48	90.61	90.45
CP, %	0.22	0.25	0.22	0.29	0.30
Ash, %	3.78	3.82	4.72	4.01	3.89
Carbohydrate, ³ %	82.67	82.97	81.82	82.53	82.58
GE, kcal/kg	3,789	3,776	3,724	3,762	3,771

¹CMC = carboxymethylcellulose sodium; INU = inulin; MCC = microcrystalline cellulose; SFC = Solka-Floc (International Fiber Corporation, North Tonawanda, NY).

²Provided, per kilogram of diet, 8,250 IU vitamin A, 825 IU vitamin D₃, 40 IU vitamin E, 4 mg menadione, 0.2 mg biotin, 600 mg choline chloride, 2 mg folic acid, 35 mg niacin, 15 mg D-pantothenate, 5.0 mg riboflavin, 1.0 mg thiamin, 2.0 mg pyridoxine, 25 µg cobalamine, 50.0 mg Cu as copper sulfate, 50.0 mg I as potassium iodide, 53.3 mg Fe as iron sulfate, 25.0 mg Mn as manganous oxide, 17.3 mg Se as sodium selenite, and 65.0 mg Zn as zinc sulfate.

³Calculated value.

successfully cannulated at the distal ileum. Pigs recovered from surgery without complications. The initial 5 d were considered an adaptation period to the diet. Fecal samples were collected via grab sampling from d 6 to 7 of each period. On d 8 and 10, ileal digesta were collected from 0830 to 1630 h for 8 h (Gao et al., 2015). Fecal and ileal digesta were stored at −20°C. At the conclusion of the experiment, these samples were thawed and combined by pig and diet, and a subsample was collected for chemical analysis. Ileal samples were lyophilized and ground before analysis.

Chemical Analysis

The NSP ingredients, diets, ileal digesta, and fecal samples in Exp. 1 were analyzed for DM (method 930.15; AOAC, 2007), CP (method 990.03; AOAC, 2007), ether extract (EE; method 996.01; AOAC, 2007), and ash (method 942.15; AOAC, 2007). The mixed linked β-glucan content of samples of diets, ileal digesta, and feces in Exp. 2 were determined using a Megazyme mixed-linkage β-glucan assay kit (Megazyme International Ireland Ltd., Bray, Co. Wicklow, Ireland). Total starch content in Exp. 2 was also enzymatically

quantified using a total starch assay kit from Megazyme International Ireland Ltd. Samples of diets, ileal digesta, and feces in Exp. 2 were analyzed for total constituent monosaccharides in total NSP and insoluble NSP using GLC (Englyst and Hudson, 1987), by measuring the neutral sugars in acidic hydrolysates as alditol acetates using gas chromatography and using a colorimetric method for uronic acids using a modification of the Uppsala procedure (Theander et al., 1995). The GLC of constituent sugars were performed on an Agilent 7890A (Agilent Technologies, Inc., Wilmington, DE). A 30-m by 0.25-mm column (Agilent DB-225, film thickness 0.25 µm; Agilent J&W Scientific, Santa Clara, CA) was used. The column and injector temperature was 220°C and the detector temperature was 250°C (Huang et al., 2015). The GE of diets, ileal digesta, and feces was analyzed using bomb calorimetry (Parr 6400 calorimeter; Parr Instrument Co., Moline, IL). Benzoic acid (6,318 kcal GE/kg; Parr Instrument Co.) was used as the standard for calibration. Samples of diets and ileal digesta samples in Exp. 2 were analyzed for AA according to method 982.30 E (a, b, c; AOAC, 2007). Chromic oxide was determined in diets, ileal digesta, and fecal subsamples using of the method of Fenton and Fenton (1979).

Table 3. Ingredient and nutrient composition of experimental diets containing 2 nonstarch polysaccharide (NSP) sources (Exp. 2; as-fed basis)

Item, %	Diet ¹		
	Control	INU	CMC
Ingredients			
Corn	76.58	66.49	66.49
Soybean meal	19.29	21.04	21.04
INU	0.00	5.00	0.00
CMC	0.00	0.00	5.00
Soybean oil	1.10	4.39	4.39
Dicalcium phosphate	1.03	1.08	1.08
Limestone	0.40	0.40	0.40
Salt	0.30	0.30	0.30
Vitamin and mineral premix ²	1.00	1.00	1.00
Cr ₂ O ₃	0.30	0.30	0.30
Analyzed nutrient content			
DM	89.34	90.11	89.28
N	2.44	2.43	2.42
Total carbohydrate	55.96	54.75	52.76
Starch	44.35	43.05	41.82
Araboxylan	3.57	2.85	2.90
Total NSP	10.10	9.04	9.68
Soluble NSP	0.92	0.86	1.54
Insoluble NSP	9.18	8.18	8.13
β-glucan	0.11	0.11	0.19
Cellulose	2.62	2.36	2.92
AA			
Indispensable AA			
Arg	0.90	0.85	0.87
His	0.44	0.42	0.42
Ile	0.54	0.52	0.52
Leu	1.38	1.28	1.31
Lys	0.72	0.69	0.70
Met	0.41	0.37	0.40
Phe	0.73	0.71	0.70
Thr	0.58	0.55	0.56
Val	0.73	0.71	0.71
Sum of indispensable AA	6.43	6.10	6.19
Dispensable AA			
Ala	0.82	0.77	0.77
Asp	1.33	1.31	1.31
Cys	0.48	0.47	0.47
Glu	2.54	2.40	2.42
Gly	0.58	0.57	0.57
Pro	1.93	1.85	1.84
Ser	0.76	0.72	0.75
Tyr	0.82	0.78	0.78
Sum of dispensable AA	9.26	8.87	8.91
Sum of all AA	15.69	14.97	15.10

¹CMC = carboxymethylcellulose sodium; INU = inulin.

²Provided, per kilogram of diet, 8,250 IU vitamin A, 825 IU vitamin D₃, 40 IU vitamin E, 4 mg menadione, 0.2 mg biotin, 600 mg choline chloride, 2 mg folic acid, 35 mg niacin, 15 mg D-pantothenate, 5.0 mg riboflavin, 1.0 mg thiamin, 2.0 mg pyridoxine, 25 µg cobalamine, 50.0 mg Cu as copper sulfate, 50.0 mg I as potassium iodide, 53.3 mg Fe as iron sulfate, 25.0 mg Mn as manganese oxide, 17.3 mg Se as sodium selenite, and 65.0 mg Zn as zinc sulfate.

Calculations and Statistical Analysis

For each dietary treatment, the apparent ileal digestibility (AID) and apparent total tract digestibility (ATTD) of nutrients and energy were calculated using the index method (Stein et al., 2007). The DE value was determined by multiplying the GE by the observed ATTD of GE of the ingredient. Hindgut disappearance was calculated by subtracting values for AID from values for ATTD (Chen et al., 2013).

The concentration of total carbohydrates (CHO) in the diets, ileal digesta, and feces was calculated according to the following equation (Urriola and Stein, 2012): CHO = DM – (CP + EE + ash). The content of cellulose and arabinoxylans (AX) was calculated as cellulose = NSP_{glucose} – β-glucan, NSP glucose, and AX = (arabinose + xylose) × 0.88, respectively (Huang et al., 2015). Insoluble and total NSP contained 5 monosaccharide residues that can be detected in NSP, namely, NSP arabinose, NSP xylose, NSP mannose, NSP glucose, and NSP galactose (Huang et al., 2015).

The UNIVARIATE procedure (SAS Inst. Inc., Cary, NC) was used to confirm the homogeneity of variance and to analyze for outliers. In Exp. 1, all data were analyzed using the MIXED procedure of SAS. The model included diet as a fixed effect and pig and period as random effects. In Exp. 2, all data were analyzed as a double 3 × 3 Latin square design using the MIXED procedure of SAS. The fixed effect of the diet ($n = 3$) and the random effect of the experimental period ($n = 3$) and pig ($n = 6$) were included in the main model. Differences among treatments were determined using ANOVA, and means were separated using the LSMEANS statement and the PDIF option with adjustment for the Tukey–Kramer test. The differences were considered significant if $P < 0.05$ and were considered a trend if the P -value was between 0.05 and 0.10.

RESULTS

Nutrient Composition of Diets Containing a Nonstarch Polysaccharide Source

Pigs consumed their diets without apparent problems throughout the experiment. The CMC diet had the highest ash content and the least content of total CHO and starch compared with the CST, INU, MCC, and SFC diets (Table 1). The starch and GE content was greater in the INU diet than in the CMC, MCC, and SFC diets. The total CHO and GE of the N-free diets in Exp. 1 were similar (Table 2). In Exp. 2, the control diet had higher starch, total NSP, insoluble NSP, and AX contents than the INU and CMC diets (Table 3). The CMC diet had higher soluble NSP, β-glucan, and cellulose contents than the control and

Table 4. Apparent ileal digestibility, apparent total tract digestibility, DE, and hindgut disappearance of nutrients in growing pigs fed the N-free experimental diets containing 4 nonstarch polysaccharide sources for Exp. 1¹

Item	Diet ²					SEM	P-value
	Cornstarch	INU	CMC	MCC	SFC		
Ileal digestibility, %							
DM	85.4 ^a	73.9 ^c	77.9 ^c	82.7 ^b	81.4 ^b	1.2	0.02
Ash	16.0 ^b	15.9 ^b	−2.3 ^c	19.3 ^a	19.9 ^a	2.0	<0.01
Ether extract	89.7 ^a	73.5 ^b	60.0 ^c	87.3 ^a	86.1 ^a	2.6	0.02
Carbohydrate	91.9 ^a	78.8 ^c	88.3 ^b	88.2 ^b	86.9 ^b	1.0	0.01
GE	90.6 ^a	76.2 ^d	80.5 ^c	85.9 ^b	84.4 ^b	1.0	0.03
Total tract digestibility and DE							
DM, %	94.6 ^a	94.3 ^a	87.9 ^c	89.8 ^b	89.8 ^b	0.5	<0.01
Ash, %	39.2 ^b	39.3 ^b	43.4 ^a	39.4 ^b	39.2 ^b	0.5	0.04
Ether extract, %	93.5 ^a	87.3 ^{ab}	65.7 ^c	93.6 ^a	93.9 ^a	2.3	<0.01
Carbohydrate, %	98.4 ^a	98.3 ^a	93.8 ^b	93.3 ^b	93.8 ^b	0.4	<0.01
GE, %	95.7 ^a	95.6 ^a	88.7 ^c	91.7 ^b	91.1 ^b	0.6	<0.01
DE, kcal/kg	4,008 ^a	3,995 ^a	3,666 ^c	3,831 ^b	3,790 ^b	27.0	<0.01
Hindgut disappearance, ³ %							
DM	9.2 ^b	21.2 ^a	10.3 ^b	7.9 ^b	8.3 ^b	1.3	0.02
Ash	22.3 ^b	24.9 ^b	43.8 ^a	19.8 ^b	20.7 ^b	2.1	0.03
Ether extract	4.8 ^b	12.0 ^a	11.1 ^a	8.5 ^{ab}	7.8 ^{ab}	1.0	0.02
Carbohydrate	6.5 ^b	19.8 ^a	5.4 ^b	5.0 ^b	6.7 ^b	1.2	0.02
GE	5.2 ^b	19.4 ^a	8.2 ^b	5.2 ^b	6.4 ^b	0.4	0.01

^{a-d}Means within a row with different superscripts differ ($P < 0.05$).

¹Least squares means of 6 pigs per treatment.

²CMC = carboxymethylcellulose sodium; INU = inulin; MCC = microcrystalline cellulose; SFC = Solka-Floc (International Fiber Corporation, North Tonawanda, NY).

³Hindgut disappearance = apparent total tract digestible nutrient or energy – apparent ileal digestible nutrient or energy.

INU diets. The AA content in the 3 diets were similar (Table 3).

Apparent Nutrient Digestibility of Pigs Fed the N-Free Diets Containing 4 Nonstarch Polysaccharide Sources

The AID of DM, CHO, and GE of the control diet were higher ($P < 0.05$) than that of the other N-free diets (Table 4). The AID of DM, ash, and GE were higher ($P < 0.05$) in the MCC and SFC diets than in the INU and CMC diets. The highest ($P < 0.01$) AID of EE was observed in pigs fed the CON, MCC, and SFC diets, intermediate in pigs fed the INU diet, and least in pigs fed the CMC diet.

The greatest total tract DE was observed in pigs fed the CON diet (4,008 kcal/kg) and the INU diet (3,995 kcal/kg), intermediate in pigs consuming the MCC diet (3,831 kcal/kg) and the SFC diet (3,790 kcal/kg), and least in pigs consuming the CMC diet (3,666 kcal/kg; $P < 0.01$; Table 4). The ATTD of CHO in the CON and INU diets was greater ($P = 0.01$) than in the CMC, MCC, and SFC diets. The ATTD of DM and GE and the DE were greatest in the CON and INU diets, intermediate in the MCC and SFC diets, and least in the CMC diet ($P < 0.01$). Pigs fed the CMC diet had a

greater ATTD of ash (43.4%) than pigs fed the other diets (ranging from 39.2 to 39.4; $P = 0.04$). Pigs fed the CMC diet had less ATTD of EE (65.7%) than pigs fed the other diets (ranging from 87.3 to 93.9; $P < 0.01$).

Hindgut disappearance of DM, CHO, and GE in the INU diet was greater ($P < 0.05$) than in the other N-free diets ($P < 0.05$; Table 4). Pigs fed the CMC diet (43.8%) had a greater hindgut disappearance of ash than pigs fed the other diets (ranging from 19.8 to 24.9%; $P = 0.03$).

Endogenous N and Ileal AA Flow of Pigs Fed the N-Free Diets Containing 4 Nonstarch Polysaccharide Sources

The ileal endogenous flow of N of pigs fed the CMC diet (2,994 mg/kg of DMI) was greater than that of pigs fed the other diets (ranging from 1,651 to 1,793 mg/kg of DMI; $P = 0.02$; Table 5). Among the indispensable AA, the ileal endogenous flow of His, Ile, Leu, Met, Thr, and Val in the CMC diet was greater than in the other diets ($P < 0.05$). Pigs fed the SFC diet (120 mg/kg of DMI) had the least ileal endogenous flow of Leu compared with pigs fed the other diets (ranging from 178 to 317%; $P < 0.01$). The ileal endogenous flow of Met in the INU and SFC diets was less than in

Table 5. Endogenous N and ileal AA flow mg/kg of DMI of growing pigs fed the N-free experimental diets containing 4 nonstarch polysaccharide sources for Exp. 1¹

Item	Diet ²					SEM	P-value
	Cornstarch	INU	CMC	MCC	SFC		
Ileal endogenous flow							
N	1,787 ^b	1,651 ^b	2,994 ^a	1,743 ^b	1,793 ^b	119	0.02
Indispensable AA							
Arg	120	139	120	114	138	6	0.69
His	94 ^b	95 ^b	132 ^a	102 ^b	108 ^b	5	0.04
Ile	177 ^b	191 ^b	247 ^a	179 ^b	173 ^b	8	<0.01
Leu	201 ^b	178 ^b	317 ^a	208 ^b	120 ^c	14	<0.01
Lys	91	72	106	94	91	5	0.47
Met	37 ^b	21 ^c	61 ^a	44 ^b	22 ^c	3	0.02
Phe	267	247	359	281	244	10	0.11
Thr	403 ^b	389 ^b	494 ^a	413 ^b	379 ^b	14.9	0.03
Val	513 ^b	535 ^b	670 ^a	509 ^b	474 ^b	22	0.02
Dispensable AA							
Ala	305 ^b	241 ^b	437 ^a	261 ^b	217 ^b	18	0.02
Asp	374 ^c	344 ^c	656 ^a	489 ^b	343 ^c	25	<0.01
Cys	125 ^b	119 ^b	192 ^a	143 ^b	117 ^b	7	0.01
Glu	598 ^b	547 ^b	841 ^a	625 ^b	476 ^b	29	0.04
Gly	558 ^b	480 ^b	870 ^a	613 ^b	472 ^b	44	0.01
Pro	2,048 ^b	1,488 ^b	5,679 ^a	2,468 ^b	1,645 ^b	336	<0.01
Ser	325 ^b	310 ^b	456 ^a	346 ^b	346 ^b	16	<0.01
Tyr	328 ^b	403 ^b	531 ^a	384 ^b	377 ^b	21	0.04
Total tract endogenous flow							
N	1,316 ^b	1,452 ^b	2,378 ^a	1,483 ^b	1,472 ^b	88	<0.01

^{a-c}Means within a row with different superscripts differ ($P < 0.05$).

¹Least squares means of 6 pigs per treatment.

²CMC = carboxymethylcellulose sodium; INU = inulin; MCC = microcrystalline cellulose; SFC = Solka-Floc (International Fiber Corporation, North Tonawanda, NY).

the CST and MCC diets ($P = 0.02$). The ileal endogenous flow of all dispensable AA in the CMC diet was greater than in the other diets ($P < 0.05$). The total tract endogenous flow of N in the CMC diet (2,378 mg/kg of DMI) was also greater than in the other diets (ranging from 1,316 to 1,483 mg/kg of DMI; $P < 0.01$).

Intestinal AA Digestibility of Pigs Fed the Corn–Soybean Meal Diets Containing 2 Nonstarch Polysaccharide Sources for Exp. 2

Among the indispensable AA, the AID of Arg, His, Ile, Leu, Lys, Phe, Thr, and Val were greater ($P < 0.05$) in the CMC diet than in the control and INU diets (Table 6). There was also a tendency ($P = 0.09$) for the AID of Met to be greater in the CMC diet than in the INU diet. Among the dispensable AA, pigs fed the CMC diet had the greater ($P < 0.05$) AID of Ala, Asp, Cys, Gly, and Ser compared with pigs fed the control and INU diets, but there were no differences in the AID of Glu, Pro, and Tyr among the 3 diets. The AID of all AA was greater ($P < 0.05$) in the CMC diet than in the control and INU diets (Table 6).

Among the indispensable AA, the SID of Arg, His, Ile, Leu, Lys, Phe, Thr and Val were greater ($P < 0.05$) in the CMC diet than in the control and INU diets (Table 7). There were no differences in the SID of Met between the INU and control diets. Among the dispensable AA, pigs fed the CMC diet had the greatest ($P < 0.05$) SID of Ala, Asp, Cys, and Ser compared with pigs fed the control and INU diets. There was also a tendency ($P = 0.08$) for the SID of Gly to be greater in the CMC diet than in the control diet. There were no differences in the SID of Met, Glu, Pro, and Tyr among the 3 diets. The SID of all AA was not affected by the incorporation of 5% INU into the corn–soybean meal diet.

Intestinal Digestibility of Nutrients in Pigs Fed the Corn–Soybean Meal Diets Containing 2 Nonstarch Polysaccharide Sources for Exp. 2

Inclusion of 5% CMC in the diet increased ($P < 0.01$) the AID of starch and β -glucan compared with the INU diet (Table 8). The AID of AX and insoluble NSP were less ($P < 0.01$) for pigs fed the INU and CMC diets than for those fed the control diet. The AID of total

Table 6. Apparent ileal digestibility of AA in growing pigs fed the experimental diets containing 2 nonstarch polysaccharide sources for Exp. 2¹

Item, %	Diet ²			SEM	P-value
	Control	INU	CMC		
Indispensable AA					
Arg	91.9 ^b	92.0 ^b	94.4 ^a	0.5	0.02
His	85.2 ^b	83.4 ^b	89.7 ^a	0.9	<0.01
Ile	77.9 ^b	76.8 ^b	84.4 ^a	1.2	0.01
Leu	83.8 ^b	82.7 ^b	89.6 ^a	1.0	<0.01
Lys	80.7 ^b	81.8 ^b	88.0 ^a	1.1	0.01
Met	86.6	84.9	89.8	1.0	0.09
Phe	82.8 ^b	81.9 ^b	86.7 ^a	0.7	0.01
Thr	71.1 ^b	68.8 ^b	81.4 ^a	1.8	<0.01
Val	72.4 ^b	71.8 ^b	79.4 ^a	1.2	<0.01
Indispensable mean ³	81.4	80.5	87.0	1.3	0.07
Dispensable AA					
Ala	71.9 ^b	67.8 ^b	81.4 ^a	1.9	<0.01
Asp	79.7 ^b	77.3 ^b	87.2 ^a	1.3	<0.01
Cys	75.7 ^b	73.4 ^b	84.4 ^a	1.9	0.01
Glu	86.7	86.1	89.0	0.7	0.10
Gly	56.4 ^b	56.2 ^b	65.3 ^a	2.2	0.04
Pro	66.8	67.3	73.2	2.9	0.37
Ser	79.7 ^b	76.8 ^b	86.7 ^a	1.3	<0.01
Tyr	80.0	78.5	81.8	1.0	0.36
Dispensable mean ⁴	74.6	73.4	81.1	1.9	0.20
All AA ⁵	78.2 ^b	77.2 ^b	84.3 ^a	1.2	0.03

^{a,b}Means within a row with different superscripts differ ($P < 0.05$).

¹Least squares means of 6 pigs per treatment.

²CMC = carboxymethylcellulose sodium; INU = inulin.

³Average apparent ileal digestibility for all indispensable AA.

⁴Average apparent ileal digestibility for all dispensable AA.

⁵Average apparent ileal digestibility for all AA (indispensable and dispensable).

NSP was the least for pigs fed the INU diet (32.5%), intermediate for pigs fed the CMC diet (35.5%), and greatest for pigs fed the control diet (38.6%; $P < 0.01$). Inclusion of 5% INU (6.3%) in the diet reduced ($P < 0.01$) the AID of soluble NSP compared with the control (20.9%) and CMC diets (29.7%).

The addition of 5% CMC to the diet reduced ($P < 0.01$) the ATTD of total NSP, insoluble NSP, soluble NSP, and cellulose compared with the control and INU diets (Table 8). The ATTD of AX tended to be less for pigs fed the control diet than those fed the control and CMC diets ($P = 0.09$), but there was no difference in the ATTD of dietary NSP components between pigs offered the INU diet and pigs offered the control diet.

The greatest ($P < 0.01$) hindgut disappearance of total NSP was observed in pigs fed the INU diet, intermediate in pigs fed the control diet, and least in pigs fed the CMC diet (Table 8). Inclusion of 5% CMC in the diet reduced ($P < 0.01$) the hindgut disappearance

Table 7. Standardized ileal digestibility of AA in growing pigs fed the experimental diets containing 2 nonstarch polysaccharide sources for Exp. 2¹

	Diet ²			SEM	P-value
Item, %	Control	INU	CMC		
Indispensable AA					
Arg	93.8 ^b	93.9 ^b	96.1 ^a	0.5	0.02
His	89.6 ^b	88.0 ^b	93.6 ^a	0.9	<0.01
Ile	82.6 ^b	81.5 ^b	88.7 ^a	1.3	0.02
Leu	86.2 ^b	85.3 ^b	92.1 ^a	1.1	<0.01
Lys	83.2 ^b	84.4 ^b	90.3 ^a	1.2	0.01
Met	89.7	88.4	93.0	1.0	0.10
Phe	88.7 ^b	88.2 ^b	92.6 ^a	0.7	0.01
Thr	80.0 ^b	78.4 ^b	90.2 ^a	1.8	<0.01
Val	85.9 ^b	85.0 ^b	91.7 ^a	1.1	0.01
Indispensable mean ³	86.6 ^b	85.9 ^b	92.0 ^a	0.9	<0.01
Dispensable AA					
Ala	78.0 ^b	74.5 ^b	87.6 ^a	2.0	<0.01
Asp	83.4 ^b	81.1 ^b	90.7 ^a	1.3	<0.01
Cys	81.2 ^b	79.5 ^b	90.0 ^a	2.0	0.01
Glu	89.7	89.4	92.0	0.7	0.13
Gly	76.8	78.1	85.2	2.5	0.08
Pro	93.1	96.3	90.0	3.8	0.80
Ser	86.4 ^b	84.1 ^b	93.2 ^a	1.3	<0.01
Tyr	95.2	94.8	96.9	1.6	0.61
Dispensable mean ⁴	85.5	83.8	90.0	1.9	0.15
All AA ⁵	86.1 ^b	84.9 ^b	91.1 ^a	0.8	<0.01

^{a,b}Means within a row with different superscripts differ ($P < 0.05$).

¹Least squares means of 6 pigs per treatment.

²CMC = carboxymethylcellulose sodium; INU = inulin.

³Average standardized ileal digestibility for all indispensable AA.

⁴Average standardized ileal digestibility for all dispensable AA.

⁵Average standardized ileal digestibility for all AA (indispensable and dispensable).

of soluble, insoluble, and total NSP, β -glucan, and cellulose compared with the control and INU diets.

DISCUSSION

Inulin is a highly fermentable and low viscosity fructan (Yan et al., 2013), whereas CMC is a low-fermentability and high-viscosity carboxymethylcellulose (Hooda et al., 2011). The MCC is a linear polymer of a β -1,4 glycosidic bond, and its degree of polymerization is about 3,000 to 10,000 glucose molecules. The MCC and SFC are low-fermentability and low-viscosity NSP.

The incorporation of 5% NSP from different sources into a CST of growing pigs had differential effect on nutrient and energy digestibility in the present study. The AID of nutrients and energy in the INU diet was less than in the other diets, which agrees with the observation that inclusion of 5% INU in the corn-soybean meal diet reduced the ileal nutrient digestibility (Gao et al., 2015). Dietary INU with low-viscosity increased

Table 8. Apparent ileal digestibility, apparent total tract digestibility, and hindgut disappearance of carbohydrate components in growing pigs fed the experimental diets containing 2 nonstarch polysaccharide (NSP) sources for Exp. 2¹

Item, %	Diet ²			SEM	P-value
	Control	INU	CMC		
Apparent ileal digestibility					
Starch	98.3 ^{ab}	97.1 ^b	99.5 ^a	0.3	<0.01
Arabinoxylan	27.0 ^a	17.1 ^b	18.4 ^b	0.2	<0.01
Total NSP	38.6 ^a	32.5 ^c	35.5 ^b	0.8	<0.01
Soluble NSP	20.9 ^a	6.3 ^b	29.7 ^a	2.7	<0.01
Insoluble NSP	40.4 ^a	35.3 ^b	36.6 ^b	0.8	<0.01
β-glucan	79.2 ^{ab}	75.4 ^b	89.0 ^a	1.7	0.01
Cellulose	36.2	29.4	32.2	1.5	0.13
Apparent total tract digestibility					
Arabinoxylan	51.2	47.1	42.9	1.3	0.09
Total NSP	66.2 ^a	66.0 ^a	57.5 ^b	1.1	<0.01
Soluble NSP	85.4 ^a	82.0 ^a	69.0 ^b	1.9	<0.01
Insoluble NSP	64.2 ^a	64.4 ^a	55.3 ^b	1.2	<0.01
β-glucan	97.8	98.7	98.3	0.2	0.21
Cellulose	60.1 ^a	60.4 ^a	42.1 ^b	2.4	<0.01
Hindgut disappearance ³					
Arabinoxylan	24.2	30.1	24.6	1.5	0.26
Total NSP	27.6 ^b	33.5 ^a	22.0 ^c	1.3	<0.01
Soluble NSP	65.0 ^a	75.7 ^a	39.7 ^b	4.0	<0.01
Insoluble NSP	23.9 ^b	29.1 ^a	18.7 ^c	1.2	<0.01
β-glucan	18.6 ^a	23.3 ^a	9.3 ^b	1.7	<0.01
Cellulose	23.8 ^a	30.4 ^a	9.3 ^b	0.3	<0.01

^{a-c}Means within a row with different superscripts differ ($P < 0.05$).

¹Least squares means of 6 pigs per treatment.

²CMC = carboxymethylcellulose sodium; INU = inulin.

³Hindgut disappearance = apparent total tract digestible nutrient or energy – apparent ileal digestible nutrient or energy.

the digesta passage rate, reduced the time of digestive enzymes binding substrate, and then decreased nutrient digestion (Hooda et al., 2011). In contrast to ileal digestion, the hindgut disappearance of nutrients increased with the inclusion of 5% INU in the N-free diet fed to pigs, because of microbial fermentation of INU in the large intestine (Yan et al., 2013; Gao et al., 2015). Although the INU diet had a low AID of nutrients, the ATTD of nutrients was not affected by the inclusion of 5% INU in the N-free diet because of its high hindgut fermentation. Incorporation of 5% CMC, MCC, and SFC into the CST of growing pigs had low ATTD of DM, CHO, and GE, because there is a low microbial fermentation capacity in the hindgut for these sources.

Starch in the N-free diet is digested by the digestive enzymes secreted by the pancreas in the small intestine to produce glucose, which is subsequently absorbed. The undigested portion is fermented in the large intestine to produce VFA (Singh et al., 2010). The AID of CHO (91.9%) of pigs fed CST in the present study agreed with

reported values for AID of starch, which varies from 83.7 to 100% (Bach Knudsen et al., 1993; Bach Knudsen, 2001; Willamil et al., 2012). The AID and ATTD of EE was not affected by inclusion of 5% SFC, which agrees with the observation that the ATTD of EE in a diet with 5% SFC is not different (Kil et al., 2010).

Endogenous N and AA in the small intestine of pigs are mainly derived from saliva, gastric juice, pancreatic juice, bile, and shedding of intestinal mucosa cells (Souffrant, 2001; Kong et al., 2014). The flow of basal endogenous ileal N reported by 16 studies with pigs (30–100 kg BW) was 1.68 g/kg DM intake (Jansman et al., 2002). The value of basal endogenous ileal flow of N in the N-free diet with 5% INU, MCC, and SFC in the present study ranged from 1.65 to 1.79 g/kg DM intake. However, the inclusion of 5% CMC increased the endogenous ileal flow of N and AA. Addition of low-viscosity cellulose to N-free diets did not improve endogenous AA flow, but inclusion of high-viscosity pectin or CMC increased endogenous AA flow (de Lange et al., 1989; Larsen et al., 1993). High-viscosity dietary fiber can increase endogenous N and AA excretion by stimulating mucin secretion and accelerating the renewal of intestinal mucosal cells (Adedokun et al., 2011). The endogenous ileal flow of Pro and Glu was greater than the flow of the other AA, which is an indication that pigs that consume a N-free diet mobilize muscle protein to supply AA. Glutamine accounted for more than 50% of the total AA, and large quantities of Gln can be metabolized to glutamate plus ammonia, citrulline, and Pro (Rodwell, 1985; Zhang et al., 2000). Therefore, the endogenous Pro flow is very high in the N-free diet, especially the endogenous Pro flow in the CMC N-free diet was greater by 2.8 times than in the CST N-free diet.

The incorporation of 5% INU or CMC into a corn-soybean meal diet of growing pigs had different effects on digestibility of AA in the present study. The AID of N and AA in the CMC diet was greater than in the control and INU diets, which agrees with the observation that the AID of AA in CMC is greater than the AID of AA in high-fermentability, low-viscosity oat β-glucan (Hooda et al., 2011). Dietary CMC with high solubility caused high digesta viscosity (Piel et al., 2005). Increasing digesta viscosity decreases digesta passage rate (Owusu-Asiedu et al., 2006; Renteria-Flores et al., 2008). Reduced digesta passage rate was positively correlated with specific nutrient digestibility (Hooda et al., 2011), because a slow digesta passage rate may lead to more time for enzymatic digestion, thereby improving digestion (Fledderus et al., 2007). This proposed mechanism increased AID of N and AA in pigs fed high-viscosity CMC. In contrast, inclusion of 5% INU did not affect the AID of N and AA because there is a minimum effect by low-viscosity fiber on AA

digestibility (Zhu et al., 2005) as well as on the basal endogenous losses of AA (Leterme et al., 1996).

The inclusion of 5% NSP source into a corn–soybean meal diet of growing pigs had differential effects on the digestibility of the NSP component in the present study. No more than 3% of dietary starch was undigested in the ileum of pigs in the present study, which agrees with published values that ranged from 83.7 to 100% AID of starch (Bach Knudsen et al., 1993; Bach Knudsen, 2001; Willamil et al., 2012). The incorporation of 5% INU or CMC into the corn–soybean meal diet of growing pigs reduced the AID of AX, total NSP, and insoluble NSP, because the natural ingredients containing NSP (e.g., corn and soybean meal) have a higher digestion by the small intestine enzymes than the purified NSP (e.g., INU or CMC). The AID of total NSP ranged from 32.5 to 38.6% in the present study, which is in agreement with the values for AID of dietary fiber in pigs fed high-fiber feed ingredients, which varies from 10 to 62% (Bach Knudsen, 2001). The ATTD of cellulose (60%) in the control and INU diet is close to reported values ranging from 42 to 65% (Urriola et al., 2013). Furthermore, around 33.5% of total NSP disappears in the hindgut as a result of microbial fermentation (Yan et al., 2013; Gao et al., 2015). However, a low hindgut disappearance of NSP in the CMC diet is a result of the limited microbial fermentation capacity of CMC in the large intestine of pigs (Hooda et al., 2011; Gao et al., 2015). Soluble dietary fiber is easier to digest and ferment than insoluble dietary fiber (Urriola and Stein, 2010). The ATTD of soluble NSP, which varied from 69.0 to 85.4%, is greater than the ATTD of insoluble NSP, which varied from 55.3 to 64.4%, in all 3 diets.

In conclusion, the results of the present study indicate that depending on the viscosity and fermentability of the NSP source, the NSP source will have different effects on the nutrient digestibility and hindgut fermentation of growing pigs. Due to the increased ileal endogenous AA flow caused by the inclusion of CMC, it is suggested not to include CMC as synthetic fiber for a N-free diet to determine the SID of AA in experimental diets. Addition of 5% INU into a corn–soybean meal diet reduced digestibility of the NSP component in the ileum and increased hindgut fermentation of total NSP. In contrast, the CMC increased the ileal digestibility of most AA and reduced total tract digestibility and hindgut fermentation of total NSP. Carboxymethylcellulose sodium is not recommended for synthetic fiber in a N-free diet to determine the SID of AA of diets. The differential effects of viscosity and fermentability of dietary NSP source on nutrient digestion and fermentation should, therefore, be considered in the formulation of diets for growing pigs to optimize diet digestibility.

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