Carbohydrate composition and in vitro digestibility of dry matter and nonstarch polysaccharides in corn, sorghum, and wheat and coproducts from these grains[1]

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ABSTRACT: The objectives of this work were to determine carbohydrate composition and in vitro digestibility of DM and nonstarch polysaccharides (NSP) in corn, wheat, and sorghum and coproducts from these grains. In the initial part of this work, the carbohydrate composition of 12 feed ingredients was determined. The 12 ingredients included 3 grains (corn, sorghum, and wheat), 3 coproducts from the dry grind industry (corn distillers dried grains with solubles [DDGS] and 2 sources of sorghum DDGS), 4 coproducts from the wet milling industry (corn gluten meal, corn gluten feed, corn germ meal, and corn bran), and 2 coproducts from the flour milling industry (wheat middlings and wheat bran). Results indicated that grains contained more starch and less NSP compared with grain coproducts. The concentration of soluble NSP was low in all ingredients. Cellulose, arabinoxylans, and other hemicelluloses made up approximately 22, 49, and 29% (DM basis), respectively, of the NSP in corn and corn coproducts and approximately 25, 43, and 32% (DM basis), respectively, of the NSP in sorghum and sorghum DDGS. Cellulose, arabinoxylans, and other hemicelluloses made up approximately 16, 64, and 20% (DM basis), respectively, of the NSP in wheat and wheat coproducts. The concentration of lignin in grains was between 0.8 and 1.8% (DM basis), whereas coproducts contained between 2.2 and 11.5% lignin (DM basis). The in vitro ileal digestibility of NSP was close to zero or negative for all feed ingredients, indicating that pepsin and pancreas enzymes have no effect on in vitro degradation of NSP. A strong negative correlation ($R^2 = 0.97$) between in vitro ileal digestibility of DM and the concentration of NSP in feed ingredients was observed. In vitro total tract digestibility of NSP ranged from 6.5% in corn bran to 57.3% in corn gluten meal. In conclusion, grains and grain coproducts contain mostly insoluble NSP and arabinoxylans make up the majority of the total NSP fraction. The in vitro digestibility of NSP depends on the amount and type of NSP and degree of lignification in the feed ingredient. The NSP composition of grains and grain coproducts plays an important role in determining the extent of fermentation of NSP; therefore, NSP composition influences the energy value of grains and grain coproducts.

Key words: carbohydrates, coproducts, dietary fiber, grain, in vitro digestibility, nonstarch polysaccharides

INTRODUCTION

As a consequence of the rapid growth in global population and the increased use of cereal grains for biofuel production, it has become difficult to economically feed pigs without reducing the amount of grain in the diet. Therefore, less expensive coproducts from grains produced from both the wet milling and dry grind industries often are included in diets fed to pigs. However, most grain coproducts contain more fiber than the parent grain (Bach Knudsen, 1997; NRC, 2012), and fiber in swine diets reduces energy and protein digestibility (Noblet and Le Goff, 2001; Cervantes-Pahm et al., 2014a). Data for the composition of carbohydrates in grain and grain coproducts produced in Europe have been reported (Bach Knudsen, 1997), but for grain coproducts, large differences among ingredients have been reported (Cromwell et al., 2000; Stein

and Shurson, 2009; Anderson et al., 2012). It is, therefore, possible that ingredients produced in the United States are different from ingredients produced in Europe. As a consequence, the first objective of this work was to determine the carbohydrate composition of grains and grain coproducts used as feed ingredients in U.S. swine diets.

An in vitro procedure that simulates the digestive processes of the pig was developed by Boisen and Fernández (1997), and results using this procedure indicate that in vitro ileal and total tract DM and OM digestibility values are well correlated with values obtained using in vivo digestibility methods (Boisen and Fernández, 1997; Noblet and Jaguelin-Peyraud, 2007). However, to our knowledge, in vitro ileal and total tract digestibility of nonstarch polysaccharides (**NSP**) has not been reported. Therefore, the second objective of this work was to determine in vitro ileal and total tract digestibility of DM and NSP in grains and grain coproducts.

MATERIALS AND METHODS

Feed Ingredients

Twelve samples of grains and grain coproducts produced in the United States and typically included in swine diets were obtained. Locally grown corn (yellow dent number 2) from the University of Illinois Feed Mill (Champaign, IL), soft wheat (Siemer Enterprises, Inc., Teutopolis, IL), and red sorghum (milo; Siemer Enterprises, Inc.) were the grain sources. Three sources of distillers dried grains with solubles (**DDGS**) from the dry grind industry were also used. One source of DDGS was from the fermentation of corn (Poet Nutrition, North Manchester, IN) and 2 sources of DDGS were from the fermentation of sorghum obtained from Kansas (White Energy, Russell, KS) and Texas (Levelland Holey Country Ethanol, Levelland, TX), respectively. The amount of solubles added to the dried grain was less for the sample from Texas than for the sample from Kansas. Four corn coproducts from the wet milling industry including corn gluten meal (ADM Alliance Nutrition, Quincy, IL), corn gluten feed (ADM Alliance Nutrition), corn germ meal (ADM Alliance Nutrition), and corn bran (National Corn-to-Ethanol Research Center, Edwardsville, IL) were acquired. Corn gluten meal is a high-protein feed ingredient that is produced when the germ and bran are removed from corn grain and the gluten remains (NRC, 2012). Corn gluten feed is a combination of corn bran, screenings, distiller's solubles, and other leftovers after the separation of corn (Rausch and Belyea, 2006). Corn germ meal is produced when germ is extracted from corn grain and oil is removed from the germ (NRC, 2012). Corn bran is left after separation and can be used as a separate coproduct or added to gluten

feed (Blasi et al., 2001). Wheat middlings (soft wheat; Hal Roberts' Son, Inc., Postville, IA) and wheat bran (soft wheat bran; Siemer Enterprises, Inc.) also were procured. Wheat bran consists of only the bran fraction, which contains the aleurone and pericarp portions of the outer layer of wheat (AAFCO, 2011).

Noncarbohydrate Analysis

All feed ingredients were analyzed in duplicate for DM (method 930.15; Hortwitz and Latimer, 2007) and ash (method 942.05; Hortwitz and Latimer, 2007). The concentration of GE was determined using an adiabatic bomb calorimeter (model 6300; Parr Instruments, Moline, IL). Benzoic acid was the standard for calibration. Crude protein was determined using the combustion procedure (method 990.03; Hortwitz and Latimer, 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 $N \times 6.25$. Acid hydrolyzed ether extract (**AEE**) was determined by acid hydrolysis using 3 N HCl (Sanderson, 1986) followed by crude fat extraction using petroleum ether (method 2003.06; Hortwitz and Latimer, 2007) on a Soxtec 2050 automated analyzer (FOSS North America, Eden Prairie, MN).

Starch and Nonstarch Polysaccharide Analysis

Starch was analyzed using an enzymatic colorimetric method as described by Bach Knudsen (1997). Nonstarch polysaccharides were quantified based on their separate sugar constituents as alditol acetates using gas chromatography for neutral sugars and colorimetry for acidic sugars according to Bach Knudsen (1997). The 12 feed ingredients were analyzed in 3 parallel runs for total NSP (**T-NSP**), insoluble NSP, and noncellulosic polysaccharides (**NCP**). By completing these 3 procedures, it was possible to calculate concentrations of cellulose, soluble NCP (**S-NCP**), and insoluble NCP (**I-NCP**). Klason lignin was determined as the insoluble residue after treatment with 12 M H_2SO_4 (Theander and Åman, 1979; Theander and Westerlund, 1986; Bach Knudsen, 1997). Dietary fiber was calculated as the sum of T-NSP and Klason lignin.

Total Nonstarch Polysaccharide Procedure. Before analysis, the 12 feed ingredients were ground through a 0.5-mm screen and weighed (250 ± 5 mg) into 50-mL tubes. After incubation with a thermostable α-amylase (Enzyme Commission number [**EC**] 3.2.1.1; catalog number E-BLAAM; 53.7 units/mg; Megazyme Int., Bray, Ireland) at 100°C for 1 h and amyloglucosidase (EC 3.2.1.3; catalog number E-AMGDF; 3,260 units/mL; Megazyme Int.) at 60°C for 2 h, starch was removed from ingredients. The soluble NSP (**S-NSP**)

were precipitated by adding 99% ethanol, to give a final concentration of 80% ethanol, while samples were kept in an ice bath for 1 h. Samples then were centrifuged at 2200 × g for 10 min at 21 °C, the supernatant containing the monosaccharides from sugars and starch was removed, and the residues containing the NSP and Klason lignin were washed twice with 85% ethanol and once with acetone and left to dry overnight. The starch-free residues were treated with 5.0 mL of 12 M H_2SO_4 for 1 h at 35°C to swell the cellulose and the NSP then were hydrolyzed to monosaccharides using 30.0 mL of 2 M H_2SO_4 for 1 h at 100°C. The acid hydrolysates were filtered through glass-fritted crucibles and the filtered hydrolysate was collected. The unfiltered residue was dried at 103°C for 20 h and then ashed at 520°C for 3.5 h, and the difference in the 2 weights was used to calculate Klason lignin. An internal standard (allose; 2 mg/L) was added to an aliquot of the hydrolysate and the sugars were reduced to alcohols with potassium borohydride and acetylated to alditol acetate derivatives using 1-methylimidazole to catalyze the reaction (Connors and Pandit, 1978) and quantified using gas–liquid chromatography. The sugars that were quantified using this procedure included rhamnose, fucose, arabinose, xylose, galactose, and glucose. Uronic acids were measured by a colorimetric method as described by Scott (1979).

Insoluble Nonstarch Polysaccharide Procedure. The total NSP procedure was followed with the exception that S-NSP were extracted from the starch-free residue using 40 mL of a 0.2 M phosphate buffer at 100°C for 1 h.

Noncellulosic Polysaccharides Procedure. The procedure described for total NSP determination was followed except that the starch-free residue was directly hydrolyzed to monosaccharides with 2 M H_2SO_4 rather than swelling the cellulose with 12 M H_2SO_4. After acid hydrolysis, the hydrolysates were filtered through filter paper in a plastic funnel; therefore, Klason lignin was not determined. Uronic acids were also not determined in this procedure. All NSP calculations were performed by summarizing the individual sugar constituents in their anhydrous form according to Bach Knudsen (1997).

In Vitro Ileal Digestibility

Using a 2-step in vitro procedure modified after Boisen and Fernández (1997), the in vitro ileal digestibility of DM of the 12 feed ingredients was determined. The incubation times were 75 min for step 1, which represented the digestion processes in the stomach, and 18 h for step 2, which mimicked the digestion processes in the small intestine. Samples were incubated in a heating cabinet at 40°C with constant stirring using 300-mL Erlenmeyer flasks to accommodate the addition of 230 mL of ethanol (99%) to each flask. The final ethanol

concentration was 80%, which was sufficient to precipitate the soluble fiber (Monro, 1993). Samples were left in an ice bath for 1 h before filtration. After determining in vitro DM digestibility, the remaining undigested residue was collected for NSP analysis enabling the calculation of in vitro ileal digestibility of NSP.

In Vitro Total Tract Digestibility

The in vitro total tract digestibility procedure was a 3 step incubation modified after Boisen and Fernández (1997). The first 2 steps of the procedure were identical to the in vitro ileal digestibility procedure, but with 3 exceptions. Ethanol was not added to precipitate the soluble fiber because the Viscozyme enzyme (Sigma-Aldrich, St. Louis, MO) added in the third step will degrade soluble fiber as well (Urriola et al., 2010). In the second step, the incubation time was reduced to 3.5 h and this was followed by a 14.5-h incubation in step 3. No sulfosalicylic acid was added after the second step because samples were further incubated to simulate the large intestine. Following the third step, contents of the flasks were filtered and in vitro total tract digestibility of DM and NSP were determined as previously described.

In Vitro Calculations

The in vitro digestibility of DM was calculated according to Boisen and Fernández (1997) and in vitro digestibility of NSP (%) was calculated using the following equation:

in vitro digestibility of NSP = 1 − (NSP in residue/NSP in ingredient) × 100,

in which NSP in residue and NSP in ingredient were measured in milligrams.

Nonstarch Polysaccharide Analysis of In Vitro Undigested Residues

Undigested residues remaining after in vitro digestion were quantitatively transferred to 50-mL tubes for determination of T-NSP. However, starch was not removed from undigested residues because it was assumed that all starch was removed in the in vitro incubations or otherwise would be considered resistant starch; therefore, the NSP procedure began with acid hydrolysis using 12 M H_2SO_4 to swell the cellulose.

Statistical Analysis

The MIXED procedure of SAS (SAS Inst. Inc., Cary, NC) was used with each feed ingredient as a

Table 1. Analyzed composition of corn and corn coproducts, DM basis[1]

Item, %	Corn	Corn DDGS[2]	Corn gluten meal	Corn gluten feed	Corn germ meal	Corn bran
DM	88.3	90.7	94.2	88.2	92.6	91.6
Ash	1.9	4.8	1.8	6.3	4.3	2.2
GE, kcal/kg	4,320	5,185	5,667	4,708	4,432	4,589
CP	11.9	29.2	66.8	25.8	26.2	9.8
AEE[3]	2.7	10.9	8.0	3.7	2.3	4.9
Starch	62.0	8.6	13.0	11.1	18.7	22.6
S-NCP[4]	2.5	3.4	0.7	5.1	6.6	5.2
Arabinose	0.5	0.9	0.1	1.2	2.3	1.1
Xylose	0.4	0.9	0.1	1.2	1.6	1.5
Mannose	0.1	0.7	0.1	0.7	ND[5]	ND
Galactose	0.4	0.2	0.1	0.3	0.8	0.4
Glucose	0.6	0.3	0.3	1.1	0.7	1.5
Uronic acids	0.4	0.4	0.1	0.5	1.1	0.7
I-NCP[6]	3.8	15.8	1.9	16.3	19.7	26.8
Arabinose	1.2	4.3	0.5	4.7	7.1	7.8
Xylose	1.7	6.2	0.6	7.4	7.5	14.2
Mannose	0.1	1.2	0.2	0.5	0.4	0.4
Galactose	0.4	1.1	0.2	1.4	1.7	2.4
Glucose	ND	1.8	0.2	0.9	0.8	ND
Uronic acids	0.4	1.2	0.2	1.4	2.2	2.0
Cellulose	1.7	5.8	0.9	7.1	8.1	10.1
Total NSP[7]	8.1	25.0	3.6	28.7	34.5	41.8
Klason lignin	0.8	3.9	9.6	2.9	2.2	3.9
Soluble dietary fiber[8]	2.5	3.4	0.7	5.1	6.6	5.2
Insoluble dietary fiber[9]	6.4	25.5	12.4	26.5	30.1	40.6
Dietary fiber[10]	8.9	28.9	13.2	31.6	36.7	45.7

[1]Total rhamnose and fucose in all ingredients ranged from not detected to 0.1% and therefore were excluded from the table.

[2]DDGS = distillers dried grains with solubles.

[3]AEE = acid hydrolyzed ether extract.

[4]S-NCP = soluble noncellulosic polysaccharides.

[5]ND = not detected.

[6]I-NCP = insoluble noncellulosic polysaccharides.

[7]NSP = nonstarch polysaccharides. Total NSP = S-NCP + I-NCP + cellulose.

[8]Soluble dietary fiber = S-NCP.

[9]Insoluble dietary fiber = I-NCP + cellulose + Klason lignin.

[10]Dietary fiber = soluble dietary fiber + insoluble dietary fiber.

fixed variable and replication as a random variable. The REG procedure was used to determine the correlation between the in vitro digestibility of DM and NSP concentration in the 12 feed ingredients. Each feed ingredient was considered the experimental unit.

RESULTS AND DISCUSSION

Concentrations of DM, CP, Ash, and Ether Extract in Ingredients

Dry matter concentrations ranged from 87.5% in sorghum DDGS from Kansas to 94.2% in corn gluten meal (Tables 1 and 2). Ash concentrations ranged from 1.4% in sorghum to 6.9% (DM basis) in wheat bran. The concentration of GE in the 3 cereal grains was 4,212 kcal/kg DM in wheat, 4,320 kcal/kg DM in corn, and 4,337 kcal/kg DM in sorghum, whereas GE in the coproducts ranged from 4,708 kcal/kg DM in corn gluten feed to 5,667 kcal/kg DM in corn gluten meal. Crude protein was 11.9, 9.0, and 12.2% (DM basis) in corn, sorghum, and wheat, respectively, but corn coproducts contained between 9.8 and 66.8% CP (DM basis). The 2 sorghum DDGS samples contained 30.5 and 38.0% CP (DM basis) and wheat middlings and wheat bran contained 18.4 and 17.2% CP (DM basis), respectively. The concentration of AEE ranged between 2.5 and 3.3% (DM basis) in grains and between 2.3 and 10.9% (DM basis) in coproducts. In general, concentrations of GE, DM, and noncarbohydrate nutrients that were analyzed for corn and corn coproducts in this work are in agreement with previously obtained values, with the exception that the corn gluten meal used in this experiment contained 8.0% AEE (DM basis), whereas previously reported values for AEE are

Table 2. Analyzed composition of sorghum and sorghum coproducts and wheat and wheat coproducts, DM basis[1]

Item, %	Sorghum	Sorghum DDGS-KS[2]	Sorghum DDGS-TX[3]	Wheat	Wheat middlings	Wheat bran
DM	89.5	87.5	91.1	92.9	91.6	92.7
Ash	1.4	5.2	3.5	2.2	6.1	6.9
GE, kcal/kg	4,337	5,249	5,208	4,212	4,446	4,312
CP	9.0	30.5	38.0	12.2	18.4	17.2
AEE[4]	3.3	10.0	9.8	2.5	4.9	3.7
Starch	69.0	3.1	2.5	61.8	16.8	16.9
S-NCP[5]	0.4	3.5	4.9	1.9	1.2	3.8
Arabinose	0.1	0.9	0.8	0.6	0.2	0.9
Xylose	ND[6]	1.0	0.9	0.7	0.2	1.8
Mannose	ND	0.5	0.3	0.1	ND	0.1
Galactose	0.1	0.3	0.2	0.2	0.2	0.2
Glucose	ND	0.4	2.2	0.2	0.2	0.6
Uronic acids	0.1	0.3	0.5	ND	0.3	0.2
I-NCP[7]	4.7	14.4	14.6	6.2	22.7	24.3
Arabinose	1.6	3.8	4.5	1.7	7.0	6.8
Xylose	1.3	4.4	5.7	2.9	11.4	12.6
Mannose	0.1	1.1	1.1	0.2	0.3	0.4
Galactose	0.2	0.5	0.6	0.2	0.5	0.6
Glucose	1.0	3.6	1.4	0.9	2.3	2.8
Uronic acids	0.3	1.0	1.3	0.3	1.2	1.1
Cellulose	1.5	6.7	10.2	1.3	6.7	6.4
Total NSP[8]	6.6	24.7	29.8	9.5	30.7	34.5
Klason lignin	1.6	8.2	11.5	1.8	7.3	6.9
Soluble dietary fiber[9]	0.4	3.5	4.9	1.9	1.2	3.8
Insoluble dietary fiber[10]	7.8	29.4	36.3	9.3	36.9	37.6
Dietary fiber[11]	8.3	32.9	41.3	11.2	38.1	41.4

[1]Total rhamnose and fucose in all ingredients ranged from not detected to 0.1% and therefore were excluded from the table.

[2]DDGS-KS = distillers dried grains with solubles from Kansas.

[3]DDGS-TX = distillers dried grains with solubles from Texas.

[4]AEE = acid hydrolyzed ether extract.

[5]S-NCP = soluble noncellulosic polysaccharides.

[6]ND = not detected.

[7]I-NCP = insoluble noncellulosic polysaccharides.

[8]NSP = nonstarch polysaccharides. Total NSP = S-NCP + I-NCP + cellulose.

[9]Soluble dietary fiber = S-NCP.

[10]Insoluble dietary fiber = I-NCP + cellulose + Klason lignin.

[11]Dietary fiber = soluble dietary fiber + insoluble dietary fiber.

much lower (Anderson et al., 2012; NRC, 2012). Also, noncarbohydrate values reported for sorghum, the 2 sources of sorghum DDGS, wheat, and wheat coproducts are in agreement with reported values except that sorghum DDGS from Kansas had a lower concentration of CP and wheat middlings contained more AEE than previously reported (NRC, 2012).

Carbohydrate Concentrations in Ingredients

Starch concentration in sorghum was 69.0% (DM basis) and in agreement with the value reported by Bach Knudsen et al. (1988) but less than the value reported by the NRC (2012). Starch concentration in corn and wheat were 62.0 and 61.8% (DM basis), respectively, which are also less than NRC (2012) values, but the starch concentration in corn was greater than reported by Bach Knudsen (1997). Starch concentration in corn DDGS was 8.6% (DM basis) whereas the 2 sources of sorghum DDGS contained only 3.1 and 2.5% starch (DM basis). The reason for the low concentration of starch in DDGS is that starch is removed through fermentation during the production of ethanol (Rausch and Belyea, 2006). The starch concentration in corn DDGS obtained in this experiment is within the range of values reported by Stein and Shurson (2009) but greater than some other values (Urriola et al., 2010; Anderson et al., 2012), whereas the starch concentration in both sorghum DDGS samples obtained in this experiment is less than the values reported by Sotak et al. (2014). Differences in starch concentrations in DDGS samples demonstrate that the production of ethanol, through fermentation of

starch, is a biological process that does not always run to completion, which makes every batch of DDGS slightly different in composition. Depending on the price of corn and ethanol, it may sometimes be economical for an ethanol plant to shorten the fermentation period, thereby fermenting less starch and producing less ethanol per batch, but plant throughput will be greater due to the shortened fermentation time (Rausch and Belyea, 2006). The other coproducts ranged from 11.1% starch (DM basis) in corn gluten meal to 22.6% starch (DM basis) in corn bran. Starch values for these corn coproducts are in agreement with Anderson et al. (2012) but less than values reported by Bach Knudsen (1997), and the starch concentration in wheat middlings is much less than the value reported by Bach Knudsen (1997). However, Bach Knudsen (1997) analyzed feed ingredients produced in Europe, whereas the coproducts used in this work are from the United States, and it is possible that production processes in the wet milling and flour milling industries are different in the United States compared with Europe, which may result in different compositions of the coproducts from these industries.

Concentrations of S-NCP were small in all samples, ranging from 0.4% in sorghum to 6.6% (DM basis) in corn germ meal. The S-NCP concentrations in corn, corn gluten feed, corn bran, wheat, and wheat bran are in agreement with reported values for European ingredients (Bach Knudsen, 1997; Gdala et al., 1997). However, the concentration of S-NCP in wheat middlings was less than reported values (Bach Knudsen, 1997; Nortey et al., 2008), which may be a result of the variation among sources of wheat middlings that has been reported (Cromwell et al., 2000). Wheat middlings consist of a combination of coproducts from flour milling such as wheat bran, wheat shorts, wheat germ, and wheat flour and variation among sources is due to the amount of different flour milling fractions added (AAFCO, 2011).

The major sugar monomers in S-NCP for the ingredients analyzed in this experiment were arabinose, xylose, and glucose. Xylose and arabinose mainly originate from soluble arabinoxylans, whereas the majority of glucose originates from soluble β-glucans. However, the amount and type of NSP (e.g., arabinoxylan, cellulose, β-glucan, etc.) is only an approximate analysis reflecting the monomeric composition of the entire NSP fraction.

Corn, corn germ meal, corn gluten meal, and wheat contained more S-NCP as a percentage of T-NSP compared with the other ingredients used in this experiment. This indicates that the fiber in these ingredients may have greater DE and ME than fiber in the other ingredients because S-NCP is almost completely fermented by the end of the large intestine (Urriola et al., 2010). This results in increased synthesis of VFA, which are used as an energy source by the

pig, thus providing more DE and ME per kilogram of diet (Urriola et al., 2010; Bach Knudsen, 2011).

Concentrations of I-NCP in corn, sorghum, and wheat were between 3.8 and 6.2% (DM basis), whereas concentrations in coproducts ranged from 1.9% (DM basis) in corn gluten meal to 26.8% (DM basis) in corn bran. The greatest fraction of I-NCP in the grains and grain coproducts analyzed in this experiment consisted of xylose and arabinose. Insoluble xylose and arabinose concentrations ranged from 0.6 and 0.5% (DM basis), respectively, in corn gluten meal to 14.2 and 7.8% (DM basis), respectively, in corn bran. Concentrations of I-NCP were much greater than concentrations of S-NCP for all ingredients. In addition, corn gluten feed, corn bran, sorghum, and wheat middlings all had a large I-NCP:T-NSP ratio, indicating that fermentation of fiber in these ingredients will be relatively low. This is partly a consequence of most I-NCP being linear, making them tightly packed and hydrophobic, which results in a low fermentability by microbes, thus providing less DE and ME per kilogram of diet (Urriola et al., 2013).

Cellulose concentrations in corn, sorghum, wheat, and corn gluten meal were between 0.9 and 1.7% (DM basis), whereas concentrations in all other ingredients ranged from 5.8 to 10.2% (DM basis). For all ingredients, the concentration of cellulose was less than the concentration of arabinoxylans.

Total NSP, which is the sum of S-NCP, I-NCP, and cellulose, ranged from 3.6 to 9.5% (DM basis) in corn gluten meal, corn, sorghum, and wheat, whereas concentrations of T-NSP ranged from 24.7 to 41.8% (DM basis) in all coproducts except corn gluten meal. The NSP composition of the T-NSP fraction was different among grains; however, most coproducts had a NSP composition of the T-NSP fraction that was similar to the composition of the parent grain. The NSP composition of the T-NSP fraction in corn included 48.6% arabinoxylans, 21.6% cellulose, and 29.8% other hemicelluloses (Fig. 1). The monomeric composition of T-NSP in corn was similar to that of corn DDGS, although corn DDGS contains approximately 3 times more T-NSP than corn. The NSP composition of the T-NSP fraction of sorghum included 44.3% arabinoxylans, 22.9% cellulose, and 32.8% other hemicelluloses (Fig. 2). The concentration of sugars from other hemicelluloses, which include mannose, galactose, noncellulosic glucose, and uronic acids, in sorghum and sorghum DDGS was close to the values calculated for corn and corn DDGS. The NSP composition of the T-NSP fraction in sorghum was similar to that in sorghum DDGS, although sorghum DDGS contains approximately 3 times more T-NSP compared with sorghum. The NSP composition of the T-NSP fraction of wheat included 63.0% arabinoxylans, 14.3% cellulose, and 22.8% other hemicelluloses (Fig. 3) and
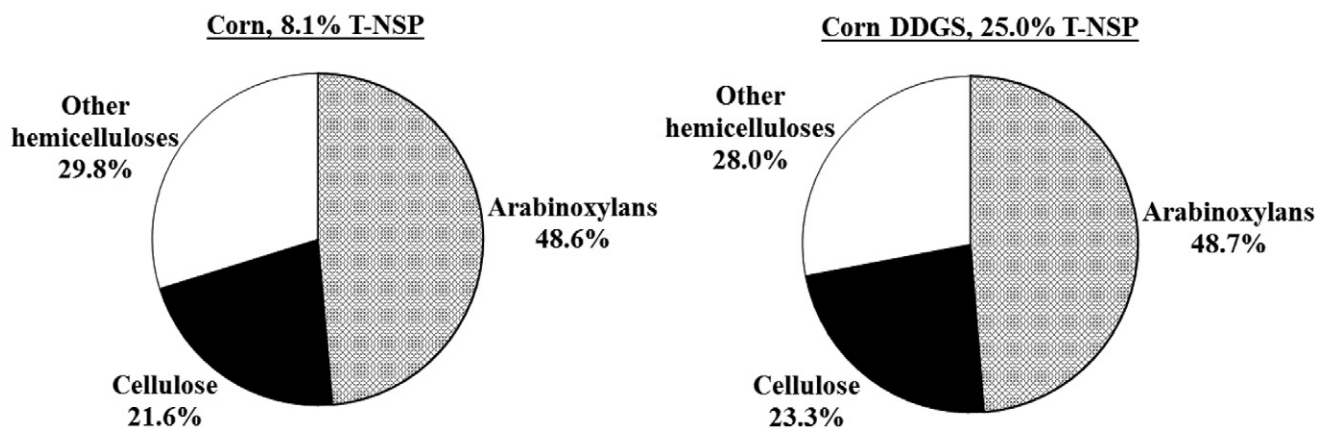
Corn, 8.1% T-NSP

Other hemicelluloses 29.8%

Arabinoxylans 48.6%

Cellulose 21.6%

Corn DDGS, 25.0% T-NSP

Other hemicelluloses 28.0%

Arabinoxylans 48.7%

Cellulose 23.3%

Figure 1. Nonstarch polysaccharide composition in corn and corn distillers dried grains with solubles (DDGS) as a percentage of total nonstarch polysaccharides (T-NSP).

the composition of the NSP fraction in wheat, therefore, was different from that of corn and sorghum. The NSP composition of the T-NSP fraction of wheat was similar to that of wheat bran, although wheat bran contains approximately 3 times more T-NSP compared with wheat.

Combined, these results indicate that the NSP composition of the T-NSP fraction in corn, sorghum, and wheat and their respective coproducts are different but the NSP composition of the T-NSP fraction in the coproducts reflects that of the parent grain. Therefore, it appears that regardless of the processes used to produce the coproducts, the NSP composition of the T-NSP fraction was not altered, which indicates that wet milling, dry grinding followed by fermentation in an ethanol plant, and flour milling does not hydrolyze the NSP in the fiber.

Klason lignin ranged from 0.8% in corn to 11.5% (DM basis) in sorghum DDGS from Texas. The concentration of dietary fiber, which includes T-NSP and Klason lignin, in corn, sorghum, and wheat ranged from 8.3 to 11.2% (DM basis), whereas dietary fiber concentration ranged from 13.2 to 45.7% (DM basis)

in the coproducts. These values are generally in agreement with recently reported values (NRC, 2012).

In summary, pigs fed grains will receive diets greater in starch, whereas pigs fed coproducts will receive diets that are greater in dietary fiber and protein. Pigs receiving high-starch diets will absorb most of their energy as glucose in the small intestine, whereas pigs fed diets containing more fiber absorb more VFA from the hind gut. Because of the reduced efficiency of converting VFA to energy than of converting glucose to energy (Bach Knudsen, 2011), pigs fed diets containing coproducts convert dietary energy to BW gain less efficiently than pigs fed diets based on grain. As a consequence, coproducts provide less ME to the pigs compared with grains, although most coproducts contain more GE than grains (NRC, 2012).

In Vitro Ileal Digestibility

In vitro ileal digestibility of DM ranged from 47.7% in corn bran to 93.5% in corn gluten meal (Table 3). Among the corn coproducts except for corn
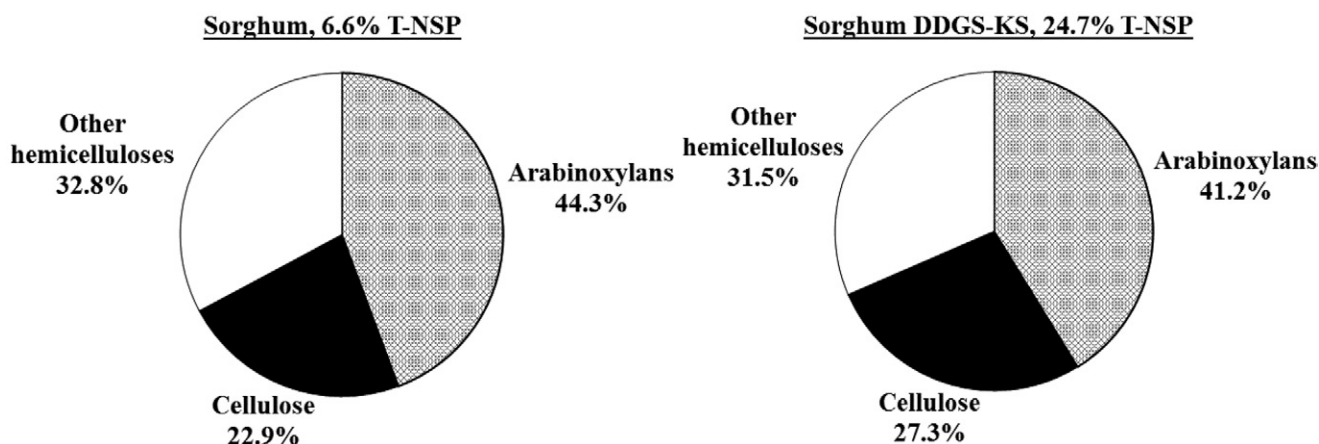
Sorghum, 6.6% T-NSP

Other hemicelluloses 32.8%

Arabinoxylans 44.3%

Cellulose 22.9%

Sorghum DDGS-KS, 24.7% T-NSP

Other hemicelluloses 31.5%

Arabinoxylans 41.2%

Cellulose 27.3%

Figure 2. Nonstarch polysaccharide composition in sorghum and sorghum distillers dried grains with solubles from Kansas (DDGS-KS) as a percentage of total nonstarch polysaccharides (T-NSP).
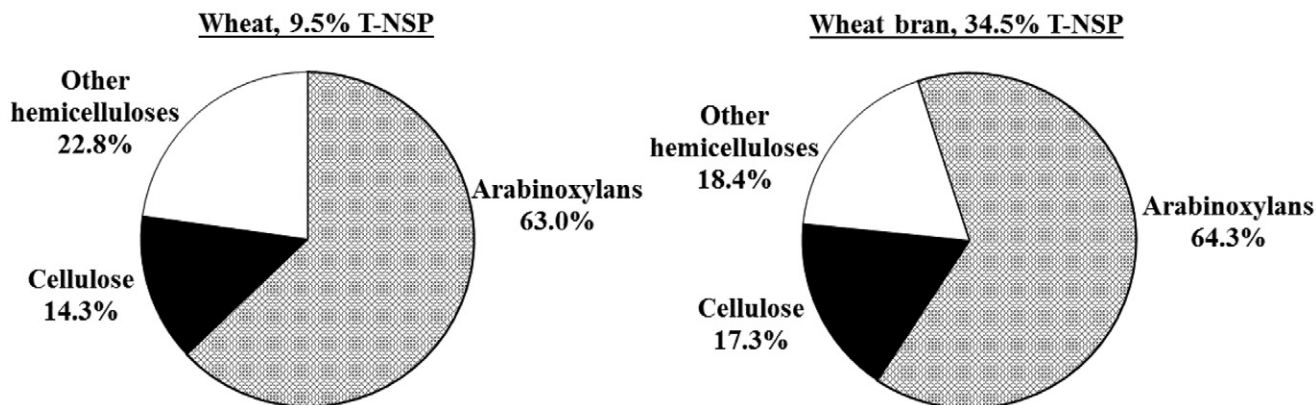
Figure 3. Nonstarch polysaccharide composition in wheat and wheat bran as a percentage of total nonstarch polysaccharides (T-NSP).

gluten meal, in vitro ileal digestibility of DM ranged from 47.7 to 64.7%. Corn DDGS and sorghum DDGS from Kansas had an in vitro ileal digestibility of DM of 64.7 and 65.6%, respectively, whereas sorghum DDGS from Texas had an in vitro ileal digestibility of DM of 57.3%. The difference in DM digestibility among samples is primarily due to differences in concentrations of T-NSP and a strong negative correlation between in vitro ileal digestibility of DM and NSP concentration of ingredients was observed ($R^2 = 0.97$; Fig. 4). This result was expected because the in vitro ileal digestibility procedure enzymatically digests almost all the protein, starch, and lipid from the sample, whereas the fiber fraction, which is primarily NSP, is left undigested. A linear reduction in the apparent ileal digestibility (**AID**) of energy by pigs fed diets containing increasing concentrations of NSP has also been observed (Yin et al., 2000). Because of the close relationship between digestibility of DM and digestibility of energy (Boisen and Fernández, 1997; Noblet and Jaguelin-Peyraud, 2007), it is likely that increased

concentration of NSP also results in reduced concentrations of DE and ME in the ingredient.

For most ingredients, in vitro ileal digestibility of NSP was close to zero (Table 3), which is in line with expectations (Cervantes-Pahm et al., 2014b). However, negative values for the in vitro ileal digestibility of NSP were obtained for some ingredients and this may have been caused by incomplete starch digestion. This was observed in corn DDGS, corn germ meal, corn bran, sorghum and sorghum coproducts, and wheat and wheat coproducts because the in vitro ileal digestibility of glucose was negative, which indicates that some glucose from starch was not completely digested and is considered resistant starch. The concentration of resistant starch in sorghum has been reported to be greater than the concentration of resistant starch in corn, whereas the concentration of resistant starch in wheat is less than in both sorghum and corn (Cervantes-Pahm et al., 2014b). Results from experiments using ileal cannulated pigs fed different breads indicate varying AID of T-NSP depending on ingredients in the bread (Le Gall et al., 2009). Although results obtained with baked products may not

Table 3. In vitro ileal digestibility of DM, sugar monomers, arabinoxylans, and total nonstarch polysaccharides (T-NSP) in grains and grain coproducts

Item, %	Corn	Corn DDGS[1]	Corn gluten meal	Corn gluten feed	Corn germ meal	Corn bran	Sorghum	Sorghum DDGS-KS[2]	Sorghum DDGS-TX[3]	Wheat	Wheat middlings	Wheat bran	SEM
DM	89.4	64.7	93.5	63.7	60.5	47.7	90.1	65.6	57.3	84.9	59.1	49.8	0.9
Arabinose	−14.7	−11.5	13.1	7.7	1.3	−4.8	18.0	−16.0	−20.7	0.7	−12.8	−2.5	4.6
Xylose	−12.8	−10.9	12.9	−1.6	−0.8	−7.2	5.4	−6.2	−21.2	2.2	−18.3	−5.1	4.4
Mannose	−6.3	26.3	46.0	59.9	15.5	19.3	28.0	20.0	18.9	7.1	27.7	11.8	8.2
Galactose	17.0	−3.9	49.5	12.7	17.4	0.7	26.7	20.7	3.5	61.0	19.0	15.4	3.2
Glucose	23.5	−10.7	20.4	7.5	−6.5	−7.8	−63.9	−8.6	−6.5	−9.2	−6.5	−11.3	6.0
Uronic acids	23.5	6.2	15.5	18.6	34.8	28.8	6.8	8.6	3.4	−7.2	1.0	15.5	2.3
Arabinoxylans	−13.7	−11.2	13.0	2.2	0.3	−6.4	12.8	−10.7	−21.0	1.6	−16.2	−4.2	4.4
T-NSP	−18.7	−6.8	22.8	8.3	3.6	−3.5	−5.9	−5.9	−10.4	0.0	−11.3	−5.2	3.7

[1]DDGS = distillers dried grains with solubles.

[2]DDGS-KS = DDGS from Kansas.
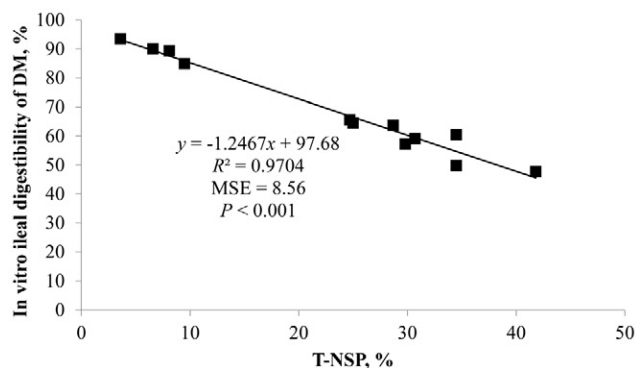
[3]DDGS-TX = DDGS from Texas.

Figure 4. In vitro ileal digestibility of DM versus total nonstarch polysaccharide (T-NSP) concentration of grains and grain coproducts. MSE = mean squared error.

always be representative of data obtained in raw ingredients, results of the present experiment confirm that the AID of T-NSP varies among ingredients. Pigs fed diets containing wheat bran had an AID of T-NSP of approximately 10% compared with the in vitro ileal digestibility of NSP equal to –5.2% for wheat bran in the present experiment (Bach Knudsen, 2001). The reason for the difference between in vivo and in vitro ileal digestibility of NSP may that approximately 20% of ingested NSP is fermented in the stomach and small intestine of pigs and this cannot be simulated in vitro without the use of microbial inoculum (Bach Knudsen, 2001).

In Vitro Total Tract Digestibility

Among corn and corn coproducts, in vitro total tract digestibility of DM ranged from 50.4% in corn bran to 94.3% in corn gluten meal (Table 4) and for sorghum and sorghum coproducts and in vitro total tract digestibility of DM ranged from 59.3% in sorghum DDGS from Texas to 91.6% in sorghum, whereas sorghum DDGS from Kansas had an in vitro total tract digest-

ibility of DM of 71.4%. The range for in vitro total tract digestibility of DM for wheat and wheat coproducts was from 63.6% in wheat bran to 92.2% in wheat. The apparent total tract digestibility (**ATTD**) of OM in corn by pigs is 92 to 93% (Cervantes-Pahm et al., 2014b) and the current data for in vitro digestibility of DM are in agreement with these values. The relationship (R^2 = 0.83) between in vitro total tract digestibility of DM and the concentration of NSP in ingredients was less than the relationship between in vitro ileal digestibility of DM and the concentration of NSP in the ingredients (Fig. 5). This discrepancy is likely occurring because the in vitro total tract digestibility procedure includes the use of a NSP-degrading enzyme (Viscozyme), and therefore, NSP were digested in this step.

In vitro total tract digestibility of NSP in corn, sorghum, and wheat were 33.6, 12.9, and 44.9%, respectively (Table 4). Pigs fed diets based on corn, wheat, or sorghum had an ATTD of total dietary fiber (**TDF**) of 65.0, 76.0, or 62.0%, respectively (Cervantes-Pahm et al., 2014b). The differences between the in vivo study and the present in vitro experiment may be attributed to the use of a NSP-degrading enzyme cocktail (Viscozyme) in the in vitro total tract digestibility procedure, whereas the pig has a diverse microflora that provides a broader spectrum and greater fermentability for the degradation of NSP.

In vitro total tract digestibility of NSP in corn DDGS was 32.7%, which is similar to in vitro total tract digestibility of TDF in 8 corn DDGS samples (Urriola, 2010). The in vitro total tract digestibility of NSP in sorghum DDGS from Kansas was 26.9%, which is in agreement with the in vitro total tract digestibility of TDF of 29.8% in sorghum DDGS reported by Urriola (2010).

In vitro total tract digestibility of arabinoxylans in corn germ meal and wheat was 53.0 and 46.2%,

Table 4. In vitro total tract digestibility of DM, sugar monomers, arabinoxylans, and total nonstarch polysaccharides (T-NSP) in grains and grain coproducts

Item, %	Corn	Corn DDGS[1]	Corn gluten meal	Corn gluten feed	Corn germ meal	Corn bran	Sorghum	Sorghum DDGS-KS[2]	Sorghum DDGS-TX[3]	Wheat	Wheat middlings	Wheat bran	SEM
DM	93.0	75.2	94.3	72.2	79.5	50.4	91.6	71.4	59.3	92.2	67.0	63.6	0.3
Arabinose	39.1	32.1	11.4	12.4	58.4	8.9	37.7	26.9	–4.1	54.7	0.1	25.0	7.4
Xylose	12.0	15.2	56.3	1.9	47.5	1.6	12.8	20.1	–10.7	40.6	12.6	20.9	1.8
Mannose	48.8	84.9	78.5	85.4	68.5	54.2	36.1	64.0	44.0	93.7	69.8	52.7	7.4
Galactose	65.9	31.7	65.8	22.8	72.7	11.6	41.1	50.7	27.2	77.9	41.1	37.5	2.6
Glucose	28.4	35.1	71.1	30.5	50.0	6.4	–28.0	23.6	13.3	33.3	21.6	16.9	5.5
Uronic acids	55.8	38.6	70.3	41.8	69.1	17.1	3.2	24.9	27.4	6.4	16.3	7.0	1.8
Arabinoxylans	24.2	22.2	35.6	6.2	53.0	4.2	27.4	23.2	–7.7	46.2	7.8	22.3	4.0
T-NSP	33.6	32.7	57.3	20.1	55.0	6.5	12.9	26.9	7.1	44.9	13.6	20.6	2.8

[1]DDGS = distillers dried grains with solubles.

[2]DDGS-KS = DDGS from Kansas.
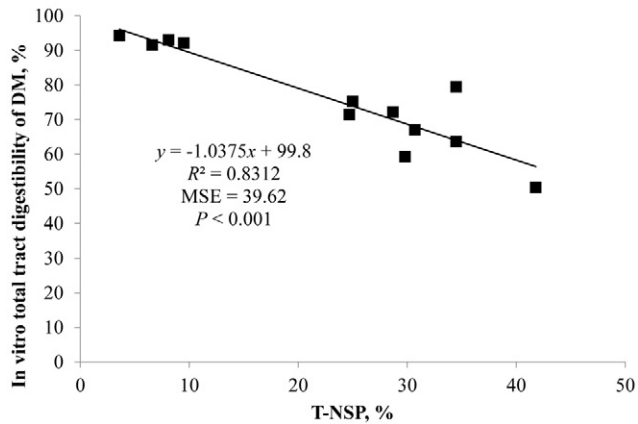
[3]DDGS-TX = DDGS from Texas.

Figure 5. In vitro total tract digestibility of DM versus total non-starch polysaccharide (T-NSP) concentration of grains and grain coproducts. MSE = mean squared error.

respectively, indicating that arabinoxylans in these ingredients may be partly digested in vitro through the use of a NSP-degrading enzyme cocktail (Viscozyme). However, in vitro total tract digestibility of arabinoxylans reported in this work are less than the ATTD of arabinoxylans in wheat breads fed to pigs (Le Gall et al., 2009), but it is possible that the ATTD determined by Le Gall et al. (2009) was improved by the processing that had taken place to bake the bread. Corn bran, corn gluten feed, and wheat middlings had very low in vitro total tract digestibility of arabinoxylans, which is in agreement with data indicating that total tract disappearance of arabinoxylans is –1.0% in pigs fed a diet containing the pericarp/testa fraction of rye (Glitsø et al., 1998). Corn germ meal and wheat middlings had the same concentration of arabinoxylans, but the difference in in vitro total tract digestibility of arabinoxylans between the 2 ingredients indicates that the structure (e.g., crystallinity, amount of cross-linking, number of side chains) of arabinoxylans in the 2 ingredients is different and that arabinoxylans in corn germ meal may be more accessible to NSP-degrading enzymes compared with wheat middlings.

Conclusion

Results of this experiment demonstrate the wide range of carbohydrate composition in feed ingredients used in U.S. swine diets. In grains, the predominant carbohydrate is starch, whereas the predominant carbohydrate in grain coproducts is NSP. Based on these results, it is suggested that exogenous enzymes that can hydrolyze arabinoxylans may be the most effective because the largest part of the NSP in corn and corn coproducts, sorghum and sorghum DDGS, and wheat and wheat coproducts is arabinoxylans. In vitro ileal and total tract digestibility of DM had a strong correla-tion with the concentration of NSP in the ingredients, which indicates that energy digestibility will be reduced if pigs are fed diets high in NSP. However, in vitro NSP degradation varied among ingredients and in vitro total tract disappearance of NSP was greatest in ingredients with the greatest concentration of S-NSP, which indicates that the composition of the NSP fraction in each ingredient plays an important role in determining the extent of fermentation of NSP. As a consequence, the composition of the NSP fraction is also expected to influence the energy value of the ingredient.

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