INFLUENCE OF PHYSICOCHEMICAL CHARACTERISTICS AND INCLUSION RATE OF FIBER-RICH INGREDIENTS ON UTILIZATION OF DIETARY FIBER AND ENERGY BY GROWING PIGS

BY

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DISSERTATION

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ABSTRACT: Five experiments were conducted to investigate the influence of physicochemical characteristics of fiber and inclusion rate of high-fiber ingredients on the utilization of dietary fiber, energy, and nutrients in diets fed to pigs. Experiment 1 was conducted to quantify nutrient and fiber fractions of feed ingredients and to determine *in vitro* apparent ileal digestibility (IVAID) and *in vitro* apparent total tract digestibility (IVATTD) of DM and OM in each ingredient. Ten ingredients that vary in fiber concentration and composition were used: corn, wheat, soybean meal (SBM), canola meal, distillers dried grains with solubles (DDGS), corn germ meal, copra expellers, sugar beet pulp (SBP), synthetic cellulose, and pectin. Correlations between chemical and physical characteristics of ingredients and IVAID and IVATTD of DM and OM were determined. The physical characteristics measured included bulk density, water binding capacity (WBC), swelling, and viscosity. The analyzed GE was compared with values for GE calculated from all energy-contributing components. Results indicated that the analyzed chemical composition of most ingredients added to 100% or greater, and the difference between the sum of the calculated GE of the analyzed components and the analyzed GE of the ingredients ranged from -2.25 MJ/kg in DDGS to 1.74 MJ/kg in pectin. No correlation was observed between swelling, WBC, or viscosity and IVAID or IVATTD of DM or OM. The stronger correlations between insoluble dietary fiber (IDF), total dietary fiber (TDF), and insoluble non-starch polysaccharides and IVAID and IVATTD of DM and OM than between ADF and NDF and IVAID and IVATTD of DM and OM indicates that the concentration of TDF in feed ingredients is a better predictor of the digestibility of DM and OM than values for NDF and ADF. Experiment 2 evaluated effects of physicochemical characteristics of feed ingredients used in Exp. 1 on DE and ME and apparent total tract digestibility (ATTD) of GE, DM, and nutrients in growing pigs using ingredients with different IDF to soluble dietary fiber ratios. Results

indicated that stronger correlations between TDF and DE and ME than between ADF or NDF and DE and ME were observed, indicating that TDF can be used to more accurately predict DE and ME than values for NDF or ADF. The DE, ME, and the ATTD of DM in ingredients were positively correlated ($P < 0.05$) with *in vitro* ATTD of DM generated in Exp. 1, indicating that the *in vitro* procedure may be used to estimate DE and ME in feed ingredients. Swelling and WBC were positively correlated ($P < 0.05$) with the ATTD of IDF, TDF, non-starch polysaccharides (NSP), and insoluble NSP, and viscosity was positively correlated ($P < 0.05$) with the ATTD of NDF, IDF, and insoluble NSP, indicating that some physical characteristics may influence digestibility of fiber but no correlations between physical characteristics and DE or ME were observed. Experiment 3 was conducted to determine the effects of inclusion rate on apparent ileal digestibility (AID), apparent hindgut disappearance (AHD), and ATTD of GE and on the concentration of DE and ME in fiber-rich ingredients fed to growing pigs. We hypothesized 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. A basal diet based on corn and SBM was formulated. 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, SBP, 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 at the expense of corn and SBM. Results indicated that inclusion rate did not affect the calculated DE and ME or AID, AHD, and ATTD of GE in canola meal, corn germ meal, SBP, or wheat middlings, indicating that concentration of DE and ME in ingredients were 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. In Exp 4 and 5, it was determined if values for AID, AHD, and ATTD of DM and nutrients in the high-fiber ingredients used in Exp. 3 measured at 15% inclusion are also accurate if 30% of that ingredient is used in diets fed to pigs. The hypothesis that much of the IDF is not fermented by the pig was also tested. Results indicated that AID, AHD, and ATTD of most nutrients measured at 15% inclusion were not different from values measured at 30% inclusion of the ingredients. The ATTD of IDF ranged from 52.9% in WM included at 15% to 86.2% in SBP included at 30% in the diet, which indicates that there was a relatively high digestibility of IDF under the conditions of this experiment. There was a reduction ($P < 0.05$) in AID of CP and all AA except Arg in canola meal and a reduction ($P < 0.05$) in AID of CP, Lys, Asp, Pro, and Ser in corn germ meal as inclusion rates of these ingredients increased in the diet. However, inclusion rate had no effect on the AID of CP and AA in sugar beet pulp or wheat middlings. In conclusion, DE and ME in feed ingredients may be predicted from some chemical constituents and from *in vitro* digestibility of DM, but not from physical characteristics. Inclusion rate of fiber-rich ingredients in diets did not affect calculated values for DE and ME in feed ingredients, but the AID, AHD, and ATTD of some nutrients and AID of AA measured at 30% inclusion is different from values obtained at 15% inclusion for some high fiber dietary ingredients in mixed diets.

Key words: digestibility, energy, dietary fiber, inclusion rate, physical characteristics, pigs

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CHAPTER 1: INTRODUCTION

Feeding pigs a traditional corn-soybean meal diet has become expensive, and a more complex diet often is fed to take advantage of less expensive feed ingredients. Most of these low-cost feed ingredients are co-products from the dry grind, wet-milling, or dry-milling industries. However, these co-products contain a larger proportion of dietary fiber (Bach Knudsen, 1997). The pig lacks digestive enzymes capable of digesting dietary fiber and, therefore, dietary fiber must be fermented by the pig to obtain energy (Jha and Berrocoso, 2015). Traditional conjecture dictates that dietary fiber is not utilized anterior to the cecum (Yen, 2001), but recent studies indicate a significant amount of dietary fiber is fermented in the upper gut (Jaworski and Stein, 2017). Products of the fermentation of dietary fiber are not as efficient an energy source as is starch, which is typically supplied by feeding pigs diets containing corn or other cereal grains. However, dietary fiber may reduce the digestibility of nutrients and energy supplied by other feed ingredients included in the diet and it is speculated that physical characteristics of fiber, such as bulk density, water binding capacity, swelling, and viscosity, may explain these negative effects (Urriola et al., 2013). A reduction in growth performance and efficiency may be the result of using high-fiber ingredients if adverse effects of fiber inclusion on digestibility are not taken into consideration in diet formulation. Furthermore, the metabolic and physiological effects of fiber vary among different sources of fiber and their intrinsic chemical and physical properties (Guillon and Champ, 2000). It is, therefore, important to characterize and quantify the fiber fractions in individual feed ingredients to have a better understanding of their properties when included in mixed diets. Knowledge of the fermentative energetic value of fibrous feed ingredients and the negative effects of dietary fiber on digestion of nutrients and energy supplied by other feed ingredients in the mixed diet will make it possible to formulate an adequate diet to

maintain growth performance. This may be accomplished by determining the mechanisms by which measurable physical and chemical characteristics of fiber components of feed ingredients influence the ability of pigs to obtain energy from the ingredients. Therefore, diet costs, which account for approximately 70% of the cost of producing pork (NRC, 2012), may be reduced as a result of the ability to include less expensive fibrous co-products while maintaining pig performance.

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CHAPTER 2: CHARACTERISTICS, UTILIZATION, AND FUNCTION OF CARBOHYDRATES IN PIGS: REVIEW OF LITERATURE

INTRODUCTION

Carbohydrates, which are made up of carbon, hydrogen, and oxygen, are organic compounds that serve as a source of energy for animals and humans (Bach Knudsen et al., 2013). The main monosaccharide is glucose, which is utilized as an energy source in animal tissue. Glucose can be derived from starch and sugars in the diet, from glycogen that is stored in the body, or synthesized from the carbon skeleton of AA, lactate, glycerol, or propionate via gluconeogenesis (Slavin, 2013b). The brain preferentially uses glucose as its main source of energy, and glucose is the required energy source for red blood cells and other cells with few or no mitochondria (Ferrier, 2014).

The fate of carbohydrates in the body of an animal is determined by the monomeric composition, the types of linkages among monomers, and the degree of polymerization (**DP**; Bach Knudsen et al., 2013). Digestible carbohydrates include monosaccharides, disaccharides, starch, and glycogen that may be digested by endogenous enzymes, and the resulting monosaccharides are absorbed in the small intestine. Glycosidic linkages within disaccharides, starch, and glycogen may be hydrolyzed by endogenous enzymes in the gastrointestinal tract, resulting in the release of their constituent monosaccharides. However, these enzymes show high specificity to their target sugar units, which consequently results in only a limited number of carbohydrates in the feed that can be digested by the animal (Slavin, 2013b). Non-digestible carbohydrates that reach the large intestine may be digested by microbial enzymes because intestinal microorganisms secrete glycoside hydrolases and polysaccharide lyases that humans and pigs do not express (Aimutis and Polzin, 2011).

Non-digestible carbohydrates include oligosaccharides, resistant starch, and non-starch polysaccharides and are collectively known as fiber (Bach Knudsen et al., 2013). The large differences in the physical properties of carbohydrates make it difficult to analyze fiber and non-digestible carbohydrates (Paeschke and Aimutis, 2011). Dietary fiber may be divided according to solubility. Soluble dietary fiber (**SDF**) may be partially or completely fermented by the microbiota in the large intestine (Slavin, 2013b), producing short-chain fatty acids (**SCFA**), which include acetate, propionate, and butyrate (Mateos-Aparicio et al., 2013). Insoluble dietary fiber (**IDF**) may also be fermented, but to a lesser extent than SDF (Urriola et al., 2010). Fermentation of dietary fiber is a major source of energy in ruminants and hindgut fermenters, but only to a lesser extent in pigs and poultry (Fuller, 2004). The relationship between the host and the gut microbiota is symbiotic. As microorganisms ferment non-digestible carbohydrates, endogenous mucosal secretions, and exfoliated epithelial cells to utilize the carbon and N to sustain themselves, SCFA and lactate are produced and absorbed by the animal (Aimutis and Polzin, 2011). The preferred energy source of intestinal microbiota is carbohydrates, but microbes also ferment protein in the absence of carbohydrates, producing branched-chain fatty acids and toxic nitrogenous metabolites such as amines, ammonia, skatole, and indoles (Ouwehand et al., 2005; Qaisrani et al., 2014).

DEFINITION OF CARBOHYDRATES

Classification according to molecular size or DP groups carbohydrates into monosaccharides, disaccharides, oligosaccharides, and polysaccharides (Bach Knudsen et al., 2013). Monosaccharides are chiral, polyhydroxylated aldoses or ketoses that cannot be hydrolyzed into smaller carbohydrate units (BeMiller, 2014). They can be classified according to

the number of carbon atoms in their structure, which range from 3 to 9 carbon atoms (i.e., triose, tetrose, pentose, hexose, heptose, octose, and nonose), by the type of carbonyl group they contain (i.e., aldose or ketose), and by their stereochemistry (i.e., D or L), and they have the general chemical formula $(CH_2O)_n$ (Vaclavik and Christian, 2014). Aldoses are referred to as reducing sugars because of their reducing effect on certain ions or compounds, oxidizing their aldehyde group to a carbonyl group (BeMiller, 2014). The simplest aldose sugar with a chiral atom is glyceraldehyde, with its second C molecule attached to 4 different groups, giving the ability for this C to have 2 spatial configurations and, thus, exist in both the D- and the L- forms (Slavin, 2013b). Chiral carbon atoms have each of their 4 tetrahedral bonds connected to a different group (BeMiller, 2007e). The chirality of sugars and AA are commonly designated by the D/L system and is named in relation to the structure of glyceraldehyde (Slavin, 2013b).

Monosaccharides

The most common monosaccharides are the 6-C aldohexoses, which include the aldohexose D-glucose, and are typically in their ring structures called a pyranose ring rather than in open-chain structures (Figure 2.1; BeMiller, 2014). In oligo- and polysaccharides, aldopentoses can occur as a 5-C ring structure known as a furanose ring (BeMiller, 2014). D-Glucose, considering all of its combined forms, is the most abundant monosaccharide that naturally occurs in nature (BeMiller, 2007e). The most abundant ketose is D-arabino-hexulose, known more commonly by its trivial name, D-fructose (Slavin, 2013b). Glucose, fructose, and many other sugars exist in their cyclic forms because they are more stable compared with their acyclic open-chain structures (Slavin, 2013b). The 3 trioses include ketose dihydroxyacetone and both enantiomeric forms of glyceraldehyde (Sinnott, 2013a). Erythrose and threose are examples of tetroses, while pentoses include ribose, arabinose, xylose, and lyxose (Slavin, 2013b).

Sugars, such as glucose, galactose, mannose, and fructose, which have different structures but have the same chemical formula, $C_6H_{12}O_6$, are called isomers (Ferrier, 2014). Sugars that differ only in configuration around only one carbon atom are called epimers, such as D-glucose and D-mannose, which vary in their structures around C-2 (Slavin, 2013b). A pair of enantiomers is a special type of isomerism where the 2 members of the pair are mirror images of each other and are designated as being in the D- or L- structure (i.e., D-glucose or L-glucose), depending on the position of the –OH group linked to the asymmetric carbon farthest from the carbonyl group (Ferrier, 2014).

Other types of monosaccharides include alditols, or polyols, are aldoses and ketoses that had their carbonyl groups reduced to an alcohol (BeMiller, 2007b). Examples of naturally occuring alditols in plants and other organisms include D-glucitol, known commonly as sorbitol, and xylitol (Slavin, 2013b). D-Xylose hydrogenation yields xylitol and is obtained in the hydrolysis of hemicelluloses, whereas sorbitol (D-glucitol) is the product of the reduction of D-glucose (BeMiller, 2007b). Absorption and metabolism of polyols vary among types, but most are fermented in the large intestine (Englyst et al., 2007).

Deoxy sugars are missing one or more hydroxyl groups attached to their carbon atoms, such as 6-deoxy-L-mannose (L-rhamnose), which is commonly associated with pectin, 2-deoxy-D-ribose, the sugar component of DNA, and 6-deoxy-L-galactose (L-fucose), a component of glycoproteins and glycolipids in cell walls and mammalian cells (BeMiller, 2007e; Slavin, 2013b, Nguema-Ona et al., 2014).

The common amino sugars include 2-amino-2-deoxy-D-glucose (D-glucosamine) and 2-amino-2-deoxy-D-galactose (D-galactosamine) that have the hydroxyl group attached to C-2 replaced with an amino group and are constituents of glycosaminoglycans and glycoproteins

(Slavin, 2013b). Uronic acids are sugar acids in which the terminal –CH_2OH group undergoes oxidation to yield a carboxylic acid (Sinnott, 2013a). Uronic acids that contribute to dietary fiber include constituents of nondigestible polysaccharides of plants and algae, such as D-glucuronic acid, D-galacturonic acid, D-mannuronic acid, and L-guluronic acids (Slavin, 2013b). Sugar from the activated form of glucuronic acid is used in the synthesis of glycosaminoglycans in mammals, and L-iduronic acid is synthesized from D-glucuronic acid after it has been incorporated into the carbohydrate chain (Ferrier, 2014).

Disaccharides

Two monosaccharide units joined together by an acetal or ketal linkage is referred to as a disaccharide (Sinnott, 2013a). A glycosidic bond joins 2 monosaccharide units and it can either be an α-glycosidic bond if the anomeric hydroxyl group of the sugar is in the α configuration or a β-glycosidic bond if it is in the β configuration (Ferrier, 2014). A glycosidic bond is named according to the position of the carbon atom being linked, for example, an α-glycosidic bond connecting C-1of a glucose molecule and C-4 of another glucose molecule in maltose is called an α-(1,4) glycosidic bond (Figure 2.2; NRC, 2012). The 3 most common disaccharides are maltose, lactose, and sucrose (BeMiller, 2014). Maltose is a reducing sugar that is a product of the hydrolysis of starch by the enzyme α-amylase (BeMiller, 2007f). Lactose is a reducing sugar that consists of a D-glucosyl unit and an α-D-galactopyranosyl unit linked by a β-(1,4) glycosidic bond and is present in milk and milk products such as skim milk and whey (NRC, 2012). Sucrose is made up of a glucose and a fructose linked by an α-(1,2) glycosidic bond (NRC, 2012). Contrary to the general head-to-tail linkage (anomeric carbon atom to carbon atom containing a hydroxyl group) in the structure of oligo- and polysaccharides, in sucrose the glycosidic bond linking an α-D-glucopyranosyl unit and a β-D-fructofuranosyl unit is in a head-

to-head fashion (anomeric carbon atom to anomeric carbon atom) making it a nonreducing sugar (BeMiller, 2007f). Sucrose is synthesized through the process of photosynthesis to provide energy and carbon atoms for the synthesis of other compounds in the plant (BeMiller, 2007e).

Maltose, lactose, and sucrose are hydrolyzed into their constituent monosaccharide units by the enzymes maltase, lactase, and sucrase, respectively (NRC, 2012). The α-glucosidases maltase-glucoamylase and sucrase-isomaltase complexes that are present in the brush border of the small intestine cleave the glycosidic bonds in maltose and sucrose, respectively, with most of the maltase activity also coming from the sucrase-isomaltase complex (BeMiller, 2007f; NRC, 2012; Slavin, 2013b). The monosaccharides that result from the digestion of these disaccharides are readily absorbed in the small intestine (Leturque and Brot-Laroche, 2013). Lactase, a β-galactosidase, also is expressed by young mammals that digest lactose into its constituent monosaccharides that are subsequently absorbed in the small intestine (BeMiller, 2007f; Bach Knudsen et al., 2013).

Other disaccharides that are present in nature include trehalose, cellobiose, and gentiobiose (NRC, 2012). Trehalose is a nonreducing disaccharide made up of 2 α-D-glucopyranosyl units linked together by an α-(1,1) glycosidic bond (Slavin, 2013b). Trehalose is found in small amounts in mushrooms, yeasts, honey, certain seaweeds, and invertebrates such as insects, shrimps, and lobsters (BeMiller, 2007f). Trehalose is digested by the α-glucosidase enzyme trehalase, which is expressed in the small intestine (Slavin, 2013b). Two glucose molecules are linked together by a β-(1,4) and a β-(1,6) glycosidic bonds to form cellobiose and gentiobiose, respectively, and these disaccharides can be utilized only after microbial fermentation because pigs lack the enzymes capable of digesting them (NRC, 2012). Cellobiose

is a product of cellulose degradation, whereas gentiobiose is suggested to play a role in the initiation of ripening of tomato fruits (Dumville and Fry, 2003).

Oligosaccharides

Oligosaccharides consist of galacto-oligosaccharides, fructo-oligosaccharides, and mannan-oligosaccharides that cannot be digested by pancreatic or intestinal enzymes, but are soluble in 80% ethanol (Roberfroid and Slavin, 2000; Englyst et al., 2007). Galacto-oligosaccharides, or α-galactosides, that are present in large amounts in legumes, are comprised of raffinose, stachyose, and verbascose, which have a structure consisting of a unit of sucrose linked to 1, 2, or 3 units of D-galactose, respectively (Figure 2.2; Slavin, 2013b). These oligosaccharides cause flatulence in pigs and humans due to the lack of an enzyme, α-galactosidase, that cleave the glycosidic bonds linking the monosaccharides that constitute these α-galactosides and are, therefore, utilized by bacteria in the large intestine (Liener, 2000; Vaclavik and Christian, 2014). In raffinose, D-galactose is linked to sucrose by an α-(1,6) bond, whereas 2 units and 3 units of D-galactose are linked to sucrose, also via an α-(1,6) glycosidic bond, in stachyose and verbascose, respectively (NRC, 2012). Transgalacto-oligosaccharides are another type of galacto-oligosaccharides that may have prebiotic effects in young pigs and are commercially synthesized from the transglycosylation actions of β-glycosidases on lactose, creating β-(1,6) polymers of galactose linked to a terminal glucose unit via an α-(1,4) glycosidic bond (NRC, 2012; Marin-Manzano et al., 2013). However, transgalacto-oligosaccharides are not naturally synthesized (NRC, 2012).

Fructo-oligosaccharides, or fructans, are chains of fructose monosaccharides with a terminal glucose unit and are classified as inulins or levans (NRC, 2012; Cromwell, 2013). Inulin is mostly found in dicotyledons, whereas levans are mainly found in monocotyledons (Han,

1990). Fructo-oligosaccharides are not hydrolyzed in the small intestine due to the β linkages between their monomers, but can be fermented to lactic acid and SCFA in the large intestine (Roberfroid and Slavin, 2000; Chawla and Patil, 2010; Slavin, 2013b). Inulin occurs naturally in onions, garlic, asparagus, bananas, Jerusalem artichoke, wheat, and chicory as a storage carbohydrate (Roberfroid and Slavin, 2000; BeMiller, 2007d; Englyst et al., 2007). Inulin is made up of β-D-fructofuranosyl units linked by β-(2,1) glycosidic linkages and have a DP that ranges from 2 to 60 (BeMiller, 2007d; NRC, 2012). The polymer is composed of fructose residues present in the furanose ring form and often have a terminal sucrose unit at the reducing end (BeMiller, 2007d; Slavin, 2013b). Levans are fructans that have an average length of 10 to 12 fructose units linked by β-(2,6) linkages, but can have a DP of more than 100,000 fructose units and are found in bacterial fructans and in many monocotyledons (Han, 1990; Vijn and Smeekens, 1999). Levans are derived from the transglycosylation reactions catalyzed by the enzyme levansucrase that is secreted by certain bacteria and fungi that preferentially use the D-glycosyl unit of sucrose, thereby converting sucrose to levans with β-(2,1) linked side chains (BeMiller, 2007b; NRC, 2012). Polysaccharides containing a significant number of β-(2,1) linkages also can be referred to as "levan" (Sinnott, 2013b). A third type of fructans, called graminan-type fructans, contain a combination of both β-(2,1) and β-(2,6) linkages that are observed in wheat and barley (Van den Ende, 2013).

Mannan-oligosaccharides are composed of polymers of mannose that are derived from yeast cell walls, and are located on the outer surface of yeast cell walls attached to β-glucans of the inner matrix via β-(1,6) and β-(1,3) glycosidic linkages (NRC, 2012). Mannan-oligosaccharides and fructo-oligosaccharides are considered prebiotics due to their beneficial health effects on the host by stimulating the growth or activity of certain bacteria in the large

intestine (Swanson et al., 2002). It has been suggested that mannan-oligosaccharides regulate the response to immunological challenges by pigs and may prevent overstimulation of the host animal's immune system following an infection (Che et al., 2012).

Polysaccharides

Polysaccharides are high-molecular-weight carbohydrates that are polymers of monosaccharides (BeMiller, 2007g). Polysaccharides are made up of sugar polymers that vary in size and may either be linear or branched (Slavin, 2013b). The DP varies with the type of polysaccharide and may range from 7,000 to 15,000 in cellulose and up to more than 90,000 in amylopectin (BeMiller, 2007g). Polysaccharides can be classified as homopolysaccharides if they contain only one type of sugar residue (e.g., starch, glycogen, and cellulose) or as heteropolysaccharides if they contain 2 or more different kinds of sugar residues in their structure (e.g., arabinoxylans, glucomannans, and hyaluronic acid; Slavin, 2013b). Polysaccharides are present in large quantities in pig diets, and are divided into starch and glycogen and nonstarch polysaccharides (**NSP**; Bach Knudsen, 2011; NRC, 2012).

Starch can be linear or branched and is the storage form of carbohydrates in plants whereas glycogen is highly branched and is present only in animal tissue, primarily in the muscle and liver (Slavin, 2013b; Kiem et al., 2014). Starch is one of the most abundant carbohydrates in nature (Slavin, 2013b). It is synthesized to store energy for plant growth and is stored in seeds, tubers, roots, stems, leaves, and some fruits (Dar, 2014). Starch is a polymer of D-glucose that is comprised of 2 types of molecules, amylose and amylopectin (Figure 2.3; Vaclavik and Christian, 2014). It may consist of amylose, which are short linear polymers of glucose with an average DP of 1,000 glucose units linked via α-(1,4) bonds, or amylopectin, which are larger chains of glucose with DP of 10,000 to 100,000 with branch points at the α-(1,6) linkages every

20 to 25 glucose units (Englyst et al., 2007; Bach Knudsen, 2011). The total number of α-(1,6) linkages are only about 4 to 5% of the total glycosidic bonds in amylopectin (Serna-Saldivar, 2010). Native starch contains both forms as semicrystalline granules of varying proportions of amylose and amylopectin, depending on the plant source (Bach Knudsen, 2011; Kiem et al., 2014). Starch granules have varying structural and chemical compositions depending on the plant species and the part of the plant where it is located (Leturque and Brot-Laroche, 2013). The size of the starch granules influences the surface-to-volume ratio, and the smaller the granule, the larger the surface-to-volume ratio resulting in more surface area for enzyme hydrolysis in the digestive tract (Bach Knudsen, 2011). Digestion of starch begins in the mouth where salivary α-amylase is secreted, which acts only on the α-(1,4) linked linear chains of amylose and amylopectin, until this enzyme is deactivated by the low pH in the stomach (Kiem et al., 2014). Large quantities of pancreatic α-amylase, also specific only to α-(1,4) linkages, then are secreted into the duodenal lumen, producing maltose and maltotriose as the products of luminal amylose and amylopectin digestion, along with the branched oligosaccharide, α-dextrin, resulting from the partial hydrolysis of amylopection due to the inability of α-amylase to cleave α-(1,6) linkages (Leturque and Brot-Laroche, 2013). Starch digestion is completed by oligosaccharidases (i.e., α-glucosidases) expressed by glands in the small intestine. These α-glucosidases include sucrose-isomaltase and maltase-glucoamylase complexes (Hill, 2006). Both complexes have differences in their degree of specificity for the products of α-amylase digestion and cleave the α-(1,4) and α-(1,6) bonds in α-dextrins in a complementary manner, producing free glucose that is transported into the enterocytes (Leturque and Brot-Laroche, 2013).

Starch can be divided into 3 types: Type A starch has an open structure and is present in cereals; Type B starch is present in tubers and appears to be more compact; and Type C starch is

a combination of types A and B starch and is present in legumes (Bach Knudsen, 2011). Raw starch granules in raw potatoes and green bananas that have high amylose content result in more tightly packed granules that are more insoluble and resistant to digestion compared with amylopectin-containing granules that are more branched and less tightly packed (Slavin, 2013b). In corn, wheat, and potato, starch may contain approximately 20% amylose and 80% amylopectin (Kiem et al., 2014). However, waxy corn may have starch containing nearly 100% amylopectin, whereas high amylose corn may contain up to 75% amylose (Sacks, 2006). Therefore, starch may not always be available for water penetration and α-amylase action unless the cereal grains are altered by physical processing (e.g., grinding or roller milling) and heating (e.g., pelleting, expansion, or extrusion; Bach Knudsen, 2011).

A proportion of the starch is not digested by α-amylase and the enzymes of the brush border and may undergo microbial fermentation in the large intestine; this is referred to as resistant starch (**RS**; BeMiller, 2007h; Kiem et al., 2014). Starch resists digestion either because it is physically inaccessible due to enclosure within whole plant cells or matrices (i.e., **RS-1**), because of the ungelatinized crystalline structure of the granule, also referred to as native or uncooked starch (i.e., **RS-2**), because it is cooled after it has been gelatinized due to heating, referred to as retrograded starch (i.e., **RS-3**), or because it has been chemically modified (i.e., **RS-4**; BeMiller, 2007h; Bach Knudsen, 2011; Kiem et al., 2014). Resistant starch may serve as a substrate for colonic fermentation and has a modest effect on fecal bulking (Chawla and Patil, 2010). Starch-containing ingredients will naturally contain RS, but the amount and type of starch will influence the proportion of total starch that is RS (Brown, 2004). Processing may influence the proportion of starch resistant to digestion and RS values typically range from 0 to 19% in most cereal grains and 10 to 20% in legumes (Table 2.1; Englyst et al., 2007; Cervantes-Pahm et

al., 2014). Cooking or ripening decreases the quantity of RS in raw or immature fruits or vegetables such as green bananas and potatoes (DeVries, 2004).

Glycogen, an α-(1,4)-D-glucan with α-(1,6) linked branches, has a higher degree of branching compared with amylopectin and is present in animal tissues, mainly in skeletal muscle and the liver (Slavin, 2013b). The branch points of glycogen occur after an average of 8 to 10 glycosyl units (Ferrier, 2014). A polymer of glycogen may contain up to 100,000 units of glucose (McGrane, 2013). Digestion of glycogen is similar to that of amylopectin, which results in glucose absorption in the small intestine (NRC, 2012). The extensive branching of glycogen enhances its solubility, which allows glucose to be mobilized more readily (Sacks, 2006).

Nonstarch Polysaccharides

Nonstarch polysaccharides are predominantly present in primary or secondary plant cell walls and consist of both soluble and insoluble polysaccharides that do not contain α-(1,4)-linked glycosyl units unlike that of starch (Englyst et al., 2007; Bach Knudsen, 2011). Primary cell walls surrounding growing cells are mainly composed of polysaccharides and some structural proteins, whereas mature cells that have already differentiated are surrounded by secondary cell walls that also contain polysaccharides and proteins, along with lignin and a larger amount of cellulose (Albersheim et al., 2011a). The cell wall polysaccharides consist of pentoses (i.e., arabinose and xylose), hexoses (i.e., glucose, galactose, and mannose), 6-deoxyhexoses (i.e., rhamnose and fucose), and uronic acids (i.e., glucuronic and galacturonic acids; Pluske et al., 2001). These components can exist in their pyranose and furanose forms and form α- or β-linkages at any of their available hydroxyl groups resulting in a broad range of functional surfaces by adapting numerous 3-dimensional shapes (Bach Knudsen, 2014). Phenolic residues of lignin or its hydroxyl side chains can also bond with glycosidic linkages of NSP (Albersheim

et al., 2011b). Nonstarch polysaccharides may acquire hydrophobic properties by linking to lignin and suberin, whereas the degree of esterification of uronic acids may influence its ionic properties (Bach Knudsen, 2011). Suberin, a hydrophobic complex mixture of hydroxylated fatty acids and fatty esters, is found in vascular tissues that provide an insoluble barrier during normal development and in response to wounding or fungal infections (Albersheim et al., 2011b). Nonstarch polysaccharides also may be classified as soluble or insoluble, where the term soluble refers to solubility of the NSP in water or weak alkali solutions (Pluske et al., 2001).

The most common NSPs in cell walls are cellulose and non-cellulosic polysaccharides (**NCP**; NRC, 2012). On average, the cellulose content of primary cell walls is 20 to 30%, whereas secondary cell walls can contain up to 50% cellulose (Albersheim et al., 2011a). Primary cell walls are deposited between the middle lamella and the plasma membrane during cell growth, whereas certain specialized cells deposit a thicker inner layer called the secondary cell wall at the onset of differentiation (Brett and Waldron, 1990). Cellulose consists of linear β-(1,4)-linked D-glucopyranosyl units with a DP that varies from 500 to 14,000 that are stabilized by hydrogen bonding between adjacent glucose residues, forming an organized arrangement of cellulose molecules within the microfibrils (Figure 2.3; Bhat and Hazlewood, 2001; Bach Knudsen, 2014). Crystalline regions are formed when highly organized cellulose microfibrils are aligned parallel to each other to allow for maximal hydrogen bonding, whereas paracrystalline or amorphous sections are formed in regions that are less organized (Paloheimo et al., 2010). The 3-dimensional lattice formed of the closely packed linear and unbranched structure of cellulose forms the microfibrils that give the structure of plant cell walls (Cummings and Stephen, 2007). The less organized amorphous regions of cellulose are hydrolyzed by endoglucanases, producing chain ends that are hydrolyzed by exoglucanases (i.e., cellobiohydrolases; Paloheimo et al.,

2010). The resulting disaccharide, cellobiose, is hydrolyzed by β-glucosidase to produce 2 glucose monomers (Bhat and Hazlewood, 2001).

Highly branched NCP consist of heteropolymers of pentoses and hexoses, the most common of which is called a xylan, or a chain of β-(1,4) linked D-xylopyranosyl units with side chains that are commonly composed of L-arabinofuranosyl, D-galactopyranosyl, D-glucuronopyranosyl, and/or 4-O-methyl-D-glucuronopyranosyl units (BeMiller, 2007a). Non-cellulosic polysaccharides may also contain uronic acids that are derived from glucose and galactose, giving the ability to form salts with Ca and Zn (Cummings and Stephen, 2007). Non-cellulosic polysaccharides often serve as structural polysaccharides in plant tissues and are closely associated with cellulose and lignin (Paloheimo et al., 2010).

Lignin is not a carbohydrate, but is highly associated with cell wall polysaccharides (Bach Knudsen et al., 2013). It consists of polymerized phenylpropane units (i.e., coniferyl, p-coumaryl, and sinapyl alcohols) linked by ether and carbon-carbon bonds in an irregular 3-dimensional pattern (Bach Knudsen, 2014). A lignified cell wall may consist of a thin primary layer, followed by a thick multilamellar secondary layer that is high in cellulose, and possibly a third layer (Boudet, 2003). Lignin may link to polysaccharides by forming covalent bonds with sugar residues or ferulic acids that are esterified to these polysaccharides (Bach Knudsen et al., 2013). Lignification occurs only after cell division, cell expansion, and cell elongation have ceased and, therefore, constitutes terminal differentiation, which is typically followed by programmed cell death (Albersheim et al., 2011b). Lignin prevents biochemical degradation and physical damage to cell walls by cementing and anchoring cellulose microfibrils and other matrix polysaccharides, hence, enforcing the structural integrity of the cell wall (Bach Knudsen, 1997). Lignin also serves as a barrier to pathogens and pests (Albersheim et al., 2011b). Plant

tissues become lignified or woody when the lignin concentration is high (Slavin, 2013a). Lignin is more concentrated in the outer husk layer of grains compared with endosperm cell walls and is evident in the elevated concentrations in ingredient byproducts (Table 2.2).

NONSTARCH POLYSACCHARIDES IN FEED INGREDIENTS

Cereal Grains and Cereal Co-products

In cereal grains, the proportion of total cell wall polysaccharides is influenced by several factors including genetics, climate, stage of maturity, the use of nitrogen fertilizers, and postharvest storage time (Paloheimo et al., 2010). Cellulose, mixed linked β-(1,3)(1,4)-D-glucans (i.e., β-glucan; **MBG**), and arabinoxylans (**AX**) are the main cereal grain cell wall polysaccharides that have varying proportions and structures depending on the species and tissue of the grain (Table 2.1; Bach Knudsen, 2011; Bach Knudsen, 2014). Arabinoxylan has a linear backbone of β-(1,4)-D-xylopyranosyl units with varying degrees of α-L-arabinofuranosyl residue substitutions and is the main polymer of cell walls in cereals such as corn, wheat, rye, and triticale (Figure 2.4; Bach Knudsen, 2014). The α-L-arabinofuranosyl residue substitutions can occur at the O-2, O-3, or both O-2 and O-3 of the xylopyranosyl unit, resulting in unsubstituted, monosubstituted, and disubstituted xylose residues in the xylan backbone (Izydorczyk and Biliaderis, 2007; Sinnott, 2013b). This polysaccharide is commonly referred to as a pentosan because it is mainly constituted of pentose sugars (Serna-Saldivar, 2010). Oats have the greatest concentration of total AX among the cereal grains followed by rye and triticale, whereas sorghum and rice contain the least (Table 2.1). Arabinoxylans are primarily located in the cell walls of the endosperm, but may also be present in the outer layers where the structure of AX differs in that glucuronic acid and galactose are also present (Pritchard et al., 2011; Bach

Knudsen, 2014). These acidic AX are called glucuronoarabinoxylans and are present in the husk and bran of cereal grains (Izydorczyk and Biliaderis, 2007). There also may be differences in the structures and characteristics of AX within the grain and among plant species, such as the arabinose to xylose ratio, the sequence and proportions of the various linkages in the structure, and the composition of substituents of the side chains (Izydorczyk and Biliaderis, 1995). The AX in wheat and rye has a larger proportion that is soluble compared with the AX in barley and oats mainly due to differences in their structural features (Bach Knudsen, 2014). Arabinoxylans in the aleurone layer, a specific tissue of cereal endosperm that is structurally similar to the starchy endosperm, may encapsulate available nutrients (Bach Knudsen, 2014). The aleurone layer contains ferulic and dihydrodiferulic acids, as well as AX that are more esterified than AX in the starchy endosperm (Bach Knudsen, 2014). An ester linkage covalently links ferulic acid to the O at C-5 of the arabinose residue (Izydorczyk and Biliaderis, 1995). Ferulic acid can dimerize into dehydrodiferulate esters because of its capability to form both ester and ether linkages, allowing cross-linking between AX chains and between AX and other components of the cell wall (Izydorczyk and Dexter, 2008). Cereal grain AX are mostly water-insoluble due to alkali-labile cross-linkages between AX and the cell wall; however, AX that are not bound to other cell wall polysaccharides can absorb water and form highly viscous solutions (Sinha et al., 2011). One-third of the fraction of AX in wheat and rye is soluble in water and this proportion is larger compared with that in barley and oats (Paloheimo et al., 2010; Bach Knudsen, 2014). The ability to bind water decreases when AX loses arabinose side chains and, therefore, becomes less soluble (Sinha et al., 2011). The arabinose to xylose ratio is lower in the insoluble aleurone AX compared with the starchy endosperm of wheat and barley (Bach Knudsen, 2014). Of the cereal grains, sorghum has the greatest arabinose to xylose ratio and the least is in oats, indicating that

sorghum can bind more water and is more soluble compared with oats (Table 2.1). Furthermore, unsubstituted regions of the backbone of AX may form intermolecular hydrogen bonding between adjacent xylopyranosyl residues, but steric hindrance imposed by arabinose side chains limit aggregation of AX (Izydorczyk and Biliaderis, 1995; Sinha et al., 2011).

Whereas the main NCP in wheat, rye, and triticale are AX, high concentrations of MBG are found in barley and oats (Table 2.1; Paloheimo et al., 2010). Rice, corn, and sorghum have the least concentration of total MBG. Mixed linked β-glucans in cereal grains are soluble linear homopolymers of D-glucopyranosyl residues that are linked by 2 to 3 consecutive β-(1,4) linkages and separated by a single β-(1,3) linkage (Figure 2.5; Paloheimo et al., 2010; Bach Knudsen, 2014). Mixed linked β-glucans are soluble in water because the presence of 2 types of linkages prevent the compact folding of the β-glucan chains (Chawla and Patil, 2010). There is currently no evidence of MBG containing 2 or more adjacent β-(1,3) linkages (Izydorczyk and Dexter, 2008). The general molecular structure of MBG is the same across different genera of cereals, but vary in features such as molecular size, the ratios of β-(1,4) to β-(1,3) linkages, the level of long cellulose-like fragments, and the ratios of trimers to tetramers (Lazaridou et al., 2007; Bach Knudsen, 2014). Genetic and environmental factors play a role in the differences in the ratio of cellotriosyl to cellotetraosyl units between different varieties within the various cereal grains (Bach Knudsen, 2014). Typically, the ratio of β-(1,4) to β-(1,3) bonds is approximately 3 to 2 (Serna-Saldivar, 2010). For example, the structure of MBG in barley consists primarily of cellotriosyl units linked by β-(1,4) bonds and β-(1,3) linked cellotetraosyl units (Paloheimo et al., 2010). Dry conditions and warmer temperatures before harvest or during growing time results in high levels of MBG (Lazaridou et al., 2007). Barley, oats, and rye contain more MBG in the endosperm, aleurone, and subaleurone cell walls compared with corn

and wheat (Bach Knudsen, 1997; Mateos-Aparicio et al., 2013; Bach Knudsen, 2014). In barley, the amount of water-soluble MBG is more than 4 times that of AX, whereas in rye, the levels of AX are at least 3-fold that of MBG (Paloheimo et al., 2010). There is no correlation between total MBG, AX, or NSP and starch content (Pritchard et al., 2011).

Oilseeds and Oilseed Meals

The cell walls of pulse crops and legumes have high concentrations of cellulose, pectin polysaccharides, lignin, and xyloglucans that serve to protect the seeds (Tables 2.3 and 2.4; Bach Knudsen, 2014). The more complex composition of primary cell walls of protein sources such as pea and soybean cotyledons include rhamnogalacturonans, cellulose, xyloglucans, glycoproteins, arabinans (in peas and rapeseed), and arabinogalactans (in soybeans and rapeseed) that can be present as free or linked to rhamnogalacturonans (Bach Knudsen, 2011). Xyloglucans have a backbone of β-(1,4)-glucosyl units similar to that of cellulose, containing side chains of xylose, galactose, fucose, and arabinose, with approximately 75% of the β-D-glucosyl residues substituted with a single α-D-xylosyl residue at the C-6 position (Figure 2.5; Albersheim et al., 2011b; Wrolstad, 2012b). Many of the α-D-xylosyl residues are substituted at C-2 with glycosyl residues, further extending the side chain (O'Neill and York, 2003). Xyloglucans are strongly associated with cellulose microfibrils in the walls of growing plant cells, forming xyloglucan bridges between the microfibrils (Albersheim et al., 2011b). However, variation exists in the structure of xyloglucans among plant species, tissues, cell types and, possibly, even in different parts of the cell wall surrounding individual cells (O'Neill and York, 2003).

In addition to cellulose and xyloglucans, primary cell walls also contain pectic polysaccharides that include homogalacturonan and rhamnogalacturonan types I and II (Albersheim et al., 2011a). Pectin is a polymer of α-(1,4) linked D-galacturonic acid units

(homogalacturonan; **HG**) with uronic acids that may form complexes with Ca and Mg and side chains that may contain the sugars rhamnose, galactose, arabinose, and xylose (Figure 2.6; Cummings and Stephen, 2007; Bach Knudsen, 2014). The degree and distribution of methyl-esterification at the C-6 carboxyl group and the acetylation at the O-2 and/or O-3 vary among sources (Caffall and Mohnen, 2009; Bach Knudsen, 2014). Esterified pectins are located in the cell wall surrounding the cellulose-NCP matrix, while nonesterified HG are located predominantly in the middle lamella and cell corner regions (Albersheim et al., 2011b). Homogalacturonans can account for 60% of total pectin or greater in plant cell walls and is abundant in potatoes (Caffall and Mohnen, 2009). Rhamnogalacturonan type I (**RG-1**) is a polymer with an alternating α-(1,2)-L-rhamnose and α-(1,4)-D-galacturonic backbone with side chains containing α-(1,5)-L-arabinans, β-D-galactans, and arabinogalactans substituted at the C-4 position (Bach Knudsen, 2014). In contrast to HG, the D-galacturonic residues of RG-1 cannot be esterified and may only be acetylated on position 3 (Sinnott, 2013b). Side chains of fucosyl, glucosyluronic acid, and 4-*O*-methyl glucosyluronic acid residues are also present in small amounts in RG-1 (Albersheim et al., 2011b). The α-(1,5)-L-arabinan side chains may also have (1,3) branch points, and the β-D-galactans that are largely (1,4) linked may also be occasionally linked (1,3) to the main chain with (1,6) branch points (Sinnott, 2013b). Solubilized RG-1 from primary cell walls treated with α-1,4-endo-polygalacturonase can account for up to 5 to 10% of the cell walls of dicotyledons and about 1% of monocotyledons (Albersheim et al, 2011b). Rhamnogalacturonan type II (**RG-2**) has a backbone of α-(1,4)-D-galacturonic units with aldehydro- and keto-sugar oligosaccharide substitutions at C-2 and C-3 (Figure 2.7; Bach Knudsen, 2014). The highly branched RG-2 has approximately 30 glycosyl residues with 11 different monosaccharides, excluding glucose and mannose, making its structure relatively more

complex than other plant polysaccharides and resistant to microbial degradation (Albersheim et al., 2011b). In addition, uncommon sugars that are associated with RG-2 include 3-deoxy-D-manno-oct-2-ulosonic acid, apiose, 2-keto-3-deoxy-D-lyxo-heptulosaric acid, and aceric acid (Sinnott, 2013b). Self-association occurs via a boron diester bond between molecules of RG-2 allowing the formation of dimers (Caffall and Mohnen, 2009; Albersheim et al., 2011b). Both RG-1 and RG-2 are covalently linked to the backbone of HG, and it has been suggested that xyloglucans also form covalent cross-linkages with HG (Caffall and Mohnen, 2009).

Pectin polysaccharides also include xylogalacturonan and arabinogalactans types I and II (Bach Knudsen, 2014). Reproductive tissue contains xylogalacturonan, which has a HG backbone with one or more β-(1,4)-D-xylose residue substitutions at the C-3 position and the first residue is frequently branched at the C-2 by another xylose residue (Figure 2.8; Caffall and Mohnen, 2009; Bach Knudsen, 2014). Arabinogalactan types I and II both have linear β-(1,4)-D-galactosyl backbones, which may have a short side chain containing α-(1,5)-L-arabinoxyl residues (i.e., type I) or have highly branched side chains containing β-(1,6)-D-galactosyl residues (Figure 2.9; Bach Knudsen, 2014).

Legumes are rich sources of protein, but also contain significant amounts of galacto-oligosaccharides, namely raffinose, stachyose, and verbascose (Tables 2.3 and 2.4). Galacto-oligosaccharides, or α-galactosides, accumulate in storage organs of plants and are only present in the leaves at low concentrations (Martinez-Villaluenga et al., 2008). Among common legumes, soybeans have the greatest concentrations of these oligosaccharides, which can make up 5-7% of DM (Tables 2.3 and 2.4; Liener, 2000; Middelbos and Fahey, 2008). Cottonseed products have elevated concentrations of raffinose, whereas soybean meal has the greatest concentrations of stachyose. High concentrations of α-galactosides interfere with digestion of

other nutrients and stimulate anaerobic fermentation in the hindgut of humans and pigs that causes flatulence and decreases NE intake (Martinez-Villaluenga et al., 2008). However, fermentation due to the presence of α-galactosides also may have a beneficial effect on the populations of ileal lactobacilli and bifidobacteria in the colon and reduce the concentration of colonic enterobacteria (Middelbos and Fahey, 2008).

Pulse Crops

Pulse crops, which include beans, lentils, lupins, and peas, are legumes that are rich sources of protein and other nutrients (Maiti et al., 2012). Peas, faba beans, and lupins are the major pulse crops used as sources of both protein and energy in diets fed to pigs (Aumiller et al., 2015). Relatively high amounts of starch in peas, faba beans, and lupins make them possible alternative sources of energy (Table 2.4). Similar to oilseed crops, the cell walls of pulse crops contain a variety of polysaccharides that play a role in protection including high concentrations of cellulose, lignin, xyloglucans, and pectin (Bach Knudsen, 2014). Pulse crops contain considerable amounts of galacto-oligosaccharides (raffinose, stachyose, and verbascose). Lupins contain little starch with relatively greater concentrations of cellulose, raffinose, and stachyose than the other pulses, which may stimulate more microbial fermentation in the hindgut. Verbascose is present in pulse crops in amounts greater than in oilseeds.

PHYSICAL CHARACTERISTICS OF FIBER

The polysaccharides that make up the cell wall and the interactions among them determine the physicochemical characteristics of fiber (Lindberg, 2014). Solubility, water holding capacity (**WHC**) and water binding capacity (**WBC**), viscosity, cation-binding capacity, and fermentability are physicochemical properties of dietary fiber that are relevant to animal

nutrition (Urriola et al., 2013). The physical and chemical properties change as fiber progresses through the gastrointestinal tract, which results in variation in physiological functions of fiber in different stages after ingestion of feed (Oakenfull, 2001). Gut environment also may be affected by the physicochemical properties of fiber by altering the growth of the gut microflora (Chawla and Patil, 2010; Jha and Berrocoso, 2015).

Hydration Properties

The hydration properties of dietary fiber are a result of the cumulative effects of porosity, particle size, ionic form, pH, temperature, ionic strength, and stresses acting on fiber (Elleuch et al., 2011). The hydration properties of fiber include swelling, solubility, WHC, and WBC (Bach Knudsen et al., 2013). Fiber is generally classified as being soluble or insoluble, the distinction being the differences in chemical properties rather than structural composition or physiological responses (Dikeman and Fahey, 2006). Solubility of dietary fiber does not only reflect its ability to dissolve in water but also its ability to dissolve in dilute acid or base or a buffer or enzyme solution that mimics the conditions of the gastrointestinal tract (Urriola et al., 2013). Solubility is determined by the structural stability of polysaccharides. Linear polysaccharides that form ordered crystalline structures, such as cellulose, are likely to be insoluble because they are stable in a solid state due to an increased strength of noncovalent bonding between chains whereas polysaccharides that have irregular structures in the backbone or side chains, such as AX and MBG, are generally soluble (Guillon and Champ, 2000). Similarly, pectic polysaccharides contain charged groups that prevent polymers from forming ordered structures due to electrostatic repulsion (Oakenfull, 2001). Soluble fiber may increase viscosity, whereas IDF may increase fecal bulk and decrease transit time (Elleuch et al., 2011). The concentrations of SDF and IDF may be altered by the use of chemical or enzyme treatment (Chawla and Patil, 2010).

Swelling is the first part of the solubilization process wherein molecules are spread out by incoming water until they are fully extended and dispersed (Bach Knudsen et al., 2013). Water holding capacity and WBC are the terms used to describe the quantity of water that can be bound in fiber without and with the application of an external force (Guillon and Champ, 2000; Urriola et al., 2013). Water binding capacity measures the water retained in the insoluble component of fiber after the application of an external force (Tosh and Yada, 2010). Insoluble fiber tends to have a lower WHC compared with SDF (Wrolstad, 2012a). In general, soluble NSP are associated with high WHC, whereas cellulose and lignin are associated with low WHC (Urriola et al., 2013). The higher WHC of SDF results in a larger surface area for enzyme degradation (Jha and Berrocoso, 2015). Fecal bulk and passage rate through the colon may be increased by feed ingredients that have high WHC (Wrolstad, 2012a). Arabinoxylans also have the ability to bind up to 20% more water than its own weight, which result in highly viscous solutions (Koehler and Wieser, 2013).

Viscosity

Viscosity is defined as the relationship between shear rate and shear stress and can be described as the resistance of a fluid to flow due to the physical interactions of polysaccharides in solution (Guillon and Champ, 2000). In other words, viscosity is caused by the physical entanglement of polysaccharide molecules in a solution (Oakenfull, 2001). The structure, molecular weight, and concentration in a solution influence the viscosity of a polymer (Bach Knudsen et al., 2013). Viscous dietary fibers thicken in the presence of fluids and the degree of thickening is influenced by the chemical composition and concentration of the polysaccharide (Schneeman, 2001). Fibrous materials associated with increased viscosity prolong gastric emptying and increases the transit time in the small intestine (Dikeman and Fahey, 2006). The

increase in the viscosity of a solution is the result of the characteristics of the water soluble component of fiber (Elleuch et al., 2011). Arabinoxylans and MBG in the soluble portion of NSP result in an increase in viscosity, but AX may have a greater impact on digestibility because it is more resistant to digestion compared with MBG (Bach Knudsen, 2014). Digestion and absorption of nutrients are affected by the viscosity of gut contents by influencing the mixing, diffusion, and flow of nutrients in the digesta (Takahashi and Sakata, 2004). Viscous polysaccharides also may increase the thickness of the unstirred water layer of the small intestine, which may slow the rate of nutrient absorption (Schneeman, 2001). The viscosity of digesta in the large intestine increases as moisture is reabsorbed due to the increase in concentration of DM (Dikeman and Fahey, 2006). The presence of large solid particles that originate from the digestion of insoluble fiber increases the viscosity of cecal contents (Takahashi and Sakata, 2004).

Particle Size and Bulk Density

The particle size of fiber is dictated by the type of cell walls present and the degree of processing of the feed ingredient (Guillon and Champ, 2000). Mastication, gastric digestion, and bacterial degradation may result in varying particle sizes along the gastrointestinal tract (Guillon and Champ, 2000). Grinding corn to different particle sizes does not affect WBC, indicating that absorption of water may not be influenced by particle size (Rojas and Stein, 2015). The concentration of digestible and metabolizable energy and digestibility of starch, but not AA or P digestibility, increased with decreasing particle size of corn (Rojas and Stein, 2015).

Bulk density is defined as the weight per unit volume of a diet or feedstuff (Cromwell et al., 2000). Bulk density was positively correlated with the apparent cecal digestibility of GE in growing pigs (Jaworski and Stein, 2017), indicating that increased bulk density may positively

influence fermentation in the cecum. An increase in bulk density may imply a decrease in fiber concentration in the diet (Jaworski et al., 2014), and therefore, more protein, fat, or digestible carbohydrates that provide more energy compared with fiber. However, bulk density was not correlated with digestibility of energy and other nutrients (Serena et al., 2008; Jaworski and Stein, 2017).

Cation-Binding Capacity

Dietary fiber may bind to and impair the absorption of organic molecules, such as bile acids, and minerals that include Ca, Mg, and Zn (Urriola et al., 2013). The structure of fiber, duration of exposure, pH, and the chemical nature of bile acids influence the adsorption capacity of fiber by the free carboxyl groups and uronic acids in pectic polysaccharides, phytates, and lignin that may bind to mineral ions and bile acids along the gastrointestinal tract (Guillon and Champ, 2000). However, it is possible that mineral ions are released and absorbed as fiber is hydrolyzed via microbial fermentation in the large intestine (Oakenfull, 2001).

Fermentability

Degradation of dietary fiber by enzymes from the pancreas or small intestine is, if any, very limited, but fiber is to some extent hydrolyzed by microbial fermentation in the large intestine (Oakenfull, 2001). However, disappearance of dietary fiber before the end of the small intestine has been observed, indicating that microbes in the small intestine may also ferment dietary fiber (Urriola et al., 2010; Jaworski and Stein, 2017). Synthesis of SCFA after fiber fermentation decreases the pH of the gut content and promotes growth of beneficial bacteria (Jha and Berrocoso, 2015). These SCFA may be absorbed by the colonic microflora and utilized in the body to contribute to the energy status of the animal (Urriola et al., 2013). However, there is no difference in the energy value between SCFA from fiber fermentation absorbed in the small

and in the large intestine (Stein, 2017). The rate of fermentation in the hindgut is influenced by the composition and physicochemical characteristics, degree of lignification, particle size, and transit time of dietary fiber (Jha and Berrocoso, 2015). Fiber sources that are slowly or partially fermented in the large intestine reduce the transit time, increase fecal weight, and promote laxation (Dikeman and Fahey, 2006). Soluble fiber is fermented mainly in the cecum and promixal colon, whereas IDF is fermented slowly, but fermentation is sustained until the distal colon (Jha and Berrocoso, 2015). Accessibility to the polysaccharide matrix is the main limiting factor in the fermentability of fiber (Guillon and Champ, 2000). However, when accessibility to the fiber matrix by the microflora is not limiting, other factors such as types of linkages, distribution of side chains and functional groups along the backbone of the polysaccharide, and the degree of branching dictate the extent of fermentation (Guillon and Champ, 2000). The amount of time digesta is exposed to fermentation dictates the extent of digestion in the hindgut and, therefore, an increase in rate of passage may reduce the efficiency of the digestion process (Jha and Berrocoso, 2015).

CONCLUSION

There are limited ways to practically quantify fractions of fiber that are of importance for assessing the energy value of fiber. Fiber fractions influences the physicochemical properties of an ingredient that have subsequent nutritional effects and alters the physiological conditions in the gastrointestinal tract of pigs. Measuring the physicochemical characteristics of fiber may provide information about the amount of energy pigs can obtain from fibrous feed ingredients. The physicochemical characteristics of fiber vary among fiber sources and may influence the digestibility and utilization of the fiber fractions and other nutrients within an ingredient.

Therefore, it is important to determine the concentration and the type of fiber fractions in mixed diets. However, there is a lack in available methods to quickly measure a fibrous feed ingredient for physicochemical characteristics and predict an accurate energy value for that ingredient. Furthermore, the physicochemical characteristics of fiber changes along the gastrointestinal tract and one measurement may not accurately represent the net effects on the animal and, thus, a robust and practical method for determination of the physicochemical characteristics of feed ingredients in mixed diets needs to be developed. Determination of how the measurable physical and chemical characteristics of the fiber components of feed ingredients influence energy and nutrient digestibility will enable more accurate diet formulations. Therefore, the swine industry will benefit from an improvement in the utilization of energy from less expensive fibrous feed ingredients, and this will result in a more sustainable pork production system due to the reduction in reliance on energy from more costly cereal grains.

TABLES

Table 2.1. Carbohydrate and lignin in cereal grains (g/kg DM)[1,2]

Item	Corn	Wheat	Barley	Oats	Rye	Sorghum	Polished Rice	Triticale
Total MBG	1	10	41	28	17	1	0.4	7
Total AX	47	73	84	97	95	24	26	85
A:X	0.74	0.62	0.48	0.22	0.66	1.23	-	0.71
Starch	680	647	587	468	613	585	837	727
Resistant starch	10	4	55	54	12	162	3	-
Cellulose	20	18	43	82	14	14	3	21
Lignin	11	18	35	66	21	24	8	20
Pectin	11	3	3	-	-	19	3	-

[1]Adapted from McCleary and Glennie-Holmes (1985), Bach Knudsen (1997), Bailoni et al. (2003), Izydorczyk and Biliaderis (2007), Bach Knudsen (2011), NRC (2012), Bach Knudsen (2014), and Cervantes-Pahm et al. (2014).

[2]MBG = mixed linked β-glucan; AX = arabinoxylan; A:X = arabinose to xylose ratio.

Table 2.2. Carbohydrate and lignin in cereal grain byproducts (g/kg DM)[1,2]

	Bran				Hulls		Middlings		
Item	Corn	Wheat	Rye	Rice	Barley	Oat	Wheat	Rye	DDGS[3]
Total MBG	2	24	45	-	16	14	26	37	-
Total AX	207	232	292	-	235	240	-	-	-
A:X	0.61	0.58	0.36	-	0.28	0.13	-	-	-
Starch	376	220	-	287	172	-	575	369	17
Resistant starch	-	2	-	-	2	-	-	-	-
Cellulose	89	72	39	166	192	196	19	27	102
Lignin	30	75	68	-	115	148	11	39	29
Pectin	-	4	-	79	-	-	2	-	-

[1]Adapted from Bach Knudsen (1997), Bailoni et al. (2003), Bach Knudsen (2011), NRC (2012), Bach Knudsen (2014), Cervantes-Pahm et al. (2014), and Curry et al. (2014).

[2]MBG = mixed linked β-glucan; AX = arabinoxylan; A:X = arabinose to xylose ratio.

[3]Corn distillers dried grains with solubles.

Table 2.3. Carbohydrate and lignin in oilseed meals and expellers (g/kg DM)[1]

	Meal				Expellers		
Item	Soybean	Rapeseed	Cottonseed	Sunflower	Rapeseed	Cottonseed	Sunflower
Starch	27	18	19	23	15	18	10
Cellulose	59	52	90	124	59	92	123
Lignin	18	133	92	130	90	83	133
Sucrose	70	58	16	-	68	10	36
Raffinose	10	4	35	-	3	39	14
Stachyose	47	12	13	-	13	14	3
Verbascose	3	0	2	-	0	1	0
Pectin	68	97	-	56	-	-	-

[1]Adapted from Bach Knudsen (1997), Malathi and Devegowda (2001), Bach Knudsen (2011), NRC (2012), and Bach Knudsen (2014).

Table 2.4. Carbohydrate and lignin in pulse crops (g/kg DM)[1,2,3]

Item	Peas	Lupins	Faba Bean	Lentils
Total MBG	ND	-	-	ND
Total AX	11	-	-	10
Starch	432	14	375	598
Resistant starch	22	-	32	74
Cellulose	53	131	81	54
Lignin	12	12	20	-
Sucrose	30	24	27	29
Raffinose	5	10	4	5
Stachyose	23	53	16	37
Verbascose	22	14	34	-
Pectin	8	-	11	-

[1]Adapted from Frias et al. (1996), Bach Knudsen (1997), Bailoni et al. (2003), Bach Knudsen (2011), Singha et al. (2011), Dodevska et al. (2013), and Bach Knudsen (2014).

[2]MBG = mixed linked β-glucan; AX = arabinoxylan; ND = not detected.

FIGURES

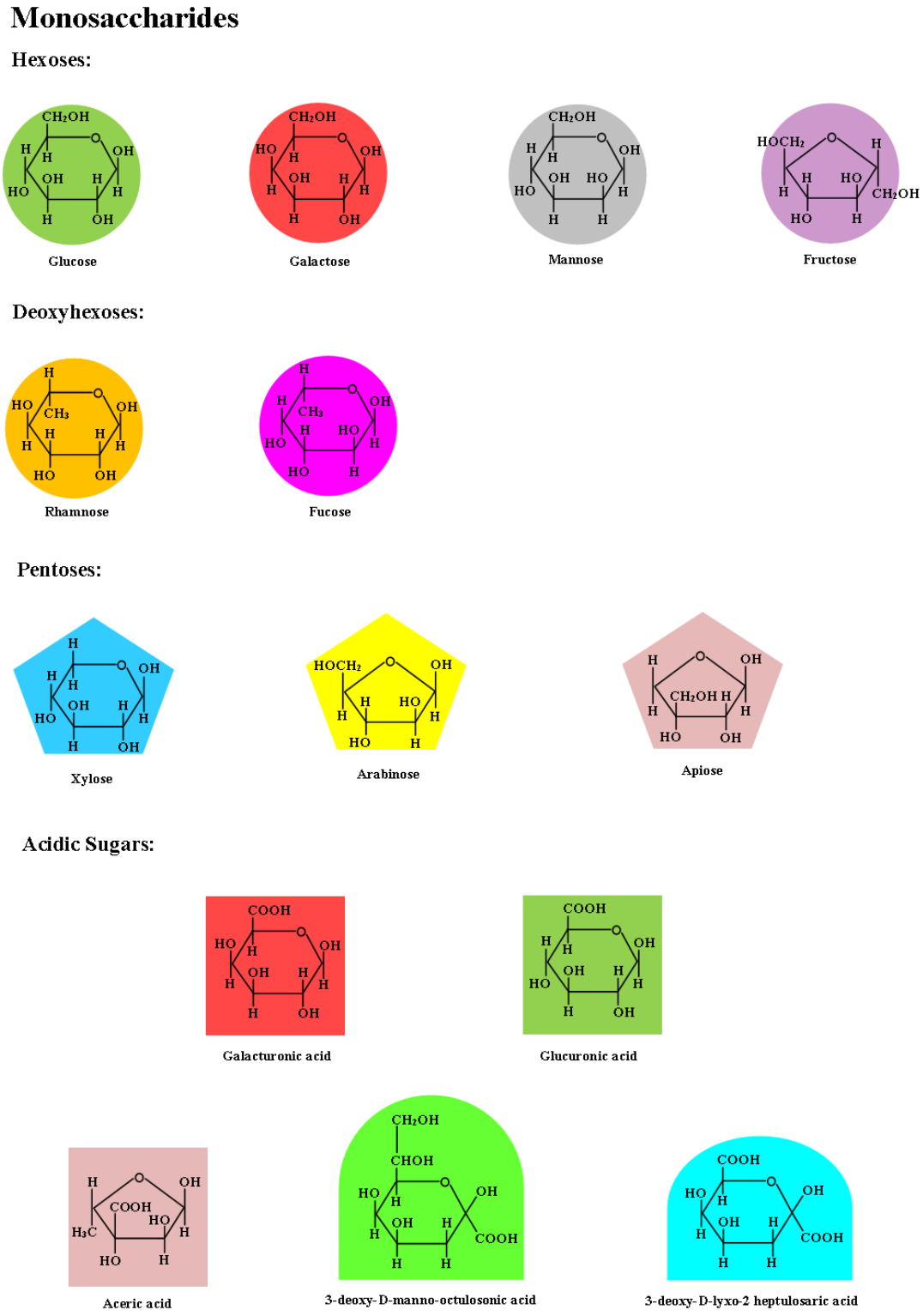
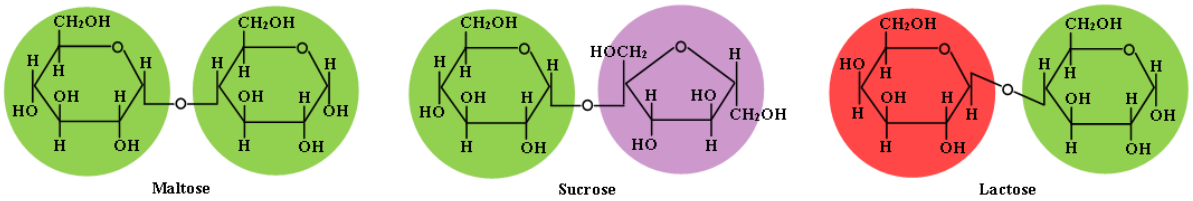


Figure 2.1. Chemical structure of monosaccharides that are commonly associated with fiber. Adapted from Albersheim et al. (2011a).

Disaccharides



Oligosaccharides

Galacto-oligosaccharides:

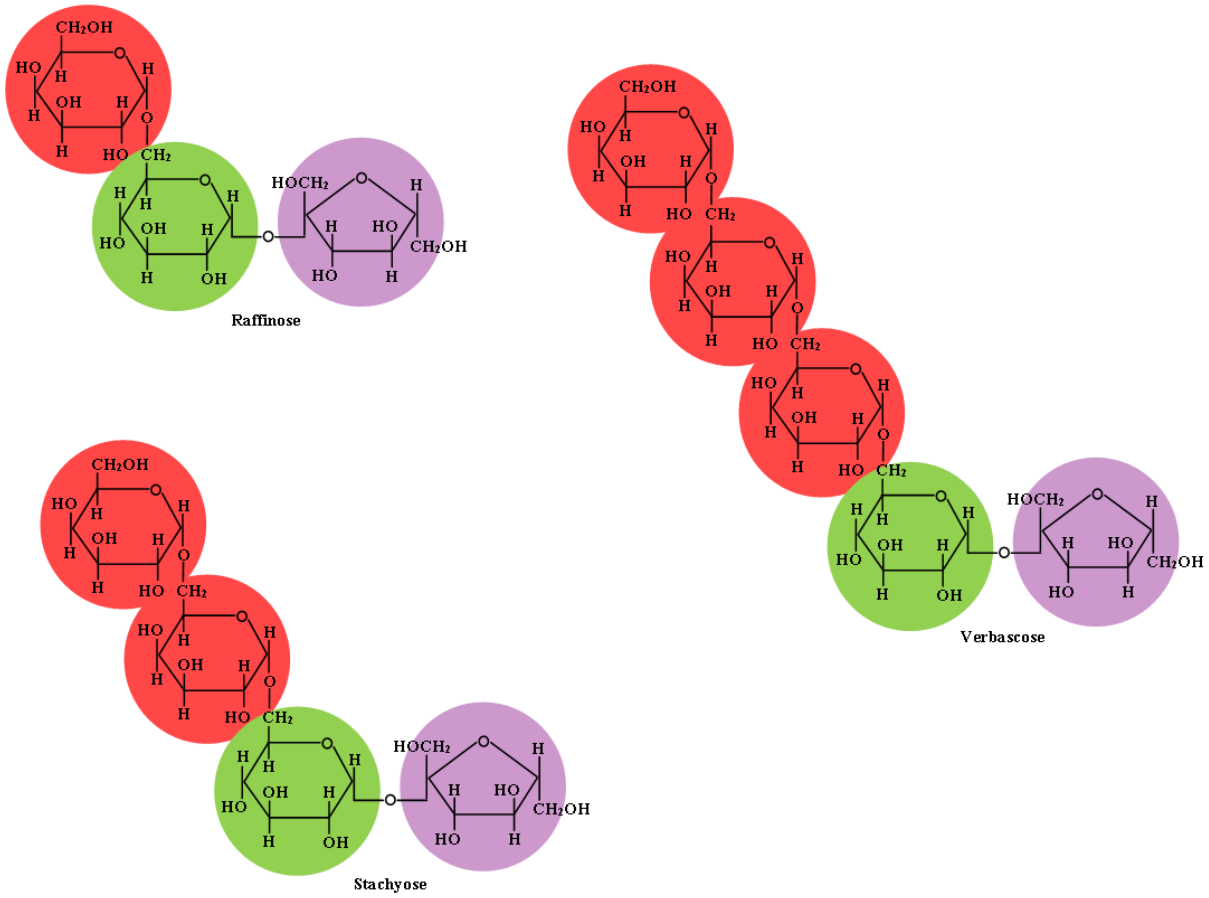
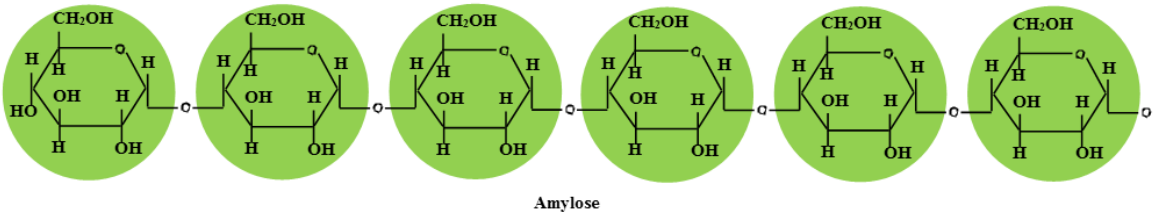
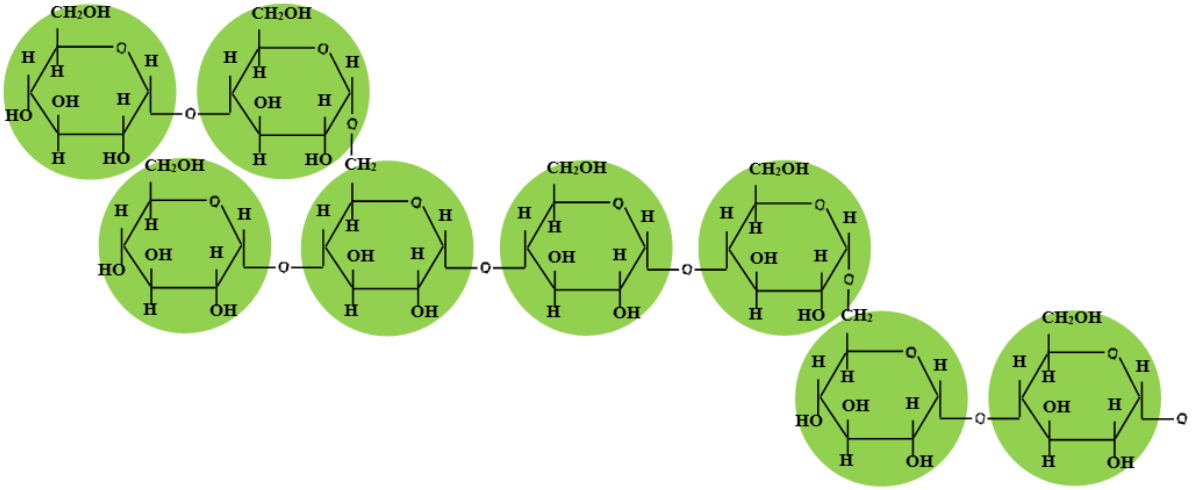


Figure 2.2. Chemical structure of di- and oligosaccharides. Adapted from Bach Knudsen et al. (2013).

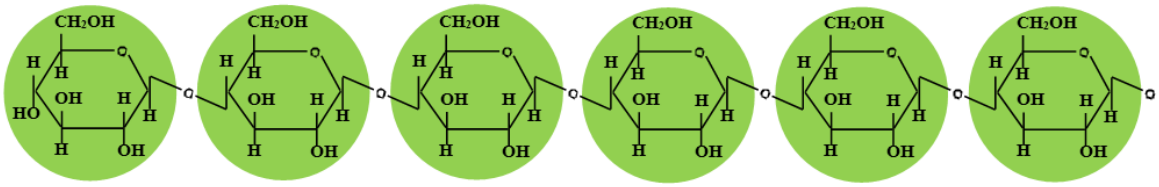
Polysaccharides



Amylose



Amylopectin



Cellulose

Figure 2.3. Chemical structure of amylose, amylopectin, and cellulose. Adapted from Bach Knudsen et al. (2013).

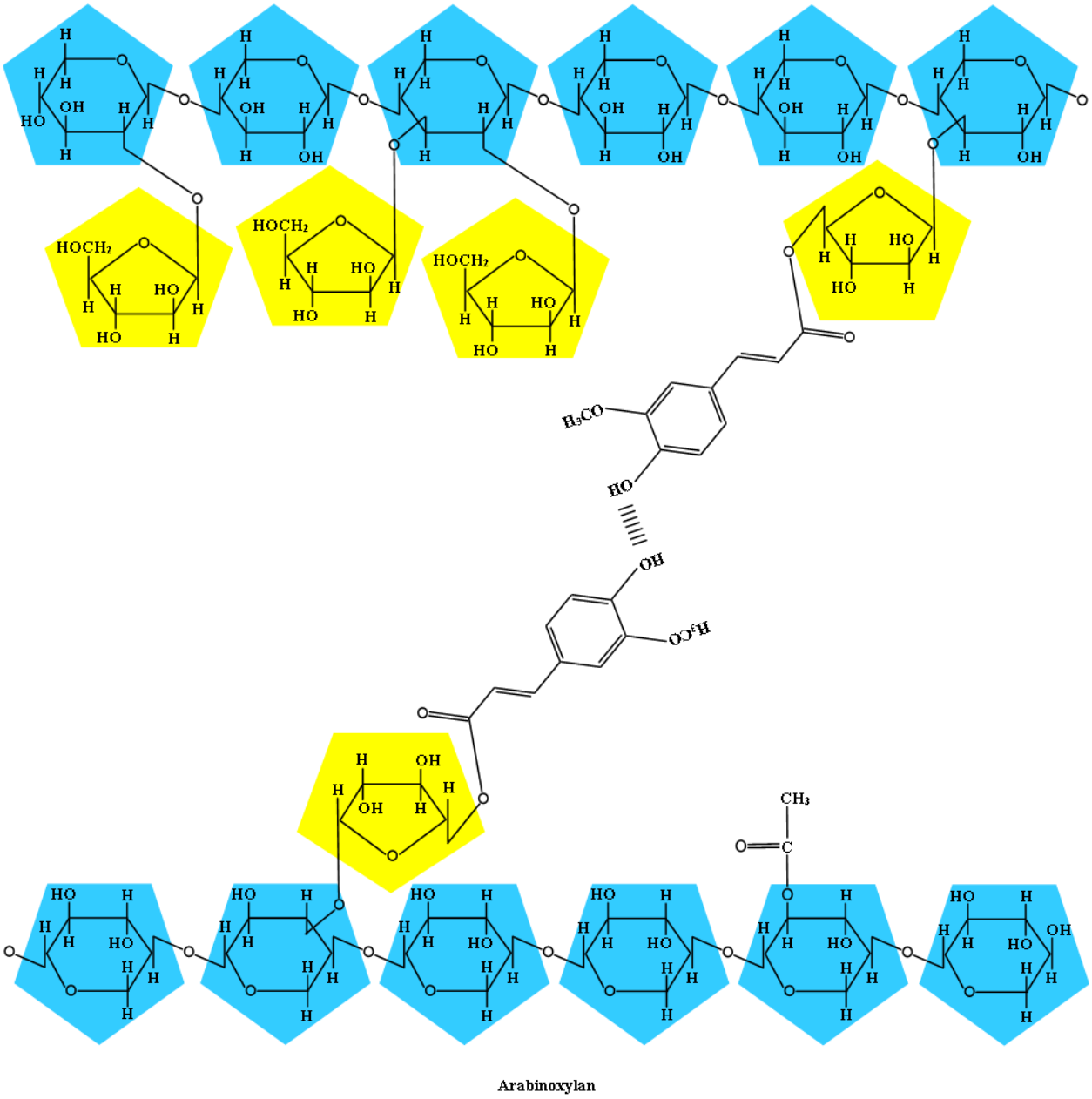
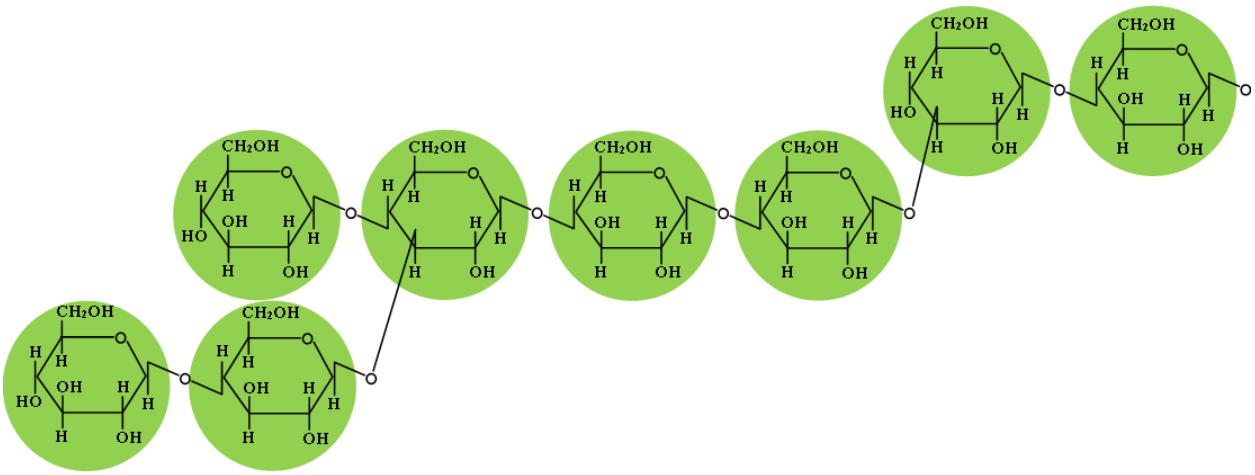


Figure 2.4. Chemical structure of arabinoxylans linked via a diferulic acid linkage. Adapted from Izydorczyk and Dexter (2008) and Bach Knudsen (2014).



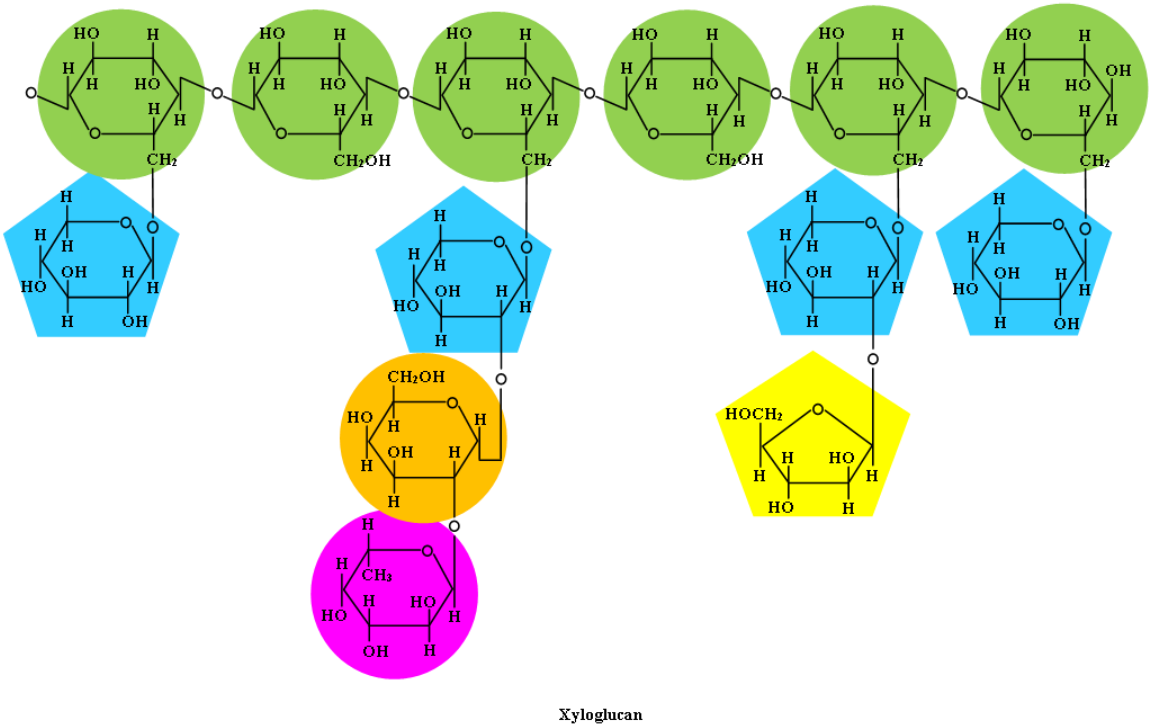


Figure 2.5. Chemical structure of mixed linked β-glucan and xyloglucan. Adapted from Bach Knudsen et al. (2013).

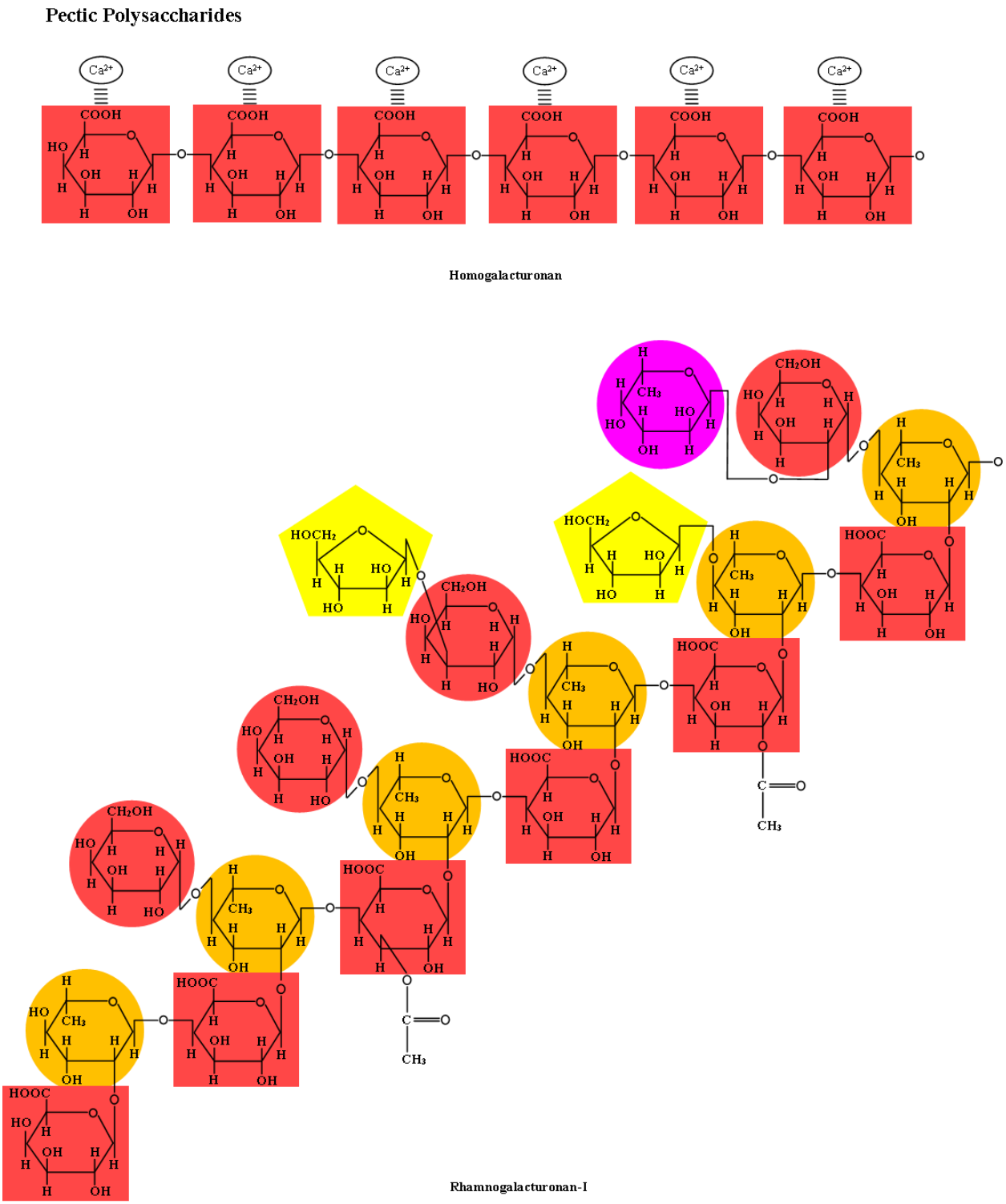


Figure 2.6. Chemical structure of homogalacturonan and rhamnogalacturonan-I. Adapted from Albersheim et al. (2011b).

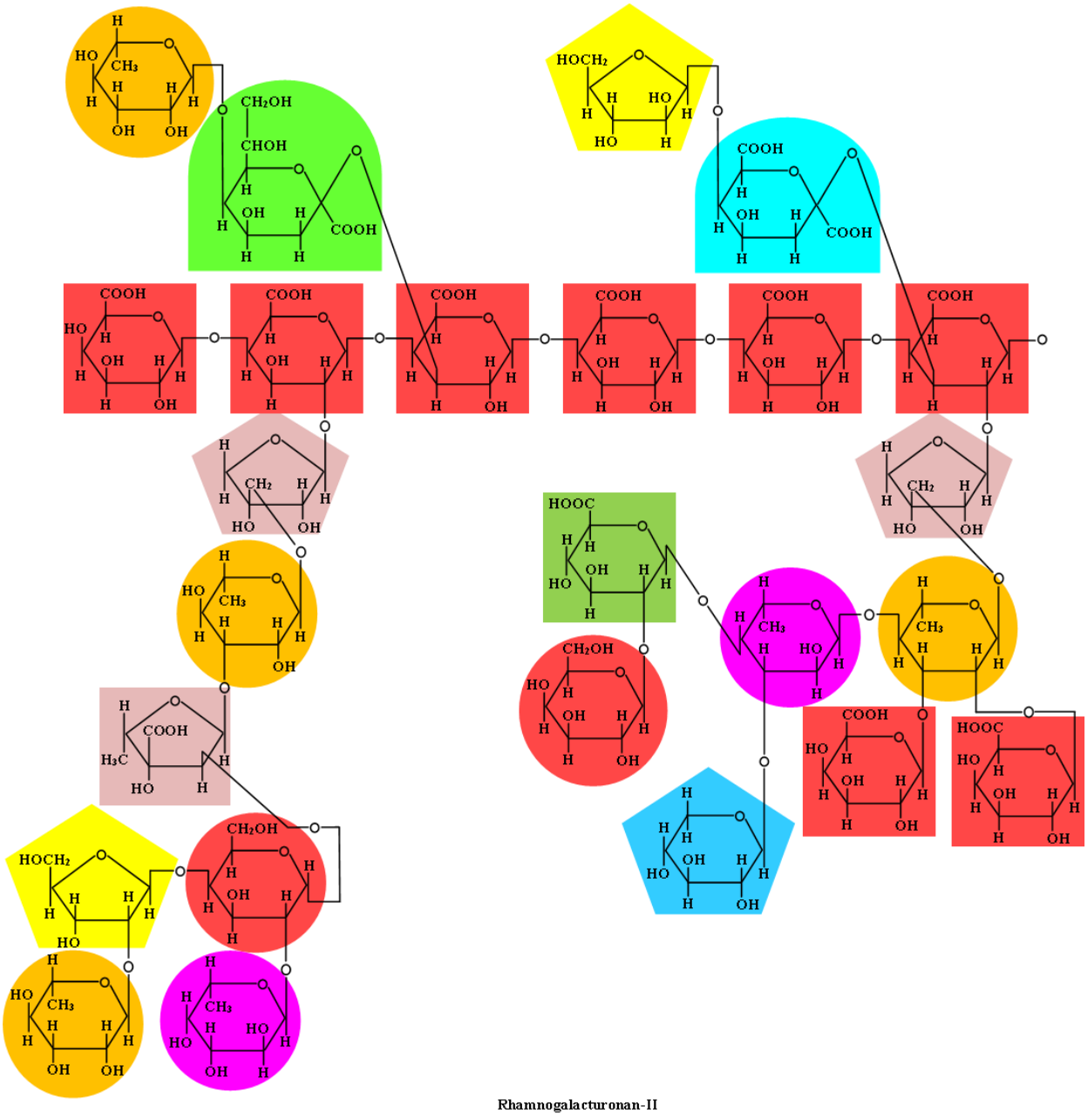
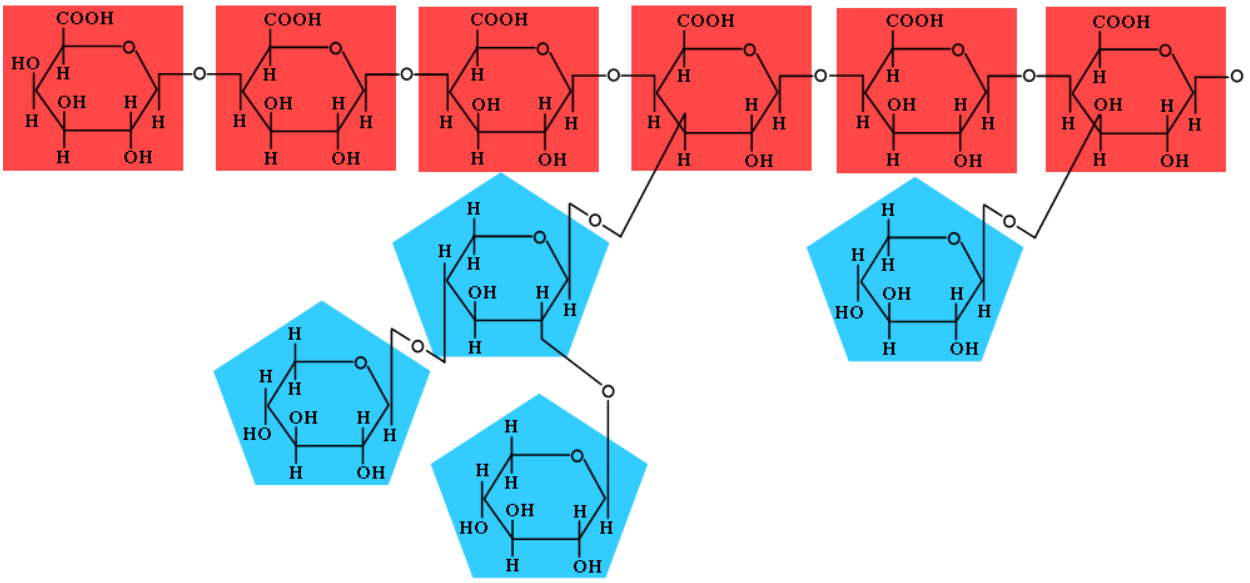
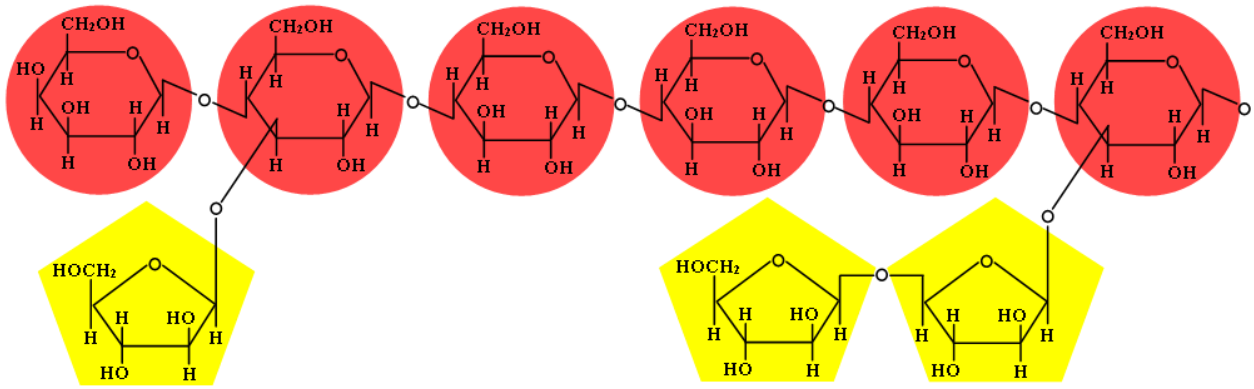


Figure 2.7. Chemical structure of rhamnogalacturonan-II. Adapted from Albersheim et al. (2011b).



Xylogalacturonan



Arabinogalactan-I

Figure 2.8. Chemical structure of xylogalacturonan and arabinogalactan-I.

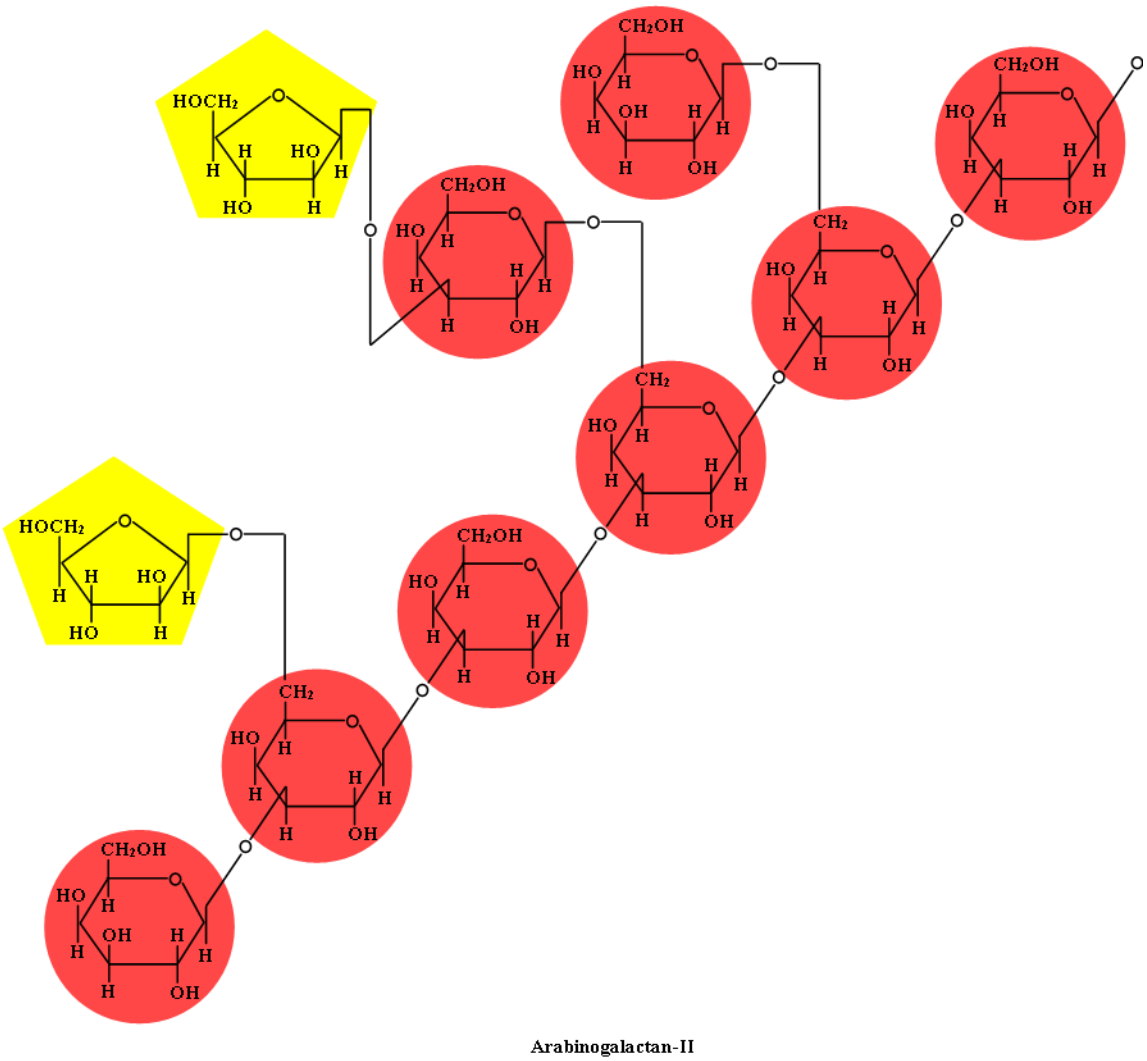


Figure 2.9. Chemical structure of arabinogalactan-II.

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CHAPTER 3: ANALYSIS FOR LOW-MOLECULAR-WEIGHT CARBOHYDRATES IS NEEDED TO ACCOUNT FOR ALL ENERGY-CONTRIBUTING NUTRIENTS IN SOME FEED INGREDIENTS, BUT PHYSICAL CHARACTERISTICS DO NOT PREDICT *IN VIVO* DIGESTIBILITY OF DRY MATTER

ABSTRACT: An experiment was conducted to quantify nutrient and fiber fractions of feed ingredients and to determine *in vitro* apparent ileal digestibility (IVAID) and *in vitro* apparent total tract digestibility (IVATTD) of DM and OM in each ingredient. Ten ingredients that vary in fiber concentration and composition were used: corn, wheat, soybean meal, canola meal, distillers dried grains with solubles (DDGS), corn germ meal, copra expellers, sugar beet pulp (SBP), synthetic cellulose (SF), and pectin. Correlations between chemical and physical characteristics of ingredients and IVAID and IVATTD of DM and OM were determined. The physical characteristics measured included bulk density, water binding capacity (WBC), swelling, and viscosity. The analyzed GE was compared with values for GE calculated from all energy-contributing components. Results indicated that the analyzed chemical composition of most ingredients added to 100% or greater, except for DDGS, SBP, and SF, where nutrients added to only 94.29, 88.90, and 96.09%, respectively. The difference between the sum of the calculated GE of the analyzed components and the analyzed GE of the ingredients ranged from -2.25 MJ/kg in DDGS to 1.74 MJ/kg in pectin. No correlation was observed between swelling, WBC, or viscosity and IVAID or IVATTD of DM or OM. The concentration of insoluble dietary fiber (IDF) and total dietary fiber (TDF) was negatively correlated ($P < 0.05$) with IVAID and IVATTD of DM and OM. There was a tendency for NDF ($r = -0.60$) and ADF ($r = -0.61$) to be

negatively correlated ($P < 0.10$) with IVAID of DM. However, no correlation was observed between the concentration of CP, GE, acid hydrolyzed ether extract, lignin, or soluble dietary fiber and IVAID and IVATTD of DM and OM. The stronger correlations between IDF, TDF, and insoluble non-starch polysaccharides and IVAID and IVATTD of DM and OM than between ADF and NDF and IVAID and IVATTD of DM and OM indicates that the concentration of TDF in feed ingredients is a better predictor of the digestibility of DM and OM than values for NDF and ADF. In conclusion, the calculated GE of some feed ingredients was in agreement with the analyzed GE, which gives confidence that energy contributing components were accounted for, but for DDGS and SBP, it was not possible to account for all analyzed GE. Concentrations of IDF and TDF, but not the physical characteristics of feed ingredients, may be used to estimate IVAID and IVATTD of DM and OM in feed ingredients.

Key words: energy, *in vitro* digestibility, physicochemical characteristics, total dietary fiber

INTRODUCTION

Diets fed to pigs have changed from being based primarily on cereal grains and soybean meal (**SBM**) to containing more byproducts and alternative ingredients (Zijlstra and Beltranena, 2013). Byproducts from the grain processing industry such as corn distillers dried grains with solubles (**DDGS**) and corn germ meal have relatively high concentrations of dietary fiber and may be fed to pigs without affecting growth performance (Weber et al., 2010; Xu et al., 2010; Cromwell et al., 2011) although that is not always the case (Whitney et al., 2006; Linneen et al., 2008). However, the implications of including more fiber in diets fed to pigs are not completely understood. Physical characteristics of dietary fiber such as bulk density, swelling, water binding capacity, and viscosity may negatively influence the digestion and availability of nutrients in

feed ingredients (Urriola et al., 2013), but limited information about the correlation between physical characteristics of feed ingredients and digestibility of nutrients is available.

Analyzing all chemical components in feed ingredients is challenging and values presented in feed composition tables usually do not add to 100% (Sauvant et al., 2004; Villamide et al., 2010; NRC, 2012), which indicates that not all nutrients or energy contributing components are accounted for. It is, however, likely that if all energy-containing components in feed ingredients are accounted for, it may be possible to predict the energy in the ingredients with greater accuracy. Therefore, the objectives of this study were to test the hypothesis that calculated GE from all energy-containing components in feed ingredients will equal analyzed GE in the ingredient if all chemical fractions are accounted for. The second hypothesis was that correlations exist between the physicochemical characteristics of feed ingredients and *in vitro* apparent ileal digestibility (**IVAID**) and *in vitro* apparent total tract digestibility (**IVATTD**) of DM and OM.

MATERIALS AND METHODS

Feed Ingredients

Ten feed ingredients that vary in fiber concentration and composition were obtained. Corn (Premier Cooperative, Philo, IL) and wheat (Siemers, Teutopolis, IL) were the 2 cereal grains used, and conventional dehulled SBM (Solae LLC, Gibson City, IL) and conventional canola meal (Dow AgroSciences, Indianapolis, IN) were obtained to represent oilseed meals that are used as protein sources in swine diets. Corn distillers dried grains with solubles (One Earth Energy LLC, Gibson City, IL), corn germ meal (Archer Daniels Midland, Decatur, IL), copra expellers (CoolStance, Stance Equine, Kenmore, Australia), and sugar beet pulp (Midwest Agri-

Commodities Company, San Rafael, CA) are co-products from commodity industries and represent high-fiber ingredients with varying degree of soluble fiber that are used in the feed industry. Synthetic cellulose (Solka-Floc 100 FCC, International Fiber Corporation, North Tonawanda, NY) and pectin (Pacific Pectin Inc., Oakhurst, CA) are purified synthetic sources of insoluble and soluble fiber, respectively, that were also included in the experiment, although these ingredients are usually not included in commercial diets fed to pigs.

Chemical Analyses

All chemical analyses were performed in duplicates. Feed ingredients were analyzed for DM by oven drying at 135°C for 2 h (Method 930.15; AOAC Int., 2007) and for ash (Method 942.05; AOAC Int., 2007). The concentration of N in all samples 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 × 6.25. Amino acids were analyzed in all samples on a Hitachi Amino Acid Analyzer (Model L8800, Hitachi High Technologies America Inc., Pleasanton, CA) using ninhydrin for postcolumn derivatization and norleucine as the internal standard. Before analysis, samples were hydrolyzed with 6*N* HCl for 24 h at 110°C [Method 982.30 E(a); AOAC Int., 2007]. Methionine and Cys were analyzed as Met sulfone and cysteic acid after cold performic acid oxidation overnight before hydrolysis [Method 982.30 E(b); AOAC Int., 2007]. Tryptophan was determined after NaOH hydrolysis for 22 h at 110°C [Method 982.30 E(c); AOAC Int., 2007]. Samples were analyzed for GE on an isoperibol bomb calorimeter (Model 6300, Parr Instruments, Moline, IL) using benzoic acid as the internal standard. Ingredients were also analyzed for total starch (Thivend et al., 1972) and resistant starch (Muir and O'Dea, 1992; 1993). Glucose, fructose, maltose, sucrose, stachyose, and

raffinose were analyzed by HPLC using a pulsed amperometric detector (Dionex Tech. Notes 21 & 92, Sunnyvale, CA). Ingredients were also analyzed for ADF and NDF using Ankom Technology methods 12 and 13, respectively, using the Ankom^{2000} 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). Total dietary fiber (**TDF**) was determined by analyzing for insoluble and soluble dietary fiber (**IDF** and **SDF**, respectively; Method 991.43, AOAC Int., 2007) using the Ankom^{TDF} Dietary Fiber Analyzer (Ankom Technology, Macedon, NY). Calcium and total P were measured using the inductively coupled plasma (**ICP**) spectroscopy method (Method 985.01 A, B, and C; AOAC, 2007) after wet ash sample preparation [Method 975.03 B(b); AOAC Int., 2007]. Copper, K, Mg, Mn, and Zn were measured by flame atomic absorption spectroscopy after wet ash sample preparation (Method 975.03 B(b); AOAC Int., 2007). Sulfur was measured by a gravimetric method (Method 956.01; AOAC Int., 2007) and I was measured by a volumetric method (Method 935.14; AOAC Int., 2007). Selenium was also determined [Method 996.16(G); AOAC Int., 2007] and Cl was measured by manual titration (Method 943.01; AOAC Int., 2007). The chromium concentration in ingredients was determined using an ICP Atomic Emission Spectrometric method (Method 990.08; AOAC Int., 2007). Samples were prepared using nitric acid-perchloric acid [Method 968.08D(b); AOAC Int., 2007]. Acid hydrolyzed ether extract (**AEE**) was analyzed by acid hydrolysis using 3*N* HCl (Ankom^{HCl}, Ankom Technology, Macedon, NY) followed by crude fat extraction using petroleum ether (Ankom^{XT15}, Ankom Technology, Macedon, NY). Canola meal was analyzed for glucosinolates (Method Ak 1-92; AOCS, 1998) and all ingredients were also analyzed for phytic acid (Ellis et al., 1977). Sinapine in canola meal and SBM were extracted using dimethylformamide and extracts were analyzed

for sinapine thiocyanate by reverse phase ultra-performance liquid chromatography with ultra violet detection (SOP-208, EPL Bio Analytics Services, Niantic, IL). Soluble condensed tannins were extracted from canola meal and SBM using sodium meta-bisulfite in 70:30 (v/v) acetone:deionized water, leaving insoluble condensed tannins in the residue, and both soluble and insoluble condensed tannins were hydrolyzed using 95:5 (v/v) butanol:concentrated HCl with added iron salt before analysis by ultraviolet-visible spectrophotometer (SOP-206, EPL Bio Analytics Services, Niantic, IL). Corn, wheat, DDGS, corn germ meal, and sugar beet pulp were analyzed for fructo-oligosaccharides and inulin by refractive index HPLC using a Phenomenex Rezex RHM column (Campbell et al., 1997). Briefly, 1.0 g of sample for each analysis was extracted at 85°C for 15 min and then was cooled and analyzed on the same day. The mobile phase for pure water had a flow rate of 0.6 mL/min. Distillers dried grains with solubles and corn germ meal were also analyzed for glycerol using HPLC (GA-SOP-419, Gorge Analytical, Hood River, OR).

Physical Characteristics

All analyses for physical characteristics were performed in triplicates with the exception of viscosity, which was analyzed in quadruplicates. The measured physical characteristics of the ingredients included bulk density, swelling, water binding capacity (**WBC**), and viscosity. Bulk density was determined by pouring samples into a 250 mL beaker and leveling off the top before weighing the sample as described by Cromwell et al. (2000). Swelling was measured using a procedure modified after Serena and Bach Knudsen (2007). Briefly, 0.3 g of sample was weighed into a 15 mL conical centrifuge tube and dissolved in 10 mL of 0.9% NaCl with 0.02% NaN_3 and placed in a shaking water bath at 39°C for 20 h. Samples were allowed to settle for 1 h before the swelling capacity was measured by reading the volume the fiber occupied. Water

binding capacity was measured using a procedure modified after Robertson et al. (2000). Briefly, 2 g of sample was hydrated in 50 mL of distilled water for 18 h in pre-weighed centrifuge tubes. Samples were then centrifuged (2,000 × *g*; 20 min) and the supernatant was decanted by carefully inverting the tube to allow water to drain and weights of the pellets were recorded.

Viscosity was measured using a procedure modified after Serena and Bach Knudsen (2007) and was expressed in centipoise (**cP**). Briefly, 2 g of sample was dissolved in 10 mL of 0.9% NaCl and 0.02% NaN_3 solution and extracted in a water bath at 40°C for 1 h. The sample was then centrifuged at 3,500 × *g* for 25 min at 23°C and 0.5 mL of the supernatant was removed by suction. Viscosity of the supernatant was measured using a Brookfield LV-DV-2T viscometer (Brookfield Eng. Lab. Inc., Middleboro, MA) with a Wells-Brookfield Cone/Plate extension and a CPA-40Z cone spindle. Values were reported as the average shear rate of 225, 240, 255, 270, 285, and 300 s^{-1}. Viscosity of solutions was measured at room temperature (23°C).

In Vitro Ileal and Total Tract Digestibility

The IVATTD was determined using a 3-step procedure modified from Boisen and Fernández (1997). The procedure simulates gastric and small intestinal digestion and large intestinal fermentation. Three separate subsamples of each ingredient were used providing 3 replicates per ingredient. Samples were incubated in 125mL Erlenmeyer flasks placed in a water bath at 39ºC with constant shaking for 2 h. Pepsin from porcine gastric mucosa (Sigma-Aldrich, St. Louis, MO) was added to the flasks and the pH was maintained at 2 by adding HCl. After 2 h, the pH was adjusted to 6.8 using NaOH, and pancreatin from porcine pancreas (Sigma-Aldrich, St. Louis, MO) was added to each flask. This step represented the digestion processes in the stomach and the small intestine, respectively. Viscozyme enzyme (Sigma-Aldrich, St. Louis, MO) was added in the third step to degrade soluble fiber and samples were incubated at 39ºC for

18 h (Jaworski et al., 2015). After the third incubation, contents of the flasks were emptied and filtered into pre-weighed glass crucibles and DM was determined in the residue to calculate IVATTD of DM. Ash analysis was performed on the remaining residue to calculate IVATTD of OM. For IVAID, the same procedure was used, but the process was discontinued after the 2nd step and DM was determined in the residue to calculate IVAID of DM and the remaining residue was analyzed for ash to calculate IVAID of OM.

Calculations and Statistical Analysis

Concentrations of TDF (IDF + SDF), cellulose (ADF – lignin), insoluble hemicelluloses (NDF – ADF), non-starch polysaccharides (**NSP**; TDF – lignin), insoluble NSP (NSP – SDF), and non-cellulosic NSP (NSP – cellulose) were calculated for all ingredients. Concentration of levans (fructo-oligosaccharides – inulin) was also calculated for corn, wheat, DDGS, corn germ meal, and sugar beet pulp. The calculated GE was the sum of all energy-contributing components calculated according to Eq. [**1**], which was modified from Atwater and Bryant (1900):

$$\text{Calculated GE, MJ/kg} = (\text{AEE} \times 39.36\ \text{MJ/kg}) + (\text{total AA} \times 23.45\ \text{MJ/kg}) + [(\text{total starch} + \text{fructo-oligosaccharides} + \text{NSP}) \times 17.58\ \text{MJ/kg}] + [(\text{glucose} + \text{fructose} + \text{sucrose} + \text{stachyose} + \text{raffinose} + \text{tannins} + \text{sinapine}) \times 15.49\ \text{MJ/kg}] + (\text{lignin} \times 29.13\ \text{MJ/kg}), \quad [\mathbf{1}]$$

where lignin is the concentration of acid detergent lignin (**ADL**). The GE contribution from lignin was calculated by multiplying the concentration of lignin in the feed ingredient by the average GE of 4 commercially available lignin preparations (Jung et al., 1999).

Data for physical characteristics and the *in vitro* analyses were analyzed using the MIXED procedure of SAS (SAS Inst. Inc., Cary, NC) with each feed ingredient as the fixed effect and replication as the random effect. Correlation coefficients among the physicochemical characteristics of the 10 feed ingredients and the IVAID and IVATTD of DM and OM were

determined using the CORR procedure of SAS treating each ingredient as one observation. Each replicate corresponding to a feed ingredient for analysis was considered the experimental unit. Statistical significance and tendency were considered at $P < 0.05$ and $0.05 \leq P < 0.10$, respectively.

RESULTS

Dry matter concentrations ranged from 85.42% in corn to 96.54% in copra expellers and the concentration of CP ranged from 6.56% in corn to 46.90% in SBM (Table 3.1). Concentrations of NDF and ADF ranged from 6.30% and 2.40% in wheat to 48.14% and 23.79% in copra expellers. Concentrations of glycerol in DDGS and corn germ meal were negligible.

The concentration of IDF ranged from 10.71% in corn to 44.57% in sugar beet pulp and the concentration of SDF ranged from 0.06% in corn to 3.97% in sugar beet pulp. Sugar beet pulp had numerically greater concentrations of IDF and SDF than all other co-products and corn germ meal had numerically greater concentrations of IDF and SDF than DDGS.

Copra expellers and DDGS had numerically greater concentrations of AEE (11.17 and 9.58%, respectively) than the other ingredients, which corresponded with greater GE in these ingredients. The concentration of ash ranged from 1.05% in corn to 7.14% in canola meal.

The analyzed nutrient composition of most ingredients added to 100% or greater, except for DDGS, sugar beet pulp, and synthetic cellulose, where nutrients added to only 94.29, 88.90, and 96.09%, respectively. However, the difference between the calculated GE of the analyzed components and the GE of the ingredients ranged from -2.25 MJ/kg in DDGS to 1.74 MJ/kg in pectin. The percentage of analyzed GE that was accounted for in the calculated GE ranged from 87.58% in sugar beet pulp to 112.31% in pectin.

The concentration of Lys ranged from 0.27% in corn to 2.99% in SBM (Table 3.2). Concentrations of individual minerals varied greatly among ingredients, but as expected, the concentration of P was the greatest for all ingredients with the exception of synthetic cellulose and pectin (Table 3.3). Bulk density was less ($P < 0.05$) in DDGS than in corn, wheat, SBM, canola meal, corn germ meal, synthetic cellulose, and pectin, but not different from copra expellers and sugar beet pulp (Table 3.4). Swelling capacity ranged from 2.48 L/kg DM in corn to 9.01 L/kg DM in pectin and WBC ranged from 1.00 g/g in wheat to 4.09 g/g in sugar beet pulp. Viscosity was greater ($P < 0.05$) in sugar beet pulp (1.45 cP) than in corn (1.12 cP), SBM (1.10 cP), canola meal (1.00 cP), DDGS (1.07 cP), corn germ meal (1.17 cP), and synthetic cellulose (0.93 cP), but not different from that in wheat (1.30 cP) and copra expellers (1.27 cP).

The IVAID of DM was greater ($P < 0.05$) in copra expellers than in corn, corn germ meal, sugar beet pulp, and synthetic cellulose, but not different from DDGS (Table 3.5). The IVAID of DM was greater ($P < 0.05$) in corn than in sugar beet pulp and synthetic cellulose, but not different from corn germ meal. The IVAID of OM was greater ($P < 0.05$) in corn germ meal than in sugar beet pulp and synthetic cellulose, but not different from corn. The IVATTD of DM and OM were different ($P < 0.05$) among all ingredients.

The concentration of NDF was positively correlated ($P < 0.05$) with concentrations of ADF, IDF, cellulose ($r = 0.93$), and insoluble hemicelluloses ($r = 0.95$), but was negatively correlated ($P < 0.01$) with bulk density (Table 3.6). The concentration of ADF was positively correlated ($P < 0.05$) with IDF, cellulose ($r = 0.96$), and insoluble hemicelluloses ($r = 0.79$), but was negatively correlated ($P < 0.05$) with bulk density. The concentration of IDF was positively correlated ($P < 0.01$) with TDF, cellulose ($r = 0.80$), NSP ($r = 0.78$), and insoluble NSP ($r = 0.99$) whereas SDF was positively correlated ($P < 0.05$) with swelling and viscosity. There was a

tendency ($P < 0.10$) for GE to be positively correlated with NDF and ADF, and a tendency for GE to be negatively correlated ($P < 0.10$) with SDF and viscosity. There was also a tendency ($P < 0.10$) for TDF to be positively correlated with WBC. Water binding capacity was positively correlated ($P < 0.01$) with swelling capacity, and there was a tendency ($P < 0.10$) for swelling capacity to be positively correlated with viscosity.

There was a tendency for bulk density to be positively correlated ($P < 0.10$) with IVAID of DM and IVAID of OM (Table 3.7). However, no correlation was observed between swelling, WBC, or viscosity and IVAID or IVATTD of DM and OM. The concentration of IDF was negatively correlated ($P < 0.01$) with IVAID of DM and OM and IVATTD of DM and OM. The concentration of TDF was negatively correlated ($P < 0.05$) with IVAID of DM and IVATTD of DM and OM. The IVAID of DM and OM were negatively correlated ($P < 0.05$) with the concentrations of cellulose and insoluble NSP. The concentrations of NSP, insoluble NSP, and non-cellulosic NSP were negatively correlated ($P < 0.05$) with IVATTD of DM and OM. There was a tendency for IVAID of DM to be negatively correlated ($P < 0.10$) with NDF ($r = -0.60$), ADF ($r = -0.59$), insoluble hemicelluloses ($r = -0.55$), and NSP ($r = -0.63$). However, no correlation was observed between the concentration of CP, GE, AEE, lignin, or SDF and IVAID or IVATTD of DM and OM. The IVAID of DM was perfectly correlated ($P < 0.01$) with IVAID of OM and IVATTD of DM was perfectly correlated ($P < 0.01$) with IVATTD of OM. The IVAID of DM was positively correlated ($P < 0.01$) with IVATTD of DM and IVATTD of OM and IVAID of OM was positively correlated ($P < 0.01$) with IVATTD of DM and IVATTD of OM.

DISCUSSION

Two sources of cereal grains, 2 sources of oilseed meals, 4 sources of co-products, and 2 sources of synthetic fiber were used to obtain a wide range of IDF and SDF concentrations among ingredients. The ingredients varied in chemical composition and measurable physical characteristics. With the exception of canola meal and copra expellers, the analyzed sum of the components for each feed ingredient differed from 100.00% by more than 1.00%, and analyzed components in corn, wheat, SBM, corn germ meal, and pectin totaled between 2 and 6% more than 100%. There may be a number of reasons for this observation. Dry matter was not measured at each analysis, which may affect the results. Inaccuracies in analyses may also happen due to human factors or non-homogenized samples. Another possible reason is that CP is calculated by multiplying the concentration of N by 6.25, with the assumption that all protein in the feed is composed of 16% N. It may be argued that the sum of total indispensable and dispensable AA should be used when adding chemical components to 100% instead of CP because only AA can be used in protein synthesis. However, this disregards the non-protein N and other AA also present in the feed and it is, therefore, most likely more accurate to use the calculated value for CP than the total concentration of AA.

Fructo-oligosaccharides serve as reserve carbohydrate compounds that are synthesized and stored in the vacuole and are often localized in the stems, leaves, roots, and kernels in grasses such as wheat and barley (Heldt and Piechulla, 2011). Fructo-oligosaccharides may be mobilized to preserve the carbon flow to the kernel during times of insufficient photosynthetic products (Verspreet et al., 2013). To our knowledge, the concentration of fructo-oligosaccharides in DDGS and corn germ meal has not been previously reported. It is possible that DDGS or corn germ meal contain bacterial inulin or levans produced by co-cultures of yeast and bacteria used

in the fermentation process of ethanol production, which may explain the presence of fructo-oligosaccharides in both ingredients. *Saccharomyces cerevisiae* is the most used source of yeast in ethanol fermentation, but it is not uncommon for an ethanol plant to encounter microbial contamination (Beckner et al., 2011). Lactic acid bacteria are common contaminants due to their tolerance for ethanol, low pH, and high temperature (Narendranath and Power, 2005). Fructo-oligosaccharide synthesis has been observed in several lactic acid bacteria including *Lactobacillus reuteri* and *Leuconostoc citreum*, both of which are contaminants of ethanol fermentations (van Hijum et al., 2006; Beckner et al., 2011).

The concentration of fructo-oligosaccharides in corn, wheat, and sugar beet pulp used in this experiment was greater than what was reported by Campbell et al. (1997), wheat has also been reported to contain 1 to 4% fructo-oligosaccharides on a DM basis (Bornet, 2001) so it appears there are some differences among varieties of wheat. The sugar beet pulp used in this experiment contained added molasses, which contributed to a high concentration of sucrose, which levansucrase- or inulosucrase-secreting bacteria may convert to fructo-oligosaccharides (van Hijum et al., 2006; BeMiller, 2007). This may be the reason fructo-oligosaccharides were detected in the sugar beet pulp used in this experiment. Differences in the concentration of fructo-oligosaccharides among different samples of the same ingredient may also be due to sample origin, sampling technique, and extraction method used (Campbell et al., 1997).

Wheat DDGS was reported to contain 4.6% glycerol (Cozannet et al., 2010), but only negligible levels of glycerol were observed in the corn DDGS and corn germ meal used in this experiment. Nevertheless, by complementing the traditional feed analyses with analyses for nutrients that are not typically analyzed we were able to characterize the entire nutritional profile of the ingredients used in this study with the exception of DDGS, sugar beet pulp, and synthetic

cellulose. Incomplete nutritional profiles has traditionally been a problem with values in most feed composition tables. As an example, the analyzed concentration of nutrients in DDGS and sugar beet pulp is 90.85 and 74.07% in NRC (2012) and 90.90 and 76.40% in Sauvant et al. (2004), whereas in this experiment, the analyzed components in these 2 ingredients were 94.29 and 88.90%, respectively. However, the fact that 5 of the 10 ingredients analyzed between 102 and 106% also indicates that additional work to improve feed ingredient analyses is needed.

Prediction equations have traditionally been used to predict the energy content of feed ingredients, but in several cases, the analyzed components in the ingredients did not add to 100% (Pedersen et al., 2007; Anderson et al., 2012; Kerr et al., 2013). This may result in erroneous prediction equations because it is possible that some of the components that were not analyzed also contributed energy to the ingredients. To predict the energy value of a feed ingredient, it is, therefore, important that all energy-contributing components are accounted for and the current data indicate that this is possible if traditional analyses are complemented by additional analyses that primarily aim at analyzing soluble carbohydrates.

In the current experiment, values for the analyzed GE of all ingredients were compared with values calculated as the sum of the theoretical GE of each energy-containing nutrient because a difference between the 2 values indicates that an energy-contributing component is unaccounted for. Thus, the comparison of the 2 values gives an indication of the accuracy of the component analyses for each ingredient. As an example, although the measured components of canola meal added to 100.97%, the calculated GE was 0.56 MJ/kg less than the analyzed GE indicating that some energy-contributing components in canola meal were not accounted for. The reason for this observation may be that sinapine, the most common phenolic compound in canola meal (Barthet and Daun, 2011), and tannins also contribute to the analyzed GE because their

organic structure consisting of polyphenolic molecules contribute energy during combustion. Combined, sinapine and tannins contributed more than 1.50% to the DM in canola meal so it is likely that this contributed to the fact that the calculated GE for canola meal was slightly less than the analyzed GE. Nevertheless, with the exception of corn, DDGS, sugar beet pulp, and pectin, the percentage of calculated GE was within 4% of analyzed GE indicating that for 6 of the 10 ingredients, the analyzed components appear to be accurate. For DDGS and sugar beet pulp, the analyzed concentrations of all components were less than 100%, which is likely the reason that the calculated GE was less than analyzed GE. So for these 2 ingredients, there are chemical components present in addition to the components analyzed in this experiment. For corn and pectin, it is possible that the reason for the differences between calculated and analyzed GE is that there may have been inaccuracies or overlaps in quantifying concentrations of energy-contributing nutrients (i.e., carbohydrate analysis). As an example, residual fructo-oligosaccharides may remain in the SDF fraction and, although unlikely, it is also possible that starch is not completely hydrolyzed in the TDF analysis resulting in residual resistant starch in the IDF fraction. Another possible reason is that the Atwater factors used to calculate GE from nutrients may not be applicable to every ingredient (Novotny et al., 2012).

A GE value was also assigned to lignin because lignin is combustible and contributes to the GE of an ingredient when analyzed using bomb calorimetry. The GE value for lignin reported by Jung et al. (1999) was used, but this value was derived from the average GE of 4 commercially available lignin preparations that may not be completely representative of the lignin that is present in the 10 feed ingredients used in this experiment. The complete structure of lignin has not been elucidated because it varies greatly in size, component subunits, location in the plant, and among different species of plants (Albersheim et al., 2011). The concentration of

lignin in the samples may also be underestimated because the ADL procedure used in this experiment underestimates the concentration of lignin in forages compared with the Klason lignin procedure (Jung et al., 1999). However, it is not known if this is also the case for non-forage feed ingredients. Therefore, it is imperative that a method to characterize and quantify lignin in specific feed ingredients be developed. This may allow for a more accurate analysis of GE, which may result in improved agreement between the analyzed and calculated GE of feed ingredients.

The concentrations of total and resistant starch in wheat are slightly greater than published values, whereas resistant starch in corn was in agreement with reported values (Bednar et al., 2000; Murray et al., 2001). The concentration of resistant starch in corn and wheat may explain the low IVAID of DM and OM and greater IVATTD of DM and OM for these 2 ingredients. The 55% increase from IVAID to IVATTD of DM in sugar beet pulp indicates that the fiber in sugar beet pulp is poorly digested in the small intestine, but highly fermentable in the hindgut. This is most likely a result of the high concentration of SDF in sugar beet pulp because SDF is much more fermentable than IDF (Urriola et al., 2010; Zhang et al., 2013). In contrast, the low IVAID and IVATTD of DM in DDGS indicates that the fiber fraction in DDGS has a low utilization by pigs, which is in agreement with *in vivo* data (Urriola et al., 2010) and most likely is a result of the high concentration of IDF in the fiber in corn and DDGS (Pedersen et al., 2014; Jaworski et al., 2015). The low IVATTD of synthetic cellulose and the high IVATTD of pectin confirm that cellulose is an indigestible fraction of fiber, whereas pectin is close to 100% fermentable, which further confirms the high fermentability of SDF.

The strong positive correlation between WBC and swelling indicates that one of these hydration properties can be measured to predict the other. Swelling is defined as the volume fiber

occupies after hydration under specified conditions, which depends on WBC or the quantity of water that can be bound to a substrate (Bach Knudsen et al., 2013; Capuano, 2017). Processes that alter physical characteristics (i.e., grinding) may also affect the hydration properties of fiber, and therefore, the same batch of sample should be used in subsequent analyses without further processing (Guillon and Champ, 2000).

The stronger correlation between IDF and TDF and IVAID and IVATTD of DM and OM than the correlations between NDF and ADF and IVAID and IVATTD indicates that measuring IDF and TDF in fiber results in an improved prediction of the digestibility of GE compared with values for NDF and ADF. This observation is in agreement with Anderson et al. (2012) and Kerr et al. (2013) who also concluded that TDF predicts energy digestibility better than analyzed values for ADF and NDF, which may be because TDF, unlike ADF and NDF, also includes the SDF fraction. However, values for TDF are less reproducible than values for crude fiber or ADF and NDF (Mertens, 2003). Alternatively, the concentration of insoluble NSP may also be calculated and used to evaluate digestibility of GE because insoluble NSP is also strongly correlated with both IVAID and IVATTD of DM and OM.

The observation that physical characteristics of the feed ingredients were not correlated with IVAID or IVATTD of DM or OM indicates that these parameters do not influence digestibility of DM or OM in feed ingredients. These results are in agreement with data from Serena and Bach Knudsen (2007), who reported that IVATTD of OM and lignin was correlated with soluble and insoluble non-cellulosic NSP, but not with WBC or swelling. It is likely that because of the relatively high concentration of water in the small intestine of pigs, physical characteristics of feed ingredients do not result in measurable changes to nutrient and energy digestibility.

Viscosity is defined as a fluid's resistance to flow due to the physical entanglement among polysaccharides within the solution and is dependent on the primary structure, molecular weight, and concentration of fiber (Dikeman and Fahey, 2006; Bach Knudsen et al., 2013). It is possible that the reason for the lack of correlation between viscosity and IVAID or IVATTD of DM or OM is that although the thermochemical conditions of the *in vitro* procedure simulates that of the gastrointestinal tract, the physical setup does not allow for an accurate representation of the flow behavior of digesta in the intestinal lumen that defines the rate of digestion and absorption of nutrients (Takahashi, 2011). A lack of correlation may also be a result of very low viscosity measurements from the ingredients used in this experiment. Only an aliquot of the supernatant after centrifugation is used in viscosity measurements (Johansen et al., 1997; Serena and Bach Knudsen, 2007), however, this disregards the effect of large particles on viscosity (Takahashi and Sakata, 2002).

CONCLUSION

It is possible to analyze nutrient composition of some, but not all, feed ingredients to account for all nutrients and GE. However, future refinements of analyses are needed to avoid overlapping fractions in analyses such as analyzed starch and analyzed dietary fiber. Likewise, it is not always that GE in ingredients calculated from analyzed energy-containing components equal analyzed GE, even if the total analyzed components are close to 100%. It is possible that some of these inaccuracies are a result of a lack of knowledge about the GE value of lignin, tannins, sinapine, and possibly other components in the ingredient. Physical characteristics of feed ingredients do not appear to influence estimates for IVAID or IVATTD of DM or OM, but the concentration of fiber fractions (i.e., IDF, TDF, cellulose, and insoluble NSP) may be used to

estimate IVAID and IVATTD of DM. If possible, IDF and TDF should be measured instead of ADF and NDF because TDF and IDF are better correlated with digestibility of DM and OM than ADF and NDF.

TABLES

Table 3.1. Analyzed nutrient composition of corn, wheat, soybean meal, canola meal, distillers dried grains with solubles, corn germ meal, copra expellers, sugar beet pulp, synthetic cellulose, and pectin, as-fed basis

	Ingredient[1]									
Item	Corn	Wheat	SBM	CM	DDGS	CGM	CE	SBP	SF	Pectin
Analyzed GE, MJ/kg	15.58	15.90	17.20	17.77	19.00	17.50	19.73	15.66	16.57	14.17
DM, %	85.42	86.81	88.80	88.90	88.77	89.28	96.54	92.48	98.35	91.50
CP, %	6.56	10.80	46.90	40.52	25.52	23.91	21.65	7.27	0.71	1.68
AEE[2], %	3.06	1.86	1.55	4.06	9.58	2.97	11.17	2.00	0.38	0.14
NDF, %	8.51	11.36	6.30	23.63	32.29	39.60	48.14	45.47	30.49	0.78
ADF, %	2.40	3.06	5.00	17.33	12.97	14.70	23.79	21.54	16.43	0.15
Lignin, %	0.47	0.69	0.16	7.39	2.29	4.29	5.14	2.46	ND	ND
Ash, %	1.05	1.61	6.78	7.14	5.91	2.61	5.63	6.96	0.04	1.62
OM, %	84.37	85.20	82.02	81.76	82.86	86.67	90.91	85.52	98.31	89.88
Tannins[3], %										
SCT	-	-	0.02	0.05	-	-	-	-	-	-

Table 3.1. (cont.)

ICT	-	-	0.04	0.32	-	-	-	-	-	-
Sinapine, %	-	-	ND	1.16	-	-	-	-	-	-
Glucosinolates, µmol/g	-	-	-	7.92	-	-	-	-	-	-
Glycerol, %	-	-	-	-	< 0.04	ND	-	-	-	-
Carbohydrates, %										
Total starch	64.71	60.01	5.80	1.87	5.11	19.20	4.02	3.88	ND	-
Resistant starch	9.72	12.83	4.41	1.79	1.30	2.91	3.54	3.55	ND	-
Glucose	0.19	0.16	ND	ND	0.26	0.06	0.12	0.20	ND	41.79
Fructose	0.15	0.09	ND	ND	0.11	0.41	0.58	0.16	ND	ND
Maltose	ND	ND	0.16	ND	0.37	ND	ND	ND	ND	ND
Sucrose	1.62	0.76	8.18	6.86	ND	0.07	9.36	10.55	ND	ND
Stachyose	ND	ND	6.01	2.34	ND	ND	ND	ND	ND	ND
Raffinose	0.28	0.51	1.42	0.66	ND	0.16	ND	0.29	ND	ND
FOS[4], %	2.09	2.53	-	-	1.54	4.33	-	1.53	-	-
Inulin	1.08	1.31	-	-	0.80	2.25	-	0.80	-	-

Table 3.1. (cont.)

Levan	1.01	1.22	-	-	0.74	2.08	-	0.73	-	-
TDF[5], %	10.76	11.40	17.84	26.42	34.66	39.78	43.84	48.54	93.31	51.69
IDF, %	10.71	10.93	16.70	25.44	34.38	38.47	42.05	44.57	93.16	0.09
SDF, %	0.06	0.47	1.14	0.98	0.29	1.31	1.79	3.97	0.15	51.60
Cellulose[6]	1.93	2.37	4.84	9.94	10.68	10.41	18.65	19.08	16.43	0.15
Insoluble hemicelluloses[7]	6.11	8.30	1.30	6.30	19.32	24.90	24.35	23.93	14.06	0.63
NSP[8]	10.29	10.71	17.68	19.03	32.37	35.49	38.70	46.08	93.31	51.69
Insoluble NSP[9]	10.24	10.24	16.54	18.05	32.09	34.18	36.91	42.11	93.16	0.09
Non-cellulosic NSP[10]	8.36	8.34	12.84	9.09	21.69	25.08	20.05	27.00	76.88	51.54
Calculated values										
Sum[11], %	105.05	102.92	105.84	100.97	94.29	104.22	99.83	88.90	96.09	105.42
Calculated GE[12], MJ/kg	16.82	16.27	17.86	17.21	16.75	17.78	19.17	13.71	16.56	15.91
Difference[13], MJ/kg	1.24	0.37	0.65	-0.56	-2.25	0.28	-0.56	-1.94	-0.01	1.74
Difference[14], %	107.97	102.36	103.80	96.85	88.17	101.63	97.16	87.58	99.97	112.31

[1]SBM = soybean meal; CM = canola meal; DDGS = distillers dried grains with solubles; CGM = corn germ meal; CE = copra expellers; SBP = sugar beet pulp; SF = synthetic cellulose; ND = not detected.

Table 3.1. (cont.)

[2]AEE = acid hydrolyzed ether extract.

[3]SCT = soluble condensed tannins; ICT = insoluble condensed tannins.

[4]FOS = fructo-oligosaccharides; Levans = FOS – inulin.

[5]TDF = total dietary fiber; IDF = insoluble dietary fiber; SDF= soluble dietary fiber.

[6]Cellulose = ADF – Lignin.

[7]Insoluble hemicelluloses = NDF – ADF.

[8]NSP = non-starch polysaccharides, TDF – Lignin.

[9]Insoluble NSP = NSP – SDF.

[10]Non-cellulosic NSP = NSP – Cellulose.

[11]Summation of moisture, ash, CP, AEE, TDF, Total starch, glucose, fructose, sucrose, stachyose, raffinose, and FOS.

[12]Calculated as (AEE × 39.36 MJ/kg) + (Total AA × 23.45 MJ/kg) + [(Total starch + FOS + NSP) × 17.58 MJ/kg] + [(glucose + fructose + sucrose + stachyose + raffinose) × 15.49 MJ/kg] + (lignin × 29.13 MJ/kg).

[13]The difference between the calculated gross energy of the components and the analyzed gross energy of the ingredient.

[14]The percentage of analyzed gross energy that is accounted for in the calculated gross energy.

Table 3.2. Analyzed amino acid composition of corn, wheat, soybean meal, canola meal, distillers dried grains with solubles, corn germ meal, copra expellers, sugar beet pulp, synthetic cellulose, and pectin, as-fed basis

	Ingredient[1]									
Item	Corn	Wheat	SBM	CM	DDGS	CGM	CE	SBP	SF	Pectin
Indispensable AA, %										
Arg	0.31	0.48	3.44	2.31	1.16	1.59	2.49	0.28	ND	0.06
His	0.20	0.24	1.22	1.01	0.70	0.68	0.41	0.23	ND	0.04
Ile	0.25	0.35	2.12	1.46	0.93	0.84	0.66	0.29	ND	0.06
Leu	0.83	0.68	3.62	2.67	2.92	1.86	1.29	0.49	ND	0.10
Lys	0.27	0.36	2.99	2.11	0.90	1.02	0.68	0.47	ND	0.12
Met	0.15	0.19	0.63	0.73	0.44	0.43	0.28	0.16	ND	0.02
Phe	0.34	0.44	2.36	1.52	1.22	1.04	0.85	0.29	ND	0.06
Thr	0.25	0.30	1.82	1.56	1.01	0.91	0.65	0.35	ND	0.06
Trp	0.06	0.15	0.66	0.53	0.20	0.22	0.18	0.07	< 0.02	< 0.02
Val	0.33	0.45	2.25	1.86	1.31	1.35	1.03	0.43	ND	0.07
Total	2.99	3.64	21.11	15.76	10.79	9.94	8.52	3.06	0.01	0.60

Table 3.2. (cont.)

Dispensable AA, %										
Ala	0.51	0.40	2.01	1.66	1.71	1.46	0.91	0.37	ND	0.07
Asp	0.47	0.56	5.21	2.55	1.57	1.71	1.69	0.56	ND	0.12
Cys	0.16	0.21	0.61	0.90	0.44	0.32	0.32	0.09	ND	0.02
Glu	1.26	2.71	8.32	6.66	3.33	3.23	3.66	0.74	0.01	0.19
Gly	0.29	0.45	1.96	1.92	0.99	1.31	0.89	0.33	ND	0.07
Pro	0.60	0.90	2.29	2.34	1.84	1.14	0.67	0.32	ND	0.08
Ser	0.33	0.44	2.11	1.36	1.21	1.04	0.85	0.34	ND	0.06
Tyr	0.13	0.17	1.67	1.07	0.87	0.65	0.44	0.25	ND	0.04
Total	3.75	5.84	24.18	18.46	11.96	10.86	9.43	3.00	0.01	0.65
Total AA, %	6.74	9.48	45.29	34.22	22.75	20.80	17.95	6.06	0.02	1.25
Calculated values										
Lys:CP ratio[2], %	4.12	3.30	6.38	5.21	3.53	4.27	3.14	6.46	-	7.14

[1]SBM = soybean meal; CM = canola meal; DDGS = distillers dried grains with solubles; CGM = corn germ meal; CE = copra expellers; SBP = sugar beet pulp; SF = synthetic cellulose; ND = not detected.

[2]The Lys:CP ratio was expressed as the concentration of Lys as a percentage of the concentration of CP in each sample (González-Vega et al., 2011).

Table 3.3. Analyzed mineral composition of corn, wheat, soybean meal, canola meal, distillers dried grains with solubles, corn germ meal, copra expellers, sugar beet pulp, synthetic cellulose, and pectin, as-fed basis

	Ingredient[1]									
Item	Corn	Wheat	SBM	CM	DDGS	CGM	CE	SBP	SF	Pectin
Ca, %	0.01	0.03	0.57	0.61	0.04	0.02	0.05	0.87	0.02	0.09
P, %	0.26	0.36	0.59	1.04	0.81	0.68	0.50	0.70	ND[2]	0.03
Phytate, %	0.85	1.15	1.62	2.65	0.26	1.66	0.96	< 0.14	< 0.14	< 0.14
Phytate P[3], %	0.24	0.32	0.46	0.75	0.07	0.47	0.27	-	-	-
Non-phytate P[4], %	0.02	0.04	0.13	0.29	0.74	0.21	0.23	-	-	-
Na, mg/kg	4.82	10.30	65.50	1,600	2,800	100	300	1,200	200	4,900
Mg, %	0.09	0.12	0.26	0.56	0.28	0.19	0.26	0.24	< 0.01	0.02
K, %	0.34	0.40	2.11	1.21	1.12	0.36	2.21	0.51	< 0.01	0.09
Cl, %	< 0.10	< 0.10	< 0.10	0.39	0.12	< 0.10	0.63	0.10	< 0.10	0.10
S, %	0.08	0.12	0.38	0.82	0.29	0.29	0.26	0.27	0.01	0.07
Fe, mg/kg	18.1	31.8	113.00	229.00	60.60	99.20	208.00	281.00	44.60	18.80
I, mg/kg	0.02	0.01	0.01	0.12	0.02	0.01	0.01	0.06	< 0.01	-

Table 3.3. (cont.)

Cu, mg/kg	1.34	5.85	13.00	5.53	6.73	6.36	31.4	6.79	0.09	1.20
Mn, mg/kg	3.60	30.60	36.30	51.00	10.60	9.82	33.70	54.30	1.82	2.10
Zn, mg/kg	18.30	27.20	38.30	55.40	45.00	89.90	47.50	9.74	1.10	2.90
Cr, mg/kg	0.20	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10	0.70	2.30	< 0.10	0.80
Co, mg/kg	< 0.13	< 0.13	< 0.13	0.13	< 0.13	< 0.13	0.18	0.21	< 0.13	< 0.10
Se, mg/kg	< 2.00	< 2.00	< 2.00	< 2.00	< 2.00	< 2.00	< 2.00	< 2.00	< 2.00	< 2.00
Mb, mg/kg	0.40	0.74	3.50	1.08	1.12	0.61	0.59	0.12	0.10	< 0.10

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

[2]ND = not detected.

[3]Calculated as 28.2% of phytate (Tran and Sauvant, 2004).

[4]Calculated as the difference between phytate P and total P.

Table 3.4. Bulk density, swelling, water binding capacity, and viscosity of corn, wheat, soybean meal, canola meal, dried distillers grains with solubles, corn germ meal, copra expellers, sugar beet pulp, synthetic cellulose, and pectin

	Ingredient[1]											
Item	Corn	Wheat	SBM	CM	DDGS	CGM	CE	SBP	SF	Pectin	SEM	*P*-value
Bulk density, g/L	728.51^{c}	676.41^{ef}	782.68^{a}	715.06^{d}	656.10^{g}	705.06^{d}	658.43^{g}	665.76^{fg}	681.41^{e}	768.36^{b}	3.79	<0.01
Swelling, L/kg DM	2.48^{i}	3.00^{h}	4.98^{e}	4.54^{f}	3.76^{g}	5.79^{d}	7.50^{c}	8.08^{b}	4.05^{g}	9.01^{a}	0.18	<0.01
WBC[2], g/g	1.21^{i}	1.00^{j}	2.74^{f}	1.82^{g}	1.72^{h}	3.14^{d}	3.61^{b}	4.09^{a}	2.86^{e}	3.39^{c}	0.03	<0.01
Viscosity, cP	1.12^{cde}	1.30^{bc}	1.10^{cde}	1.00^{de}	1.07^{cde}	1.17^{cde}	1.27^{bcd}	1.45^{b}	0.93^{e}	7.00^{a}	0.11	<0.01

[a-j]Means within a row lacking a common superscript letter differ ($P < 0.05$).

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

[2]WBC = water binding capacity.

Table 3.5. *In vitro* apparent ileal digestibility (IVAID) and *in vitro* apparent total tract digestibility (IVATTD) of DM and OM in corn, wheat, soybean meal, canola meal, dried distillers grains with solubles, corn germ meal, copra expellers, sugar beet pulp, synthetic cellulose, and pectin

	Ingredient[1]											
Item, %	Corn	Wheat	SBM	CM	DDGS	CGM	CE	SBP	SF	Pectin	SEM	*P*-value
IVAID												
DM	47.57^{f}	69.50^{c}	78.63^{b}	59.75^{d}	54.75^{e}	47.27^{f}	56.61^{e}	26.23^{g}	5.03^{h}	85.37^{a}	1.04	<0.01
OM	46.15^{g}	66.57^{c}	76.97^{b}	58.37^{d}	50.93^{f}	46.22^{g}	54.10^{e}	27.57^{h}	4.92^{i}	87.38^{a}	0.75	<0.01
IVATTD												
DM	87.14^{d}	88.60^{c}	94.45^{b}	80.34^{f}	58.90^{i}	62.28^{h}	79.34^{g}	81.28^{e}	7.09^{j}	99.26^{a}	0.33	<0.01
OM	86.96^{d}	88.59^{c}	94.17^{b}	79.60^{f}	56.10^{i}	60.95^{h}	78.35^{g}	83.39^{e}	7.32^{j}	99.40^{a}	0.28	<0.01

[a-j]Means within a row lacking a common superscript letter differ ($P < 0.05$).

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

Table 3.6. Correlation coefficients between the chemical composition and physical characteristics of feed ingredients

	Correlation coefficient[1]										
Item	DM	GE	NDF	ADF	IDF	SDF	TDF	Bulk	Swelling	WBC	Viscosity
DM	1.00	0.22	0.53	0.62*	0.77***	0.09	0.88***	-0.33	0.48	0.68**	0.06
GE	–	1.00	0.60*	0.62*	0.33	-0.58*	-0.01	-0.47	-0.14	0.00	-0.59*
NDF	–	–	1.00	0.94***	0.65**	-0.44	0.42	-0.77***	0.27	0.49	-0.47
ADF	–	–	–	1.00	0.69**	-0.43	0.47	-0.67**	0.29	0.51	-0.47
IDF	–	–	–	–	1.00	-0.41	0.81***	-0.54	-0.04	0.34	-0.45
SDF	–	–	–	–	–	1.00	0.20	0.47	0.64**	0.33	1.00***
TDF	–	–	–	–	–	–	1.00	-0.28	0.36	0.57*	0.16
Bulk	–	–	–	–	–	–	–	1.00	0.11	-0.01	0.48
Swelling	–	–	–	–	–	–	–	–	1.00	0.89***	0.62*
WBC	–	–	–	–	–	–	–	–	–	1.00	0.30
Viscosity	–	–	–	–	–	–	–	–	–	–	1.00

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

[1]Bulk = bulk density; WBC = water binding capacity; IDF = insoluble dietary fiber; SDF = soluble dietary fiber; TDF = total dietary fiber.

Table 3.7. Correlation coefficients between fiber content, physical characteristics, and *in vitro* ileal and total tract digestibililty of DM and OM of feed ingredients

	Correlation coefficient[1]										
Item	TDF	Cell	iNSP	Bulk	Swelling	WBC	Viscosity	IVAID of DM	IVAID of OM	IVATTD of DM	IVATTD of OM
IDF	0.81***	0.80***	0.99***	-0.54	-0.04	0.34	-0.45	-0.87***	-0.88***	-0.92***	-0.91***
TDF	1.00	0.59*	0.99***	-0.28	0.36	0.57*	0.16	0.65**	-0.62*	-0.76**	-0.75**
Cell	–	1.00	0.75**	-0.69**	0.29	0.57*	-0.45	-0.70**	-0.71**	-0.54	-0.53
iNSP	–	–	1.00	-0.50	-0.05	0.34	-0.41	-0.88***	-0.88***	-0.93***	-0.91***
Bulk	–	–	–	1.00	0.11	-0.01	0.48	0.56*	0.60*	0.46	0.46
Swelling	–	–	–	–	1.00	0.89***	0.62*	0.15	0.20	0.27	0.28
WBC	–	–	–	–	–	1.00	0.30	-0.21	-0.17	-0.07	-0.05
Viscosity	–	–	–	–	–	–	1.00	0.48	0.54	0.38	0.38
IVAID of DM	–	–	–	–	–	–	–	1.00	1.00***	0.81***	0.79***
IVAID of OM	–	–	–	–	–	–	–	–	1.00	0.82***	0.80***
IVATTD of DM	–	–	–	–	–	–	–	–	–	1.00	1.00***

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

Table 3.7. (cont.)

[1]IDF = insoluble dietary fiber; TDF = total dietary fiber; Cell = cellulose; iNSP = insoluble non-starch polysaccharides; Bulk = bulk density; WBC = water binding capacity; IVAID = *in vitro* apparent ileal digestibility; IVATTD = *in vitro* apparent total tract digestibility.

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CHAPTER 4: EFFECTS OF PHYSICOCHEMICAL CHARACTERISTICS OF FEED INGREDIENTS ON THE APPARENT TOTAL TRACT DIGESTIBILITY OF ENERGY, DRY MATTER AND NUTRIENTS BY GROWING PIGS

ABSTRACT: Effects of physicochemical characteristics of feed ingredients on DE and ME and apparent total tract digestibility (ATTD) of GE, DM, and nutrients were determined in growing pigs using ingredients with different ratios between insoluble dietary fiber (IDF) and soluble dietary fiber (SDF). Eighty growing barrows (BW: 48.41 ± 1.50 kg) were allotted to a randomized complete block design with 10 diets and 8 replicate pigs per diet. Dietary treatments included a corn-based diet, a wheat-based diet, a corn-soybean meal (SBM) diet, and 7 diets based on a mixture of the corn-SBM diet and canola meal, distillers dried grains with solubles (DDGS), corn germ meal (CGM), copra expellers, sugar beet pulp (SBP), synthetic cellulose, or pectin. Values for the ATTD of DM and nutrients were also compared with the *in vitro* digestibility of GE, DM, and nutrients. Results indicated that the ATTD of GE was greater ($P < 0.05$) in wheat than in canola meal, DDGS, CGM, copra expellers, SBP, and synthetic cellulose, but not different from corn, SBM, or pectin. Soybean meal had greater ($P < 0.05$) DE and ME (DM basis) compared with all other ingredients. The concentration of ME (DM basis) was greater ($P < 0.05$) in wheat than in canola meal, DDGS, CGM, copra expellers, SBP, synthetic cellulose, and pectin, but not different from corn. Stronger correlations between total dietary fiber (TDF) and DE and ME than between ADF or NDF and DE and ME were observed, indicating that TDF can be used to more accurately predict DE and ME than values for NDF or ADF. The DE, ME, and the ATTD of DM in ingredients were positively correlated ($P < 0.05$)

with *in vitro* ATTD of DM, indicating that the *in vitro* procedure may be used to estimate DE and ME in feed ingredients. Swelling and water binding capacity were positively correlated ($P < 0.05$) with the ATTD of IDF, TDF, non-starch polysaccharides (NSP), and insoluble NSP, and viscosity was positively correlated ($P < 0.05$) with the ATTD of NDF, IDF, and insoluble NSP, indicating that some physical characteristics may influence digestibility of fiber. However, physical characteristics of feed ingredients were not correlated with the concentration of DE and ME, which indicates that these parameters do not influence *in vivo* energy digestibility in feed ingredients. It is concluded that the DE and ME in feed ingredients may be predicted from some chemical constituents and from *in vitro* digestibility of DM, but not from physical characteristics.

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

INTRODUCTION

Feed costs represent approximately 70% of the total cost of swine production and energy is the most expensive component in diets for pigs (Noblet and van Milgen, 2013). Increasing concentrations of alternative feed ingredients and coproducts from the ethanol and biofuel industries are included in diets fed to pigs to reduce diet costs (Zijlstra and Beltranena, 2013). However, these coproducts contain more dietary fiber than corn and other cereal grains, which may negatively affect the digestibility of energy and nutrients and thus growth performance of pigs (Urriola et al., 2013). Dietary fiber is not digested in the small intestine, but may be hydrolyzed in the large intestine via microbial fermentation, which results in synthesis and absorption of VFA that may contribute to the energy status of the pig (Urriola et al., 2013). The chemical and physical characteristics of dietary fiber determine the extent to which it is

fermented, and thus, the rate of fermentation and the amount of VFA absorbed may vary among different sources of fibrous ingredients. There is, however, a lack of information about how the physicochemical characteristics of feed ingredients influence fermentation of fiber and the apparent total tract digestibility (**ATTD**) of energy and nutrients in feed ingredients fed to pigs. Therefore, the objective of this experiment was to test the hypothesis that the physicochemical characteristics of feed ingredients are correlated with concentrations of DE and ME and the ATTD of energy, DM, and nutrients in corn, wheat, soybean meal (**SBM**), canola meal, distillers dried grains with solubles (**DDGS**), corn germ meal, copra meal, sugar beet pulp, synthetic cellulose, and pectin. The second objective was to test the hypothesis that ATTD of DM and energy and the concentration of DE and ME are correlated with *in vitro* digestibility of DM and energy in feed ingredients.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocol for this experiment. Pigs used were the offspring of Line 359 boars mated to Camborough females (Pig Improvement Company, Hendersonville, TN).

Diets, Animals, Housing, and Experimental Design

Eighty growing barrows (initial BW: 48.41 ± 1.50 kg) were allotted to a randomized complete block design with 4 blocks of 20 pigs, 10 diets, and 2 replicate pigs per diet in each block for a total of 8 replicate pigs per diet. Dietary treatments included a corn-based diet, a wheat-based diet, a corn-SBM diet, and 7 diets based on a mixture of the corn-SBM diet and one of 7 fiber sources (i.e., canola meal, DDGS, corn germ meal, copra expellers, sugar beet pulp, synthetic cellulose, or pectin; Table 4.2). The ingredients were chosen to represent a range of

different ratios between insoluble dietary fiber (**IDF**) and soluble dietary fiber (**SDF**). The ratio between corn and SBM was the same in the basal corn-SBM diet and in the 7 corn-SBM diets that also contained a fiber source so the contribution of corn and SBM to those diets could be calculated. Vitamins and minerals were included in all diets to meet or exceed the estimated nutrient requirements for growing pigs (NRC, 2012).

Experimental diets were fed for 26 d. Pigs were housed in individual pens in an environmentally controlled room with slatted floors, a self-feeder, and a nipple waterer for 14 d to adapt to the diets. Pigs were allowed ad libitum access to feed and water during this period. On d 15, pigs were moved to metabolism crates where they were housed individually for the remaining 12 d of the experiment. Metabolism crates were equipped with a feeder, a nipple waterer, fully slatted floors, a screen floor, and urine trays that allowed for the total, but separate, collection of urine and fecal materials from each pig. All diets were fed in a meal form. Day 15 to 19 were considered the adaptation period to metabolism crates, but urine and feces were collected from the feed provided from d 20 to 25. While in the metabolism crates, pigs were provided feed corresponding to 3.2 times the energy requirement for maintenance (i.e., 197 kcal of ME/kg $BW^{0.60}$; NRC, 2012), which was provided each day in 2 equal meals at 0800 and 1700 h. Pigs had free access to water at all times.

Data Recording and Sample Collection

The BW of each pig was recorded at the beginning of the adaptation period and on d 15 and feed consumption was recorded daily during the 5-d collection period from d 20 to d 25. Non-digestible fecal markers were included in the morning meal on d 20 (chromic oxide) and on d 25 (ferric oxide) to mark the beginning and the conclusion of fecal collections, respectively (Adeola, 2001). Feces were collected twice daily and stored at –20ºC immediately after

collection. Urine buckets with a preservative of 50 mL of 3*N* HCl were placed under the metabolism crates for urine collection and buckets were emptied every morning from d 21 to 25. The collected urine was weighed and a 20% subsample was stored at –20ºC. At the conclusion of the experiment, urine samples were thawed and mixed within animal and diet, and a sub-sample was lyophilized before analysis. Fecal samples were thawed and mixed within pig and diet, and dried in a 60°C forced air drying oven prior to analysis.

Chemical Analyses and Physical Characteristics of Diets and Ingredients

Diets, ingredients, and fecal samples were analyzed for DM, ash, GE, CP, acid hydrolyzed ether extract (**AEE**), ADF, NDF, ADL, IDF, and SDF using standard procedures described by Navarro et al. (2018). All analyses of physical characteristics were performed in triplicates with the exception of viscosity, which was analyzed in quadruplicates. The physical characteristics of diets and ingredients were determined by measuring the bulk density, swelling, water binding capacity, and viscosity according to Navarro et al. (2018).

Calculations and Statistical Analysis

Concentrations of TDF (IDF + SDF), cellulose (ADF – lignin), insoluble hemicelluloses (NDF – ADF), non-starch polysaccharides (**NSP**; TDF – lignin), insoluble NSP (NSP – SDF), and non-cellulosic NSP (NSP – cellulose) were calculated for each ingredient and diet. The DE and ME for each diet were calculated by subtracting the GE excreted in the feces and in urine, respectively, from the intake of GE (Adeola, 2001). The DE and ME in the corn and wheat diets were divided by the inclusion rate of corn or wheat to calculate the DE and ME in corn or wheat. The DE and ME in the corn diet was used to calculate the contribution of corn to the corn-SBM diet and the DE and ME in SBM was calculated by difference. The DE and ME in the corn-SBM diet was used to calculate the contribution of corn and SBM to the diets containing corn, SBM,

and each of the test ingredients and the DE and ME in each test ingredient was subsequently calculated by difference (Widmer et al., 2007). The ATTD of DM, energy, and nutrients was calculated using the direct procedure for diets, corn, and wheat, whereas the difference procedure was used for the other ingredients (Adeola, 2001). The ATTD of CP, AEE, and SDF in synthetic cellulose and the ATTD of CP, AEE, NDF, ADF, IDF, cellulose, insoluble hemicellulose, and insoluble NSP in pectin were not analyzed because these nutrients are not present in synthetic cellulose and pectin, respectively.

Data were analyzed as a randomized complete block design with the pig as the experimental unit. An analysis of variance was conducted using the MIXED procedure in SAS (SAS Institute Inc., Cary, NC). Homogeneity of the variances was confirmed using the UNIVARIATE procedure in PROC MIXED. Diet was the fixed effect and block and pig within block were the random effects. Least squares means were calculated using a Least Significant Difference test and means were separated using the PDIFF statement in PROC MIXED. Correlation coefficients among the physical characteristics of experimental diets or feed ingredients and concentration of DE and ME and ATTD of energy and nutrients were determined using the CORR procedure of SAS. Likewise, the results of this experiment were correlated with *in vitro* apparent ileal digestibility (**IVAID**) and apparent total tract digestibility (**IVATTD**) of DM in ingredients from an experiment using the same ingredients (Navarro et al., 2018) using PROC CORR. Results were considered significant at $P < 0.05$ and considered a trend at $0.05 \leq P < 0.10$.

RESULTS

Bulk density ranged from 254 g/L in the synthetic cellulose diet to 787 g/L in the SBM diet and was greater ($P < 0.05$) in the wheat diet than in the DDGS, copra expellers, sugar beet pulp, and synthetic cellulose diets, but not different from the canola meal and pectin diets (Table 4.3). Bulk density was greatest ($P < 0.01$) in SBM among ingredients. Water binding capacity ranged from 0.8 g/g in the wheat diet to 2.3 g/g in the pectin diet and was greater ($P < 0.05$) in the corn germ meal diet than in the corn, wheat, SBM, canola meal, DDGS, and synthetic cellulose diets, but not different from the copra expellers diet. Sugar beet pulp had the greatest ($P < 0.01$) WBC capacity among ingredients. Swelling capacity ranged from 2.7 L/kg DM in the corn diet to 6.0 L/kg DM in the pectin diet and was greater ($P < 0.05$) in the copra expellers diet than in the corn, wheat, SBM, corn germ meal, and synthetic cellulose diets, but not different from the canola meal and DDGS diets. Pectin had the greatest ($P < 0.01$) swelling capacity and viscosity among ingredients. Viscosity ranged from 1.0 cP in the corn germ meal diet to 2.7 cP in the pectin diet and viscosity of the sugar beet pulp diet was less ($P < 0.05$) than in the pectin diet, but not different from all other diets.

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

Pigs fed the wheat diet had greater ($P < 0.05$) ATTD of GE compared with pigs fed the other diets (Table 4.4). The ATTD of GE was greater ($P < 0.05$) in pigs fed the corn diet compared with pigs fed the canola meal, DDGS, corn germ meal, copra expellers, sugar beet pulp and synthetic cellulose diets, but not different from pigs fed the SBM or pectin diets. Among all diets, the concentration of DE was greatest ($P < 0.05$) in the copra expellers diet. The concentration of DE was greater ($P < 0.05$) in the SBM diet than in the corn, canola meal, DDGS, corn germ meal, sugar beet pulp, synthetic cellulose, and pectin diets, but not different

from the wheat diet. The concentration of ME was greater ($P < 0.05$) in the copra expellers diet than in the corn, canola meal, DDGS, corn germ meal, sugar beet pulp, synthetic cellulose, and pectin diets, but not different from the wheat or SBM diets.

The ATTD of GE was greater ($P < 0.05$) in wheat than in canola meal, DDGS, corn germ meal, copra expellers, sugar beet pulp, and synthetic cellulose, but not different from corn, SBM, or pectin. Soybean meal had greater ($P < 0.05$) concentration of DE and ME compared with all other ingredients. The concentration of DE and ME (as-fed basis) was greater ($P < 0.05$) in copra expellers than in corn, canola meal, DDGS, corn germ meal, sugar beet pulp, synthetic cellulose, and pectin, but not different from wheat. The concentration of DE (DM basis) was greater ($P < 0.05$) in wheat than in canola meal, DDGS, corn germ meal, sugar beet pulp, synthetic cellulose, and pectin, but not different from corn or copra expellers. The concentration of ME (DM basis) was greater ($P < 0.05$) in wheat than in canola meal, DDGS, corn germ meal, copra expellers, sugar beet pulp, synthetic cellulose, and pectin, but not different from corn.

Apparent Total Tract Digestibility of DM, OM, and Nutrients in Diets

The ATTD of DM and OM was greater ($P < 0.05$) in pigs fed the wheat diet than in pigs fed the corn, canola meal, DDGS, corn germ meal, copra expellers, sugar beet pulp, and synthetic cellulose diets, but not different from pigs fed the SBM or pectin diets (Table 4.5). The ATTD of CP was greater ($P < 0.05$) in pigs fed the SBM diet than in pigs fed the corn, canola meal, DDGS, corn germ meal, copra expellers, sugar beet pulp, synthetic cellulose, and pectin diets, but not different from pigs fed the wheat diet. The ATTD of AEE was greater ($P < 0.05$) in pigs fed the copra expellers diet than in pigs fed the corn, SBM, canola meal, DDGS, corn germ meal, sugar beet pulp, synthetic cellulose, and pectin diets, but not different from pigs fed the wheat diet. A negative value was observed for the ATTD of AEE in the pectin diet. The ATTD

of NDF was less ($P < 0.05$) in pigs fed the canola meal diet than in pigs fed the wheat, SBM, DDGS, corn germ meal, copra expellers, and sugar beet pulp diets, but not different from pigs fed the corn, synthetic cellulose, or pectin diets. The ATTD of ADF was less ($P < 0.05$) in pigs fed the pectin diet than in pigs fed the SBM, canola meal, DDGS, corn germ meal, copra expellers, sugar beet pulp, and synthetic cellulose diets, but not different from pigs fed the corn or wheat diets. The ATTD of IDF was greater ($P < 0.05$) in pigs fed the sugar beet pulp diet than in pigs fed the corn, wheat, SBM, canola meal, DDGS, corn germ meal, synthetic cellulose, and pectin diets, but not different from pigs fed the copra expellers diet. The ATTD of TDF was greater ($P < 0.05$) in pigs fed the sugar beet pulp diet than in pigs fed the corn, wheat, SBM, canola meal, DDGS, corn germ meal, and synthetic cellulose diets, but not different from pigs fed the copra expellers or pectin diets. The ATTD of cellulose was greater ($P < 0.05$) in pigs fed the sugar beet pulp diet than in pigs fed the corn, wheat, canola meal, corn germ meal, synthetic cellulose, and pectin diets, but not different from pigs fed the SBM, DDGS, or copra expellers diets. The ATTD of insoluble hemicelluloses was less ($P < 0.05$) in the canola meal diet than in all other diets. The ATTD of NSP was greater ($P < 0.05$) in pigs fed the pectin diet than in pigs fed the corn, wheat, SBM, canola meal, DDGS, and synthetic cellulose diets, but not different from pigs fed the corn germ meal, copra expellers, or pectin diets. The ATTD of insoluble NSP was greater ($P < 0.05$) in pigs fed the sugar beet pulp diet than in pigs fed the corn, wheat, SBM, canola meal, DDGS, synthetic cellulose, and pectin diets, but not different from pigs fed the corn germ meal or copra expellers diets. The ATTD of non-cellulosic NSP was less ($P < 0.05$) in pigs fed the canola meal diet than in pigs fed the corn, wheat, SBM, DDGS, corn germ meal, copra expellers, sugar beet pulp, and pectin diets, but not different from pigs fed the synthetic cellulose diet.

Apparent Total Tract Digestibility of DM, OM, and Nutrients in Ingredients

The ATTD of DM, OM, and TDF was less ($P < 0.05$) in synthetic cellulose than in all other ingredients (Table 4.6). The ATTD of CP was greater ($P < 0.05$) in SBM than in corn, canola meal, corn germ meal, copra expellers, and sugar beet pulp, but not different from wheat or DDGS. The ATTD of AEE was greater ($P < 0.05$) in copra expellers than in all other ingredients. The ATTD of NDF was less ($P < 0.05$) in canola meal than in wheat, SBM, DDGS, corn germ meal, copra expellers, and sugar beet pulp, but not different from corn or synthetic cellulose. The ATTD of IDF was greater ($P < 0.05$) in sugar beet pulp than in corn, wheat, canola meal, DDGS, corn germ meal, and synthetic cellulose, but not different from SBM or copra expellers. Soybean meal had the greatest ($P < 0.05$) ATTD of ADF and cellulose and the least ($P < 0.05$) ATTD of insoluble hemicelluloses among all other ingredients. The ATTD of NSP was greater ($P < 0.05$) in SBM than in corn, wheat, canola meal, DDGS, corn germ meal, and synthetic cellulose, but not different from copra expellers, sugar beet pulp, or pectin. The ATTD of insoluble NSP and non-cellulosic NSP was less ($P < 0.05$) in canola meal than in corn, wheat, SBM, DDGS, corn germ meal, copra expellers, sugar beet pulp, and pectin, but not different from synthetic cellulose.

Correlation Coefficients

There was a perfect positive correlation ($P < 0.01$) between DE and ME, and both DE and ME were positively correlated ($P < 0.05$) with ATTD of DM and GE (Table 4.7). There was also a positive correlation ($P < 0.05$) between ATTD of DM and GE. The concentrations of TDF, NSP, and non-cellulosic NSP were negatively correlated ($P < 0.05$) with the concentration of DE and ME and ATTD of DM and GE. The concentrations of TDF and NSP were negatively correlated ($P < 0.05$) with ATTD of CP. The concentration of IDF was also negatively correlated

($P < 0.05$) with the concentration of DE and ATTD of DM, and had a tendency to be negatively correlated ($P < 0.10$) with the concentration of ME and ATTD of CP. The concentration of insoluble NSP was also negatively correlated ($P < 0.05$) with the concentration of DE ($r = -0.67$) and ME ($r = -0.64$), ATTD of DM ($r = -0.88$), and ATTD of CP ($r = -0.72$). However, no correlation was observed between concentration of NDF, ADF, SDF, cellulose, or insoluble hemicelluloses with the concentration of DE and ME or ATTD of GE.

Swelling capacity and WBC of ingredients were positively correlated ($P < 0.05$) with ATTD of IDF, TDF, NSP, and insoluble NSP (Table 4.8). Swelling capacity and WBC of ingredients were positively correlated ($P < 0.05$) with ATTD of non-cellulosic NSP ($r = 0.73$ and 0.64, respectively). Swelling capacity and WBC of ingredients were also negatively correlated ($P < 0.05$) with ATTD of CP ($r = -0.74$ and -0.72, respectively). Viscosity of ingredients was positively correlated ($P < 0.05$) with ATTD of NDF, IDF, and insoluble NSP. Bulk density of ingredients was negatively correlated ($P < 0.01$) with ATTD of AEE ($r = -0.91$) and ATTD of insoluble hemicelluloses ($r = -0.84$). There was a tendency for WBC of ingredients to be correlated ($P < 0.10$) with ATTD of cellulose ($r = 0.60$) and for viscosity of ingredients to be correlated ($P < 0.10$) with ATTD of CP ($r = -0.68$). However, no correlation was observed between bulk density, swelling, WBC, or viscosity of ingredients with ATTD of DM, OM, GE, ADF, and SDF or the concentration of DE and ME.

Bulk density of the diet was positively correlated ($P < 0.01$) with the ATTD of DM and GE and the concentration of DE and ME, but was negatively correlated ($P < 0.01$) with ATTD of AEE (Table 4.9). Viscosity of the diet was negatively correlated ($P < 0.01$) with ATTD of CP. There was a tendency for WBC of diets to be negatively correlated ($P < 0.10$) with ATTD of CP

and GE. Swelling capacity, WBC, and viscosity of diets were not correlated with the concentration of DE and ME.

The concentration of DE and ATTD of CP in ingredients were positively correlated ($P < 0.05$) with IVAID of DM, whereas DE, ME, and ATTD of DM in ingredients were positively correlated ($P < 0.05$) with IVATTD of DM (Table 4.10). There was also a tendency for ME and ATTD of DM to be positively correlated ($P < 0.10$) with IVAID of DM, and a tendency for ATTD of CP, TDF, and SDF to be positively correlated ($P < 0.10$) with IVATTD of DM. However, no correlation was observed between ATTD of GE, AEE, NDF, ADF, IDF, cellulose, insoluble hemicelluloses, NSP, insoluble NSP, or non-cellulosic NSP with IVAID or IVATTD of DM.

DISCUSSION

Concentrations of DE and ME were generally within the range of published values for corn (Anderson et al., 2012; Rojas et al., 2013; Sulabo et al., 2013; Berrocoso et al., 2015), wheat (NRC, 2012; Bolarinwa and Adeola, 2016), and canola meal (NRC, 2012; Berrocoso et al, 2015; Maison et al., 2015; Liu et al., 2016). For SBM, values for DE and ME were also within the range of previous estimates (Rojas and Stein; 2013; Berrocoso et al., 2015; Liu et al., 2016) and results from this experiment confirm that SBM has a greater concentration of ME than corn (Sotak-Peper et al., 2015). Concentrations of DE and ME in DDGS and corn germ meal were also within the range of published values (Pedersen et al., 2007; Anderson et al., 2012; Rojas et al., 2013; Gutierrez et al., 2014). Concentrations of DE and ME in copra expellers were greater than values reported by Kwon and Kim (2015) because of a higher concentration of AEE in the copra expellers used in this experiment and concentration of DE and ME in sugar beet pulp was

less than published values (NRC, 2012). To our knowledge, concentrations of DE and ME in synthetic cellulose and pectin have never been reported. It is likely that the reason DE and ME of pectin was approximately 2 times greater than the DE and ME in synthetic cellulose is that pectin is highly fermentable in the large intestine, which results in production of SCFA that are absorbed and utilized by the pig (Urriola et al., 2013). The source of pectin used in this experiment consisted of 50% citrus pectin and 50% sucrose, and because sucrose is highly digestible, this also contributed to the high energy value of the pectin source that was used.

Negative correlations between fiber fractions and concentrations of DE and ME indicate that digestibility of energy will decrease if pigs are fed high fiber diets (Jaworski et al., 2015). Almost all the TDF in pectin is soluble fiber that is highly fermentable in the gastrointestinal tract of the pig, which likely contributed to the high energy in pectin (Urriola et al., 2010; Jaworski and Stein, 2017). The negative correlation between the concentration of TDF and NSP and ATTD of CP indicates that the presence of fiber in the diet reduces the digestibility of CP by pigs (Yin et al., 2000; Wilfart et al., 2007; Le Gall et al., 2009). This may be explained by the shift in N excretion from the urine to the feces due to greater use of N for bacterial metabolism and growth and a decrease in the amount of N absorbed in the blood and excreted in the urine (Mroz et al., 2000; Zervas and Zijlstra, 2002). The ATTD of AEE was very low in some ingredients because of low fat concentrations in the diet, which resulted in a greater impact of endogenous losses of fat on the calculated value for ATTD of AEE (Kil et al., 2010). The ATTD of SDF was generally greater compared with IDF, which is in agreement with Urriola et al. (2010). This indicates that the soluble fraction of fiber is better utilized by the pig than the insoluble fraction, presumably because of greater fermentability. However, values for ATTD of fiber may be influenced by endogenous secretions or microbial matter that may be analyzed as

carbohydrates (Cervantes-Pahm et al., 2014; Montoya et al., 2015). Therefore, a more accurate estimate for fiber digestibility may be obtained if endogenous components in the feces that are analyzed as TDF are quantified, which allows for calculation of the standardized total tract digestibility of TDF rather than the ATTD of TDF (Montoya et al., 2016).

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

The stronger correlation between TDF and DE and ME than the correlations between ADF and NDF and DE and ME indicates that TDF is a better measure for estimating the concentration of DE and ME in a feed ingredient. This is supported by the observation that greater SE and reduced R^2 result from using NDF or ADF instead of TDF in prediction equations for DE and ME (Anderson et al., 2012; Kerr et al., 2013). The likely reason is that detergent fiber analysis does not take into account the entire soluble fraction of hemicellulose that includes pectins, mucilages, gums, and β-glucans, and therefore, underestimates the concentration of soluble fiber (Urriola et al., 2013). Acid detergent fiber also contains a portion of the insoluble fraction of hemicellulose, creating an overlap with the analyzed content of NDF. The relatively strong correlation between the IVAID or the IVATTD of DM and the concentration of DE and ME as well as the ATTD of DM indicates that the *in vitro* procedure may be used to estimate digestibility of DM and energy. However, IVATTD of DM is more appropriate than IVAID because of the stronger correlation between IVATTD of DM and DE, ME, and ATTD of DM.

The positive correlations between swelling capacity or WBC and ATTD of TDF, IDF, NSP, insoluble NSP, and non-cellulosic NSP, and between viscosity and ATTD of NDF, IDF, and insoluble NSP, indicates that these physical characteristics may be used to evaluate the digestibility of fiber *in vivo*. This observation is in contrast with results from Jaworski and Stein (2017) who did not observe any correlations between physical characteristics and digestibility of fiber fractions. Swelling capacity and WBC indicate increased digestibility of fiber, which may subsequently result in the release of encapsulated protein in fiber matrices in the feed and increased access for proteolytic enzymes. However, the negative correlation between WBC of ingredients and ATTD of CP may be due to increased ileal endogenous losses of N induced by an increase in WBC (Leterme et al., 1998). This indicates that the increase in endogenous losses of N outweighs the proposed protein-releasing effect of the swelling capacity or WBC of ingredients. The positive correlation between bulk density of the diet and ATTD of GE and the concentration of DE and ME is in agreement with previous data, which indicate that apparent cecal digestibility of GE was positively correlated with bulk density of the diet (Jaworski and Stein, 2017). This may be explained by the negative correlation between bulk density and fiber fractions (i.e., ADF, NDF, cellulose, insoluble hemicellulose; data not shown), indicating that an increase in bulk density may also imply less concentration of fiber in the diet (Jaworski et al., 2014), which has less available energy compared with protein, fat, and digestible carbohydrates. Dusel et al. (1997) observed a negative correlation between viscosity and apparent metabolizable energy (**AME**) in 34 varieties of wheat fed to broilers, but no correlation between viscosity and AME in 5 varieties of wheat was observed by Svihus and Gullord (2002). It is likely that a lack of a correlation between viscosity and energy digestibility or concentration of DE and ME in pigs, as opposed to poultry, is a result of pigs being less affected by viscosity because poultry

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

CONCLUSION

Total dietary fiber and IDF are more appropriate than ADF and NDF in estimating the concentration of DE and ME in feed ingredients but the IVATTD of DM may also be used to estimate DE and ME. However, the physical characteristics of feed ingredients used in this experiment were not correlated with the concentration of DE and ME, which indicates that these parameters cannot be used to evaluate energy digestibility in feed ingredients *in vivo*. However, swelling, WBC, and viscosity may be used to evaluate digestibility of fiber fractions. Furthermore, the bulk density of the diet was positively correlated with concentration of DE and ME likely because increased bulk density indicates less concentration of fiber.

TABLES

Table 4.1. Analyzed nutrient composition of corn, wheat, soybean meal, canola meal, distillers dried grains with solubles, corn germ meal, copra expellers, sugar beet pulp, synthetic cellulose, and pectin, as-fed basis

	Ingredient[1]									
Item	Corn	Wheat	SBM	CM	DDGS	CGM	CE	SBP	SF	Pectin
GE, kcal/kg	3,722	3,797	4,109	4,267	4,537	4,179	4,713	3,740	3,957	3,384
DM, %	85.42	86.81	88.80	88.90	88.77	89.28	96.54	92.48	98.35	91.50
CP, %	6.56	10.80	46.90	40.52	25.52	23.91	21.65	7.27	0.71	1.68
AEE[2], %	3.06	1.86	1.55	4.06	9.58	2.97	11.17	2.00	0.38	0.14
NDF, %	8.51	11.36	6.30	23.63	32.29	39.60	48.14	45.47	30.49	0.78
ADF, %	2.40	3.06	5.00	17.33	12.97	14.70	23.79	21.54	16.43	0.15
Lignin, %	0.47	0.69	0.16	7.39	2.29	4.29	5.14	2.46	ND	ND
Ash, %	1.05	1.61	6.78	7.14	5.91	2.61	5.63	6.96	0.04	1.62
OM, %	84.37	85.20	82.02	81.76	82.86	86.67	90.91	85.52	98.31	89.88
TDF[3], %	10.76	11.40	17.84	26.42	34.66	39.78	43.84	48.54	93.31	51.69
IDF[3], %	10.71	10.93	16.70	25.44	34.38	38.47	42.05	44.57	93.16	0.09

Table 4.1. (cont.)

SDF[3], %	0.06	0.47	1.14	0.98	0.29	1.31	1.79	3.97	0.15	51.60
Cellulose[4]	1.93	2.37	4.84	9.94	10.68	10.41	18.65	19.08	16.43	0.15
Insoluble hemicelluloses[5]	6.11	8.30	1.30	6.30	19.32	24.90	24.35	23.93	14.06	0.63
NSP[6]	10.29	10.71	17.68	19.03	32.37	35.49	38.70	46.08	93.31	51.69
Insoluble NSP[7]	10.24	10.24	16.54	18.05	32.09	34.18	36.91	42.11	93.16	0.09
Non-cellulosic NSP[8]	8.36	8.34	12.84	9.09	21.69	25.08	20.05	27.00	76.88	51.54

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

[2]AEE = acid hydrolyzed ether extract.

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

[4]Cellulose = ADF – Lignin.

[5]Insoluble hemicelluloses = NDF – ADF.

[6]NSP = non-starch polysaccharides, TDF – Lignin.

[7]Insoluble NSP = NSP – SDF.

[8]Non-cellulosic NSP = NSP – Cellulose.

Table 4.2. Ingredient and chemical composition of experimental diets (as-fed basis)

	Diet[1]									
Ingredient, %	Corn	Wheat	SBM	CM	DDGS	CGM	CE	SBP	SF	Pectin
Corn	96.70	-	72.90	42.90	42.90	42.90	50.10	50.70	61.65	61.65
Wheat	-	97.10	-	-	-	-	-	-	-	-
Soybean meal	-	-	24.30	14.30	14.30	14.30	16.70	16.90	20.55	20.55
Canola meal	-	-	-	40.90	-	-	-	-	-	-
Distillers dried grains with solubles	-	-	-	-	40.30	-	-	-	-	-
Corn germ meal	-	-	-	-	-	40.20	-	-	-	-
Copra expellers	-	-	-	-	-	-	30.60	-	-	-
Sugar beet pulp	-	-	-	-	-	-	-	30.20	-	-
Solka floc	-	-	-	-	-	-	-	-	15.00	-
Pectin	-	-	-	-	-	-	-	-	-	15.00
Monocalcium phosphate	1.20	0.60	0.70	0.20	0.10	0.25	1.25	0.79	0.75	0.75
Limestone	1.00	1.20	1.00	0.60	1.30	1.25	0.25	0.31	0.95	0.95
Salt	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40

Table 4.2. (cont.)

Vitamin-mineral premix[2]	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Titanium dioxide	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Analyzed composition										
GE, kcal/kg	3,592	3,670	3,779	3,912	3,983	3,872	3,981	3,714	3,780	3,624
CP, %	7.12	10.86	17.36	25.83	20.62	18.99	18.05	13.49	14.04	13.35
DM, %	87.08	88.75	87.45	87.91	87.77	89.31	90.32	89.42	89.89	88.35
Ash, %	4.34	4.22	4.86	6.12	5.81	5.29	6.06	5.83	4.70	4.63
AEE[3], %	2.83	1.79	1.60	4.41	5.08	2.46	4.66	1.78	2.29	1.26
NDF, %	6.88	9.17	7.29	12.83	16.55	20.20	18.31	16.41	12.77	6.69
ADF, %	3.36	3.32	5.64	11.15	7.45	7.30	8.86	9.50	8.24	3.06
Lignin, %	0.84	0.98	1.27	4.20	1.52	1.70	1.73	1.04	0.30	0.44
TDF[4], %	9.31	10.80	11.87	18.99	20.54	22.32	21.23	21.20	23.98	15.37
IDF[4], %	8.82	10.32	9.71	17.62	20.25	21.32	19.64	19.68	22.90	7.46
SDF[4], %	0.48	0.48	2.16	1.37	0.28	0.99	1.59	1.52	1.08	7.92

Table 4.2. (cont.)

Cellulose[5], %	2.52	2.34	4.37	6.94	5.93	5.61	7.13	8.46	7.93	2.61
Insoluble hemicelluloses[6], %	3.52	5.85	1.65	1.68	9.10	12.89	9.44	6.91	4.54	3.63
NSP[7], %	8.46	9.82	10.60	14.79	19.02	20.62	19.50	20.15	23.67	14.93
Insoluble NSP[8], %	7.98	9.34	8.44	13.42	18.74	19.62	17.91	18.64	22.60	7.01
Non-cellulosic NSP[9], %	5.95	7.48	6.23	7.85	13.09	15.01	12.37	11.70	15.74	12.31

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

[2]The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kilogram of complete diet: Vitamin A as retinyl acetate, 11,136 IU; vitamin D3 as cholecalciferol, 2,208 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B12, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper sulfate 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.

[3]AEE = acid hydrolyzed ether extract.

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

Table 4.2. (cont.)

[5]Cellulose = ADF – Lignin.

[6]Insoluble hemicelluloses = NDF – ADF.

[7]NSP = non-starch polysaccharides, TDF – Lignin.

[8]Insoluble NSP = NSP – SDF.

[9]Non-cellulosic NSP = NSP – Cellulose.

Table 4.3. Bulk density, swelling, water binding capacity, and viscosity of experimental diets and test ingredients[1]

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

[a-h]Means within a row lacking a common superscript letter differ ($P < 0.05$).

[1]Data are means of 3 observations per diet or ingredient except for viscosity where 4 observations were used.

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

Table 4.4. Concentration of digestible and metabolizable energy and apparent total tract digestibility (ATTD) of GE in corn, wheat, soybean meal, canola meal, distillers dried grains with solubles, corn germ meal, copra expellers, sugar beet pulp, synthetic cellulose, and pectin, as-fed basis[1]

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

Table 4.4. (cont.)

ME, kcal/kg	3,174[c]	3,328[bc]	3,828[a]	2,517[e]	2,902[d]	2,923[d]	3,464[b]	2,657[e]	963[g]	2,179[f]	86	<0.01
ME, kcal/kg DM	3,714[bc]	3,835[b]	4,312[a]	2,830[e]	3,267[d]	3,273[d]	3,589[c]	2,874[e]	978[g]	2,381[f]	93	<0.01

[a-h]Means within a row lacking a common superscript letter differ ($P < 0.05$).

[1]Data are means of 8 observations per treatment.

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

Table 4.5. Apparent total tract digestibility (ATTD) of DM, OM, CP, acid hydrolyzed ether extract (AEE), NDF, ADF, total dietary fiber (TDF), insoluble dietary fiber (IDF), and soluble dietary fiber (SDF) in experimental diets

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

Table 4.5. (cont.)

Ins. NSP[6]	54.3^{cd}	60.3^{bc}	64.5^{b}	52.0^{d}	60.1^{bc}	76.4^{a}	77.4^{a}	82.8^{a}	53.1^{d}	60.5^{bc}	2.68	<0.01
NC NSP[7]	53.5^{bc}	61.9^{b}	64.3^{b}	42.0^{d}	53.3^{bc}	77.7^{a}	77.0^{a}	81.0^{a}	44.3^{cd}	85.2^{a}	4.30	<0.01

[a-g]Means within a row lacking a common superscript letter differ ($P < 0.05$).

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

[2]AEE = acid hydrolyzed ether extract.

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

[4]Ins. Hemi = insoluble hemicelluloses.

[5]NSP = non-starch polysaccharides.

[6]Ins. NSP = insoluble non-starch polysaccharides.

[7]NC NSP = non-cellulosic non-starch polysaccharides.

Table 4.6. Apparent total tract digestibility (ATTD) of DM, OM, CP, acid hydrolyzed ether extract (AEE), NDF, ADF, total dietary fiber (TDF), insoluble dietary fiber (IDF), and soluble dietary fiber (SDF) in ingredients

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

Table 4.6. (cont.)

Ins. NSP[6]	54.4^{cd}	60.2^{c}	80.4^{b}	43.5^{e}	58.3^{c}	80.0^{b}	83.9^{ab}	91.2^{a}	47.2^{de}	-	4.07	<0.01
NC NSP[7]	53.6^{cd}	61.7^{bc}	80.9^{ab}	19.9^{e}	48.6^{cd}	81.9^{a}	86.1^{a}	89.5^{a}	35.1^{de}	99.3^{a}	7.28	<0.01

[a-f]Means within a row lacking a common superscript letter differ ($P < 0.05$).

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

[2]AEE = acid hydrolyzed ether extract.

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

[4]Ins. Hemi = insoluble hemicelluloses.

[5]NSP = non-starch polysaccharides.

[6]Ins. NSP = insoluble non-starch polysaccharides.

[7]NC NSP = non-cellulosic non-starch polysaccharides.

Table 4.7. Correlation coefficients between the concentration of fiber in ingredients, concentration of DE and ME, and apparent total tract digestibility (ATTD) of DM and nutrients in ingredients

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

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

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

Table 4.8. Correlation coefficients between the physical characteristics of ingredients, concentration of DE and ME, and apparent total tract digestibility (ATTD) of nutrients in ingredients

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

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

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

Table 4.9. Correlation coefficients between the physical characteristics of diets, concentration of DE and ME, and apparent total tract digestibility (ATTD) of nutrients in ingredients

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

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

[1]Bulk = bulk density; WBC = water binding capacity; AEE = acid hydrolyzed ether extract.

Table 4.10. Correlation coefficients between *in vitro* apparent ileal digestibility (IVAID) and *in vitro* apparent total tract digestibility (IVATTD) of DM, concentration of DE and ME, and *in vivo* apparent total tract digestibility (ATTD) of DM and nutrients in ingredients

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

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

[1]IVAID = *in vitro* apparent ileal digestibility; IVATTD = *in vitro* apparent total tract digestibility; AEE = acid hydrolyzed ether extract; TDF = total dietary fiber.

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CHAPTER 5: 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

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 were 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

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 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 5.1). 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 –20ºC immediately after collection. Urine buckets with a preservative of 50 mL of 3*N* 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 –20ºC. 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 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 minutes 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 × 6.25. Diets and ingredients were analyzed for ADF and NDF via Ankom Technology methods 12 and 13, respectively, using the Ankom^{2000}

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, 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 3*N* HCl (Ankom^{HCl}, Ankom Technology, Macedon, NY) followed by crude fat extraction using petroleum ether (Ankom^{XT15}, Ankom Technology, Macedon, NY). The concentration of titanium in diet and ileal digesta samples was analyzed following the procedure of Myers et al. (2004).

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]:

$$AID = [1 - \{(GE_d/GE_f) \times (TiO_{2f}/ TiO_{2d})\}] \times 100 \quad \textbf{[1]}$$

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]:

$$ATTD = [(GE_i - GE_o)/GE_i] \times 100 \quad \textbf{[2]}$$

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]:

$$D_{bd} + [(D_{td} - D_{bd})/P_{ti}] \quad \textbf{[3]}$$

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 disappearance (**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 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 5.3). 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 15 or 30% canola meal, corn germ meal, sugar beet pulp, or wheat middlings were added to the diet. 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 is 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 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 5.4). 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 was 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 concurs 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 are 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 were 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, 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 make sure that added fiber was supplied only by the test ingredient, whereas a portion of the basal diet may be replaced in a typical digestibility experiment (Adeola, 2001) as was the case in 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 5.5). 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 as 15 or 30% canola meal, corn germ meal, sugar beet pulp, or wheat middlings was added to the diet. This may explain the reduction in ATTD of GE in diets that was observed as the fiber-rich ingredients were added, resulting in a decrease in transit time in the hindgut and therefore 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 reduces transit time. Purified guar gum and cellulose increased retention time in the small intestine compared with a control diet containing less non-starch polysaccharides when fed to growing pigs, but only guar gum increased total

tract retention time (Owusu-Asiedu et al., 2006). In contrast, non-starch polysaccharides provided by palm kernel expellers or soy hulls did not change passage rate of digesta in the small intestine, but reduced transit 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 transit 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 transit 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.

TABLES

Table 5.1. Composition of experimental diets (as-fed basis)

			Canola meal		Corn germ meal		Sugar beet pulp		Wheat middlings	
Ingredient, %	Basal	CS[1]	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[2]	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Titanium dioxide	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
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

Table 5.1. (cont.)

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[3], %	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[4], %	11.14	8.25	11.34	12.74	13.17	19.29	15.77	26.70	13.36	19.79
IDF[4], %	10.55	7.64	10.92	12.07	12.56	17.64	13.54	21.62	13.03	18.80
SDF[4], %	0.59	0.60	0.42	0.67	0.61	1.64	2.23	5.08	0.32	0.99

[1]CS = corn starch diet.

[2]The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kilogram of complete diet: Vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 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 B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg;

Table 5.1. (cont.)

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.

[3]AEE = acid hydrolyzed ether extract.

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

Table 5.2. Analyzed nutrient composition of corn, soybean meal, canola meal, corn germ meal, sugar beet pulp, and wheat middlings, as-fed basis

Item[1]	Corn	Soybean meal	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, %	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, %	8.27	14.38	26.42	35.89	48.54	34.65
IDF, %	7.86	12.98	25.44	33.41	44.57	33.68
SDF, %	0.41	1.40	0.98	2.48	3.97	0.96

[1]AEE = acid hydrolyzed ether extract; TDF = total dietary fiber; IDF = insoluble dietary fiber; SDF= soluble dietary fiber.

Table 5.3. Apparent ileal digestibility (AID) of GE, apparent hindgut disappearance (AHD) of GE, apparent total tract digestibility (ATTD) of GE, and concentration of DE and ME in experimental diets, as-fed basis[1]

	Diet										
			Canola meal		Corn germ meal		Sugar beet pulp		Wheat middlings		Pooled
Item	Basal	CS[2]	15%	30%	15%	30%	15%	30%	15%	30%	SEM
GE intake[3], 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[3], 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[4], %	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[5], %	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[4], %	90.9	93.0	90.0	88.0	88.5	84.5	89.8	85.4	89.1	85.5	0.74
DE[4], kcal/kg	3,517	3,532	3,440	3,415	3,417	3,313	3,420	3,241	3,409	3,314	28
ME[4], kcal/kg	3,392	3,420	3,348	3,305	3,290	3,221	3,316	3,125	3,310	3,213	28

[1]Data are means of 8 observations per treatment except for 15% sugar beet pulp diet where only 7 observations were used.

[2]CS = corn starch diet.

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

Table 5.3. (cont.)

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

[5]Linear increase ($P < 0.05$) for inclusion of 15 or 30% canola meal, corn germ meal, or sugar beet pulp.

Table 5.4. Apparent ileal digestibility (AID) of GE, apparent hindgut disappearance (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[1]

	Inclusion rate			
Item	15%	30%	SEM	*P*-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

Table 5.4. (cont.)

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

Table 5.4. (cont.)

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

[1]Data are means of 8 observations per treatment except for the diet with 15% sugar beet pulp where only 7 observations were used.

Table 5.5. First appearance of indigestible marker, minutes

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

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

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CHAPTER 6: EFFECTS OF INCLUSION RATE OF HIGH FIBER DIETARY INGREDIENTS ON APPARENT ILEAL, HINDGUT, AND TOTAL TRACT DIGESTIBILITY OF DRY MATTER AND NUTRIENTS IN INGREDIENTS FED TO GROWING PIGS

ABSTRACT: An experiment was conducted to determine if values for the apparent ileal digestibility (AID), apparent hindgut disappearance (AHD), and apparent total tract digestibility (ATTD) of DM and nutrients in high-fiber ingredients measured at 15% inclusion are also accurate if 30% of that ingredient is used in diets fed to pigs. The second objective was to confirm that much of the insoluble dietary fiber (IDF) is not fermented by the pig. 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 corn and soybean meal (SBM) basal diet 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 (CGM), sugar beet pulp (SBP), or wheat middlings (WM). Two additional diets were formulating by adding 15 or 30% canola meal (CM) to the diet containing corn, SBM, and 30% corn starch at the expense of corn and SBM. Effects on AID, AHD, and ATTD of DM and nutrients of including 15 or 30% of each fiber source to the diets were analyzed using orthogonal contrasts. Two-independent-sample t-tests were used to compare inclusion rates within each ingredient. Results indicated that the AID and AHD of CP, acid hydrolyzed ether extract (AEE), and most fiber fractions in CM decreased ($P < 0.05$) as inclusion level increased from 15 to 30%, but that was not the case for CGM, SBP, or WM. The

AID of soluble dietary fiber (SDF) increased ($P < 0.05$), but the AHD of SDF decreased ($P < 0.05$) for WM as inclusion level increased from 0 to 30%, but that was not observed for CM, CGM, or SBP. The ATTD of DM, OM, AEE, and SDF in CGM increased ($P < 0.05$) if 30% rather than 15% was included in the diet and the ATTD of DM, OM, ADF, and SDF in WM increased ($P < 0.05$) as inclusion level increased from 15 to 30%. No differences in ATTD of DM and nutrients in CM and SBP were observed between 15 and 30% inclusion rate. The ATTD of IDF ranged from 52.9% in WM included at 15% to 86.2% in SBP included at 30% in the diet. In conclusion, the AID, AHD, and ATTD of most nutrients measured at 15% inclusion is not different when measured at 30% inclusion of test ingredients. Under the conditions of this experiment, there was relatively high digestibility of IDF.

Key words: digestibility, fiber, inclusion rate, pigs

INTRODUCTION

Dietary fiber is generally not well utilized by pigs, but soluble dietary fiber (**SDF**) can easily be fermented to synthesize VFA that contribute to the energy status of the animal (Urriola et al., 2013). However, results of some studies have indicated that the digestibility of insoluble dietary fiber is relatively high (**IDF**; Jaworski et al., 2017; Navarro et al., 2018a), which indicates that digestibility of fiber may have traditionally been underestimated.

Increased concentration of dietary fiber in the diet may negatively affect digestibility of DM and nutrients (Urriola et al., 2013). It is possible that dietary fiber reduces digestibility of DM and nutrients by reducing transit time of digesta in the gastrointestinal tract of the pig (Wilfart et al., 2007; Navarro et al., 2018b). However, the concentration of DE and ME in canola meal, corn germ meal, sugar beet pulp, and wheat middlings was not different between 15 and

30% inclusion rate in the diet (Navarro et al., 2018b). It is not known if apparent ileal digestibility (**AID**), apparent hindgut disappearance (**AHD**), and apparent total tract digestibility (**ATTD**) of DM and nutrients in high fiber dietary ingredients are also not affected by inclusion rate in the diet. Therefore, the first objective of this experiment was to determine if values for the AID, AHD, and ATTD of DM and nutrients in 4 high-fiber ingredients measured at 15% inclusion are also accurate if 30% of that ingredient is included. The hypothesis was that increasing concentrations of high fiber dietary ingredients results in a linear reduction in digestibility of DM and nutrients in mixed diets, but that the AID, AHD, and ATTD of DM and nutrients in ingredients is not different between 15 and 30% inclusion rates. The second objective was to determine the location and extent of fiber fermentation in growing pigs. The hypothesis was that fermentation of dietary fiber occurs mainly in the hindgut and that most of the SDF is fermented, whereas most of the IDF is not.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocol for this experiment. Pigs were the offspring of Line 359 boars mated to Camborough females (Pig Improvement Company, Hendersonville, TN).

Animals and Experimental Design

Twenty ileal-cannulated pigs (initial 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. Experimental diets, feeding, data recording, and sample collection were discussed in detail by Navarro et al. (2018b).

Chemical Analysis

Diets, ingredients, ileal digesta, and fecal samples were analyzed for DM, ash, GE, CP, acid hydrolyzed ether extract (**AEE**), ADF, NDF, lignin, IDF, and SDF using standard procedures described by Navarro et al. (2018b). Total dietary fiber (**TDF**) in all samples was determined as the sum of IDF and SDF analyses using the Ankom^{TDF} Dietary Fiber Analyzer (AOAC 991.43, AOAC Int., 2007; Ankom Technology, Macedon, NY). The concentration of titanium in diets and ileal digesta samples were measured following the procedure of Myers et al. (2004).

Calculations and Statistical Analysis

By analyzing for the 5 fiber components in diets, ingredients, ileal digesta, and fecal samples (i.e., NDF, ADF, ADL, IDF, and SDF) it was possible to calculate the concentrations of TDF, cellulose, insoluble hemicellulose, non-starch polysaccharides (**NSP**), insoluble NSP, and non-cellulosic NSP (Table 6.3).

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

$$AID = [1 - \{(TDF_d/TDF_f) \times (TiO_{2f}/ TiO_{2d})\}] \times 100 \quad \textbf{[1]}$$

where AID is the apparent ileal digestibility value of total dietary fiber (%), TDF_d is the analyzed TDF of the ileal digesta DM, TDF_f is the analyzed TDF 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 AID of DM and all other nutrients in each diet was also calculated using this equation. The ATTD of DM and nutrients in each diet were also calculated (Adeola, 2001). The AID and ATTD of nutrients in ingredients were calculated using the difference procedure (Widmer et al.,

2007) with the exception of AID and ATTD of DM and OM, which were calculated as described by Navarro et al. (2018b). The digestibility of DM and nutrients in the corn-SBM diet was used to calculate the contribution of corn and SBM to the digestibility of DM and nutrients in all other diets and the digestibility of DM and nutrients in test ingredients for each inclusion level was calculated by difference (Widmer et al., 2007). Apparent hindgut disappearance was calculated as the difference between ATTD and AID.

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. Analysis of variance was used with the MIXED procedure. Diet was the fixed effect and period, replicate, and pig within replicate were random effects. Least squares means were calculated using a Least Significant Difference test and effects of adding 15 or 30% of each fiber source to the corn-SBM-corn starch basal diet were analyzed using orthogonal contrasts. Two-independent-sample t-tests were conducted using the TTEST procedure to compare response variables between 15 and 30% inclusion rates within each ingredient. Results were considered significant at $P < 0.05$.

RESULTS

Apparent Ileal Digestibility of DM and Nutrients in Diets and Ingredients

The AID of DM, OM, and CP decreased (linear, $P < 0.05$) and the AID of insoluble hemicelluloses increased (linear, $P < 0.05$) with addition of 15 or 30% canola meal, corn germ meal, sugar beet pulp, or wheat middlings to the corn starch diet (Table 6.4). Addition of 15 or 30% corn germ meal or sugar beet pulp reduced (linear, $P < 0.05$) the AID of AEE compared with the corn starch diet. The AID of NDF increased (linear, $P < 0.05$) with addition of 15 or

30% corn germ meal or wheat middlings compared with the corn starch diet. The AID of TDF, IDF, SDF, and NSP decreased (linear, $P < 0.05$) with addition of canola meal and the AID of insoluble NSP and non-cellulosic NSP decreased (linear, $P < 0.05$) with inclusion of corn germ meal in the corn starch diet.

The AID of CP, AEE, TDF, IDF, NSP, insoluble NSP, and non-cellulosic NSP in canola meal decreased ($P < 0.05$) as inclusion level increased from 15 to 30%, but not in corn germ meal, sugar beet pulp, or wheat middlings (Table 6.5). The AID of SDF in wheat middlings increased ($P < 0.05$) as inclusion level increased from 15 to 30%, but that was not the case in canola meal, corn germ meal, or sugar beet pulp. No differences in AID of DM, OM, NDF, ADF, cellulose, or insoluble hemicelluloses were observed in any of the test ingredients as inclusion level increased from 15 to 30%.

Apparent Hindgut Disappearance of DM and Nutrients in Diets and Ingredients

The AHD of DM and OM increased (linear, $P < 0.05$) with addition of canola meal, corn germ meal, sugar beet pulp, or wheat middlings to the corn starch diet (Table 6.6) and the AHD of CP increased (linear, $P < 0.05$) with addition of canola meal to the corn starch diet. The AHD of non-cellulosic NSP increased (linear, $P < 0.05$) with addition of canola meal, corn germ meal, or sugar beet pulp to the corn starch diet. The AHD of NSP increased (linear, $P < 0.05$) with addition of sugar beet pulp but decreased (linear, $P < 0.05$) with addition of wheat middlings to the corn starch diet. The AHD of NDF and ADF decreased (linear, $P < 0.05$) with addition of canola meal or wheat middlings to the corn starch diet and inclusion of wheat middlings reduced (linear, $P < 0.01$) the AHD of TDF, IDF, cellulose, insoluble hemicelluloses, NSP, and insoluble NSP.

The AHD of CP, AEE, TDF, IDF, insoluble hemicelluloses, NSP, insoluble NSP, and non-cellulosic NSP in canola meal increased ($P < 0.05$) as inclusion level increased from 15 to 30%, but no changes in the AHD of these nutrients were observed in corn germ meal, sugar beet pulp, or wheat middlings (Table 6.7). The AHD of SDF in wheat middlings decreased ($P < 0.05$) as inclusion rate increased from 15 to 30%, but no change in AHD of SDF was calculated for canola meal, corn germ meal, or sugar beet pulp. No differences in AHD of DM, OM, NDF, ADF, or cellulose were observed in any of the test ingredients as inclusion level increased from 15 to 30%.

Apparent Total Tract Digestibility of DM and Nutrients in Diets and Ingredients

The ATTD of DM, OM, and CP decreased (linear, $P < 0.05$) with addition of canola meal, corn germ meal, sugar beet pulp, or wheat middlings to the corn starch diet (Table 6.8). The ATTD of AEE increased (linear, $P < 0.05$) with addition of canola meal or wheat middlings, but decreased (linear, $P < 0.05$) with addition of corn germ meal and sugar beet pulp to the diet. In contrast, the ATTD of NDF decreased ($P < 0.05$) with addition of canola meal or wheat middlings to the corn starch diet, but increased (linear, $P < 0.05$) with addition of corn germ meal or sugar beet pulp. The ATTD of ADF, TDF, IDF, SDF, and cellulose decreased ($P < 0.05$) with inclusion of canola meal in the diet, but increased (linear, $P < 0.05$) with addition of sugar beet pulp. Addition of wheat middlings decreased (linear, $P < 0.05$) the ATTD of ADF, TDF, IDF, and cellulose. Addition of corn germ meal to the corn starch diet increased (linear, $P < 0.05$) the ATTD of insoluble hemicelluloses and addition of canola meal increased (linear, $P < 0.05$) the ATTD of non-cellulosic NSP. The ATTD of NSP, insoluble NSP, and non-cellulosic NSP was increased (linear, $P < 0.05$) by inclusion of sugar beet pulp but decreased (linear, $P < 0.05$) with addition of wheat middlings to the corn starch diet.

The ATTD of DM, OM, AEE, and SDF in corn germ meal increased ($P < 0.05$) if 30% rather than 15% was included in the diet (Table 6.9) and the ATTD of DM, OM, ADF, and SDF in wheat middlings increased ($P < 0.05$) as inclusion level increased from 15 to 30%. However, no differences in ATTD of DM and nutrients in canola meal and sugar beet pulp were observed between 15 and 30% inclusion rate.

DISCUSSION

The ATTD of NDF and ADF in canola meal was less than values obtained by Maison et al. (2015) but differences in ATTD of NDF and ADF among sources of canola meal were observed and attributed to differences among varieties or growing conditions that may have affected the chemical composition of the seeds (Maison et al. 2015). The AID and ATTD of DM and NDF in corn germ meal was slightly greater than reported data (Gutierrez et al., 2014). The ATTD of DM, OM, and CP in wheat middlings was in agreement with values reported by Huang et al. (2013), and the AID and ATTD of DM and most nutrients in wheat middlings were close to values reported by Jaworski and Stein (2017).

Low or negative values for AHD and ATTD of AEE were observed due to low concentrations of AEE in the diets and the synthesis of endogenous microbial lipids in the hindgut, which contribute to increased endogenous losses of AEE (Gutierrez et al., 2016). Dietary fiber also may impede micelle formation and directly inhibit lipolytic activity which may contribute to the reduction in AID of AEE (Schneeman and Gallaher, 2001). The observation that there were no differences for the ATTD of DM or OM in canola meal and sugar beet pulp between inclusion rates indicate that the hindgut microbes were not overwhelmed by the increased quantities of fiber entering the hindgut at 30% inclusion rate. The ATTD of CP was

not different between inclusion levels of canola meal, corn germ meal, sugar beet pulp, and wheat middlings, which is in agreement with values for wheat middlings reported by Huang et al. (2013). Increasing the inclusion rate of SBM resulted in greater ATTD of CP and fiber in the diet, but a decrease in ATTD of GE in the diet when fed to growing pigs (Huang et al., 2013), which may be because of increased concentration of digestible protein and the replacement of starch with protein and fiber. This indicates that digestibility of some nutrients may be dependent upon inclusion rate of the test ingredient in the diet and the extent of reduction in digestibility depends on the type of fiber source that is used (Le Gall et al., 2009).

The reason inclusion of test ingredients in the corn starch diet reduced AID and ATTD of DM, OM, and CP is that increased dietary fiber usually reduces the ATTD of GE and CP (Yin et al., 2000; Le Goff and Noblet, 2001; Le Goff et al., 2002; Owusu-Asiedu et al., 2006; Le Gall et al., 2009). The reduction in digestibility of DM and nutrients is a result of a decrease in transit time in the hindgut, resulting in less time for microbial fermentation of digesta (Morel et al., 2006; Wilfart et al., 2007). However, transit time likely had no effect on digestibility because there were no differences in the time it took for digesta to first appear at the end of the ileum and in the feces between experimental diets (Navarro et al., 2018b). Therefore, the reduction in AID of CP and AEE in canola meal when the inclusion rate increased from 15 to 30% may be a result of impaired rate of nutrient absorption due to increased concentration of mucin in the unstirred water layer, which is a consequence of increased fiber intake (Montagne et al., 2004).

The AHD of IDF, cellulose, insoluble hemicelluloses, NSP, insoluble NSP, and non-cellulosic NSP was generally greater than the AID of these fiber fractions in both diets and ingredients, which indicates that fermentation of fiber occurs mainly in the hindgut of the pig. Sugar beet pulp fiber is more easily fermented in the gastrointestinal tract of the pig as indicated

by greater ATTD of most of its fiber fractions compared with the other ingredients. Furthermore, the increase in AHD of DM, OM, and CP in diets is due to the greater flow of these nutrients into the hindgut due to a decrease in their digestibility in the upper gut.

The negative values for the AID of SDF in canola meal, corn germ meal, sugar beet pulp, and wheat middlings are a result of more SDF being analyzed at the end of the ileum than in the diet, which is likely due to endogenous mucin secretion or microbial matter that may be analyzed as carbohydrates (Cervantes-Pahm et al., 2014). A major source of the nondietary interfering material in the SDF fraction of ileal digesta is mucin, whereas microbial matter represents 99% of nondietary interfering material in the IDF fraction of both ileal digesta and feces (Montoya et al., 2015). Mucin contains N-acetylgalactosamine, N-acetylglucosamine, galactose, fucose, sialic acids, and mannose attached to the protein core, some of which are monosaccharides that are also present in dietary fiber (Bansil and Turner, 2006). Consequently, calculated values for AID of TDF is expected to underestimate the actual AID because TDF is the sum of IDF and SDF. It was unexpected that the calculated ATTD of IDF was greater than the ATTD of SDF in diets, but this is likely due to the greater ratio between endogenous sources of carbohydrates analyzed as SDF to dietary SDF than that of endogenous sources of carbohydrates analyzed as IDF to dietary IDF. However, the calculated AHD of SDF was greater than 100% for most diets and was greater than the AHD of IDF indicating that SDF is more fermentable than IDF (Urriola et al., 2010).

High digestibility of IDF has been reported (Jaworski et al., 2017; Navarro et al., 2018a), and indicates that a fraction of analyzed IDF is solubilized along the gastrointestinal tract. The AID of IDF was 35.2% in the diet containing 30% wheat middlings, indicating that a significant amount of IDF was solubilized in the small intestine and may have been analyzed as SDF in the

ileal digesta, which may also have contributed to the negative values that were calculated for AID of SDF in experimental diets. Solubilization of IDF may not necessarily indicate that IDF is digested and absorbed in the small intestine, but it indicates that the fiber structure may have been altered and subsequently analyzed as SDF. However, to our knowledge, this has never previously been reported and needs to be further investigated. It is possible that the analytical procedures used may have influenced results because current analytical methods were developed to determine fiber in food and feedstuff and not in ileal digesta or feces (Montoya et al., 2016), which may explain the high AID and ATTD of IDF in this experiment.

CONCLUSION

Fiber may have a negative effect on the digestibility of DM and nutrients in the diet, the extent to which is dependent on the concentration and the source of fiber. Inclusion of high fiber dietary ingredients in the diet increases the flow of DM and nutrients into the hindgut of the pig, resulting in greater fermentation of these nutrients. Although there is degradation of some fiber fractions before the end of the small intestine, the majority of fermentation takes place in the hindgut. The AID, AHD, and ATTD of most nutrients measured at 15% inclusion is not different when measured at 30% inclusion of test ingredients, indicating that the inclusion rate of high fiber dietary ingredients may only negatively influence digestibility of some nutrients. There was a high digestibility of IDF under the conditions of this experiment, which indicates that digestibility of fiber may have traditionally been underestimated. However, current methods for determination of fiber fractions were developed for food and feedstuff and it is not known if they are also applicable to ileal digesta and fecal samples.

TABLES

Table 6.1. Composition of experimental diets (as-fed basis)

			Canola meal		Corn germ meal		Sugar beet pulp		Wheat middlings	
Ingredient, %	Basal	CS[1]	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[2]	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Titanium dioxide	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
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

Table 6.1. (cont.)

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[3], %	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[4], %	11.14	8.25	11.34	12.74	13.17	19.29	15.77	26.70	13.36	19.79
IDF[4], %	10.55	7.64	10.92	12.07	12.56	17.64	13.54	21.62	13.03	18.80
SDF[4], %	0.59	0.60	0.42	0.67	0.61	1.64	2.23	5.08	0.32	0.99
Cellulose[5], %	2.87	1.85	2.96	3.97	3.40	4.67	5.02	8.18	2.61	3.59
Insoluble hemicelluloses[6], %	3.45	2.31	3.01	3.16	5.80	9.19	3.81	5.45	6.50	9.77
NSP[7], %	10.60	7.95	9.92	10.42	12.19	17.52	14.85	25.17	12.59	18.58
Insoluble NSP[8], %	10.01	7.35	9.50	9.75	11.58	15.88	12.61	20.09	12.26	17.60
Non-cellulosic NSP[9], %	7.73	6.10	6.96	6.45	8.79	12.86	9.82	16.99	9.98	14.99

Table 6.1. (cont.)

[1]CS = corn starch diet.

[2]The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kilogram of complete diet: Vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 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 B_{12}, 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.

[3]AEE = acid hydrolyzed ether extract.

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

[5]Cellulose = ADF – Lignin.

[6]Insoluble hemicelluloses = NDF – ADF.

[7]NSP = non-starch polysaccharides, TDF – Lignin.

[8]Insoluble NSP = NSP – SDF.

[9]Non-cellulosic NSP = NSP – Cellulose.

Table 6.2. Analyzed nutrient composition of corn, soybean meal, canola meal, corn germ meal, sugar beet pulp, and wheat middlings, as-fed basis

Item	Corn	Soybean meal	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[1], %	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[2], %	8.27	14.38	26.42	35.89	48.54	34.65
IDF, %	7.86	12.98	25.44	33.41	44.57	33.68
SDF, %	0.41	1.40	0.98	2.48	3.97	0.96
Cellulose[3], %	1.53	5.55	9.94	9.81	19.08	6.87

Table 6.2. (cont.)

Insoluble hemicelluloses[4], %	4.27	3.05	6.30	23.06	23.93	24.93
NSP[5], %	7.88	14.17	19.03	31.39	46.08	31.26
Insoluble NSP[6], %	7.47	12.77	18.05	28.91	42.11	30.30
Non-cellulosic NSP[7], %	6.34	8.62	9.09	21.58	27.00	24.39

[1]AEE = acid hydrolyzed ether extract.

[2]TDF = total dietary fiber; IDF = insoluble dietary fiber; SDF= soluble dietary fiber.

[3]Cellulose = ADF – Lignin.

[4]Insoluble hemicelluloses = NDF – ADF.

[5]NSP = non-starch polysaccharides, TDF – Lignin.

[6]Insoluble NSP = NSP – SDF.

[7]Non-cellulosic NSP = NSP – Cellulose.

Table 6.3. Quantification of fiber fractions in feed ingredients

Component	Procedure
Insoluble dietary fiber	Analyzed
Soluble dietary fiber	Analyzed
Total dietary fiber	Calculated (insoluble + soluble dietary fiber)
Lignin	Analyzed
ADF	Analyzed
NDF	Analyzed
Cellulose	Calculated (ADF – lignin)
Insoluble hemicelluloses	Calculated (NDF – ADF)
Soluble hemicelluloses	Calculated (soluble hemicellulose = soluble dietary fiber)
NSP[1]	Calculated (total dietary fiber – lignin)
Soluble NSP	Calculated (Soluble NSP = soluble dietary fiber)
Insoluble NSP	Calculated (NSP – soluble NSP)
Non-cellulosic NSP	Calculated (NSP – cellulose)

[1]NSP = non-starch polysaccharides.

Table 6.4. Apparent ileal digestibility (AID) of dry matter and nutrients in experimental diets

Item[1], %			Canola meal		Corn germ meal		Sugar beet pulp		Wheat middlings		Pooled
	Basal	CS[2]	15%	30%	15%	30%	15%	30%	15%	30%	SEM
DM[3]	64.1	76.8	73.7	65.6	65.9	56.0	61.4	48.6	66.1	62.1	2.68
OM[3]	67.1	79.3	76.3	69.2	68.7	59.4	65.7	54.5	68.9	65.3	2.53
CP[3]	77.0	79.6	76.8	70.1	73.6	66.6	74.6	70.0	74.9	71.0	2.2
AEE[4]	27.3	43.9	55.0	44.2	19.6	22.9	23.5	21.7	22.2	36.2	9.02
NDF[5]	-1.0	0.7	15.9	1.5	17.1	23.7	5.4	13.9	16.6	29.1	9.27
ADF	2.0	-1.1	4.8	-10.9	9.8	8.7	0.9	8.3	-6.7	9.3	8.1
TDF[6]	4.1	22.8	25.3	6.2	12.6	17.7	6.9	16.4	15.9	28.9	6.89
IDF[6]	13.9	28.2	32.2	13.4	18.1	17.3	20.3	27.2	24.5	35.2	6.98
SDF[6]	-162.2	-42.7	-154.5	-120.0	-90.5	-11.2	-68.8	-27.7	-333.9	-88.6	21.45
Cellulose	-2.0	-2.1	2.7	-11.8	4.2	-0.7	-2.2	5.7	-7.8	7.6	8.22
Ins. Hemi[7]	-3.6	2.1	31.9	26.6	23.0	34.8	12.1	24.0	28.3	39.2	11.23
NSP[6]	3.1	24.3	27.7	9.6	11.1	13.2	6.2	16.0	17.0	29.9	6.94
Ins. NSP[8]	13.6	30.0	35.5	19.0	17.4	15.6	20.1	27.6	26.1	36.9	7.04

Table 6.4. (cont.)

NC NSP[8]	5.3	32.1	38.2	23.0	14.0	18.3	10.3	21.1	23.5	35.3	6.91

[1]AEE = acid hydrolyzed ether extract; TDF = total dietary fiber; IDF = insoluble dietary fiber; SDF= soluble dietary fiber; Ins. Hemi = insoluble hemicelluloses; NSP = non-starch polysaccharides; Ins. NSP = insoluble non-starch polysaccharides; NC NSP = non-cellulosic non-starch polysaccharides.

[2]CS = corn starch diet.

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

[4]Linear reduction ($P < 0.05$) for inclusion of 15 or 30% corn germ meal or sugar beet pulp.

[5]Linear increase ($P < 0.05$) for inclusion of 15 or 30% corn germ meal or wheat middlings.

[6]Linear reduction ($P < 0.05$) for inclusion of 15 or 30% canola meal.

[7]Linear increase ($P < 0.05$) for inclusion of 15 or 30% canola meal, corn germ meal, sugar beet pulp, or wheat middlings.

[8]Linear reduction ($P < 0.05$) for inclusion of 15 or 30% corn germ meal.

Table 6.5. Apparent ileal digestibility (AID) of dry matter and nutrients in ingredients at 15 or 30% inclusion rate[1]

Item[2], %	Canola meal			Corn germ meal			Sugar beet pulp			Wheat middlings		
	15%	30%	SEM	15%	30%	SEM	15%	30%	SEM	15%	30%	SEM
DM	41.0	23.3	12.1	30.4	50.8	9.8	13.9	38.3	10.6	37.1	60.2	17.0
OM	44.4	28.4	11.7	33.9	54.7	9.6	25.1	46.0	10.6	40.4	66.6	17.7
CP	76.3	64.4	4.8*	53.7	43.0	9.3	42.7	17.1	24.6	40.9	47.3	28.8
AEE	125.6	61.6	17.7*	1.0	20.9	34.5	32.6	16.5	43.8	18.0	54.9	39.2
NDF	34.1	1.6	17.7	31.2	34.1	11.5	12.7	19.0	7.9	32.9	42.2	14.3
ADF	6.9	-14.6	14.3	17.9	12.6	10.8	1.8	10.7	7.8	-19.7	14.5	18.4
TDF	57.5	6.7	15.3*	23.9	28.3	13.4	11.6	22.9	10.4	33.4	46.7	15.8
IDF	60.5	12.0	13.9*	23.2	20.2	14.1	31.0	34.6	10.3	40.7	49.8	16.6
SDF	-141.0	-77.1	94.0	-17.8	76.3	75.0	-6.1	16.8	13.1	-825.5	22.8	63.5*
Cellulose	7.9	-16.0	17.4	11.0	0.2	13.4	-0.2	8.4	8.1	-18.8	16.3	22.6
Ins. Hemi.	104.8	45.8	29.2	39.2	47.1	13.1	27.7	32.9	9.8	50.1	52.0	13.0
NSP	76.8	13.6	17.7*	22.7	21.1	15.0	11.5	22.9	10.7	38.8	50.1	16.7
Ins. NSP	81.5	21.2	15.9*	21.7	17.5	15.9	32.3	35.5	11.1	46.7	53.5	17.5

Table 6.5. (cont.)

NC NSP	139.6	41.5	19.9*	27.7	29.2	16.8	19.6	31.6	13.9	50.5	56.5	15.7

*15% and 30% values differ ($P < 0.05$).

[1]Data are means of 8 observations per treatment except for the diet with 15% sugar beet pulp where only 7 observations were used.

[2]AEE = acid hydrolyzed ether extract; TDF = total dietary fiber; IDF = insoluble dietary fiber; SDF= soluble dietary fiber; Ins. Hemi = insoluble hemicelluloses; NSP = non-starch polysaccharides; Ins. NSP = insoluble non-starch polysaccharides; NC NSP = non-cellulosic non-starch polysaccharides.

Table 6.6. Apparent hindgut disappearance (AHD) of dry matter and nutrients in experimental diets

Item[1], %			Canola meal		Corn germ meal		Sugar beet pulp		Wheat middlings		Pooled
	Basal	CS[2]	15%	30%	15%	30%	15%	30%	15%	30%	SEM
DM[3]	27.8	16.6	16.5	22.2	24.0	30.1	29.2	38.1	23.3	21.3	2.8
OM[3]	26.3	15.5	15.8	21.0	23.0	28.5	26.6	34.5	22.3	20.2	2.7
CP[4]	14.5	11.5	10.9	16.8	14.3	15.5	13.6	13.1	16.9	14.2	2.5
AEE	16.3	-1.9	-6.4	11.5	-0.6	6.2	-3.1	-11.5	21.5	9.5	11.1
NDF[5]	75.9	67.9	40.4	47.9	57.2	51.8	71.9	64.4	44.0	26.5	10.6
ADF[5]	79.0	75.2	46.0	50.8	65.0	65.8	81.0	74.4	57.6	32.9	8.9
TDF[6]	75.6	55.4	44.9	57.4	64.0	63.0	75.3	68.9	52.2	34.1	7.7
IDF[6]	67.0	50.5	38.7	51.0	59.8	60.4	60.8	57.1	44.8	27.8	7.6
SDF	223.7	115.3	204.6	172.0	145.5	90.4	156.3	118.0	354.4	152.4	22.6
Cellulose[6]	87.1	85.0	64.6	72.0	77.4	80.5	91.4	83.9	69.3	45.4	9.1
Ins. Hemi.[6]	72.3	61.1	32.4	42.2	51.0	41.4	58.0	46.3	37.4	23.2	13.5
NSP[7]	77.5	56.0	50.3	66.9	67.3	66.6	78.5	71.6	54.4	36.6	7.8
Ins. NSP[6]	68.5	51.0	43.5	59.6	62.9	64.2	63.7	59.6	46.5	29.9	7.7

Table 6.6. (cont.)

NC NSP[8]	73.7	47.5	44.2	63.7	63.2	61.6	72.4	65.7	50.5	34.4	7.7

[1]AEE = acid hydrolyzed ether extract; TDF = total dietary fiber; IDF = insoluble dietary fiber; SDF= soluble dietary fiber; Ins. Hemi = insoluble hemicelluloses; NSP = non-starch polysaccharides; Ins. NSP = insoluble non-starch polysaccharides; NC NSP = non-cellulosic non-starch polysaccharides.

[2]CS = corn starch diet.

[3]Linear increase ($P < 0.05$) for inclusion of 15 or 30% canola meal, corn germ meal, sugar beet pulp, or wheat middlings.

[4]Linear increase ($P < 0.05$) for inclusion of 15 or 30% canola meal.

[5]Linear decrease ($P < 0.05$) for inclusion of 15 or 30% canola meal or wheat middlings.

[6]Linear decrease ($P < 0.01$) for inclusion of 15 or 30% wheat middlings

[7]Linear increase ($P < 0.05$) for sugar beet pulp but linear decrease ($P < 0.01$) for wheat middlings with inclusion of 15 or 30% of ingredient.

[8]Linear increase ($P < 0.05$) for inclusion of 15 or 30% canola meal, corn germ meal, or sugar beet pulp.

Table 6.7. Apparent hindgut disappearance (AHD) of dry matter and nutrients in ingredients at 15 or 30% inclusion rate [1]

Item[2], %	Canola meal			Corn germ meal			Sugar beet pulp			Wheat middlings		
	15%	30%	SEM	15%	30%	SEM	15%	30%	SEM	15%	30%	SEM
DM	28.4	48.3	14.3	41.4	31.6	9.6	64.7	45.1	12.1	33.0	16.8	20.0
OM	28.8	47.2	13.9	41.1	29.9	9.6	56.3	40.1	12.3	33.1	18.6	19.1
CP	-3.2	15.9	6.0*	-2.0	11.8	8.4	-58.4	-19.8	33.3	9.6	25.7	34.5
AEE	-63.8	2.5	26.4*	-70.0	-16.8	46.1	-138.1	-99.1	44.1	26.8	5.9	53.0
NDF	2.0	38.4	19.8	43.1	41.9	12.7	64.6	60.4	9.5	13.7	8.9	16.8
ADF	21.9	43.9	16.4	50.2	58.0	9.9	79.0	72.7	8.1	22.9	1.9	22.3
TDF	-1.7	48.2	18.2*	48.3	53.9	14.6	72.8	65.4	10.7	17.6	10.8	18.1
IDF	-3.8	43.3	16.3*	50.3	55.6	14.9	50.9	51.6	10.7	12.2	7.6	18.7
SDF	162.2	126.3	111.9	62.1	15.3	71.5	109.9	82.7	14.0	725.5	40.4	52.7*
Cellulose	40.2	66.6	19.6	66.1	75.7	14.0	90.7	82.6	8.4	33.3	9.8	26.9
Ins. Hemi.	-50.5	23.4	31.9*	38.9	32.2	16.0	41.5	37.9	13.8	12.5	12.3	15.0
NSP	-4.4	60.2	21.2*	52.7	58.2	17.0	77.2	68.5	11.2	18.1	12.3	18.8
Ins. NSP	-7.3	54.4	18.9*	55.3	60.6	17.6	54.5	54.5	11.6	12.3	9.0	19.4

Table 6.7. (cont.)

NC NSP	-45.9	54.2	25.1*	47.1	51.6	19.6	67.8	60.4	14.3	16.5	14.0	17.3

*15% and 30% values differ ($P < 0.05$).

[1]Data are means of 8 observations per treatment except for the diet with 15% sugar beet pulp where only 7 observations were used.

[2]AEE = acid hydrolyzed ether extract; TDF = total dietary fiber; IDF = insoluble dietary fiber; SDF= soluble dietary fiber; Ins. Hemi = insoluble hemicelluloses; NSP = non-starch polysaccharides; Ins. NSP = insoluble non-starch polysaccharides; NC NSP = non-cellulosic non-starch polysaccharides.

Table 6.8. Apparent total tract digestibility (ATTD) of dry matter and nutrients in experimental diets

Item[1], %			Canola meal		Corn germ meal		Sugar beet pulp		Wheat middlings		Pooled
	Basal	CS[2]	15%	30%	15%	30%	15%	30%	15%	30%	SEM
DM[3]	91.6	93.6	90.3	87.7	89.7	86.2	90.7	86.8	89.5	85.7	0.6
OM[3]	93.3	95.0	92.2	90.0	91.4	88.1	92.4	89.1	91.3	87.8	0.6
CP[3]	91.7	91.2	88.0	86.8	86.9	82.3	87.8	83.1	89.7	88.8	1.1
AEE[4]	42.8	42.0	49.1	55.7	18.3	29.1	20.8	10.3	43.7	51.4	3.6
NDF[5]	74.7	68.5	56.3	49.7	74.4	75.7	76.9	78.5	60.8	58.9	2.2
ADF[6]	81.2	74.2	50.8	39.9	75.0	74.4	81.6	82.9	50.9	44.8	2
TDF[6]	79.2	78.0	70.3	63.8	76.3	78.0	82.3	85.5	68.3	66.8	1.5
IDF[6]	80.2	78.5	71.1	64.4	77.5	77.8	81.5	84.5	69.5	67.1	1.5
SDF[7]	61.8	70.1	49.0	54.1	52.6	81.0	87.4	89.8	19.7	61.8	5.3
Cellulose[6]	84.8	82.9	67.2	60.5	81.8	79.6	88.6	89.7	61.6	55.6	1.7
Ins. Hemi.[8]	69.0	63.2	64.3	69.3	74.0	76.6	69.6	70.4	65.4	65.7	3.7
NSP[9]	80.3	80.2	78.0	76.8	78.4	79.8	84.7	87.8	71.5	70.3	1.6
Ins. NSP[9]	81.4	80.9	79.3	78.4	79.8	79.7	84.3	87.3	72.9	70.8	1.6

Table 6.8. (cont.)

NC NSP[10]	78.8	79.6	82.5	86.9	77.1	79.9	82.7	86.8	74.1	73.9	1.8

[1]AEE = acid hydrolyzed ether extract; TDF = total dietary fiber; IDF = insoluble dietary fiber; SDF= soluble dietary fiber; Ins. Hemi = insoluble hemicelluloses; NSP = non-starch polysaccharides; Ins. NSP = insoluble non-starch polysaccharides; NC NSP = non-cellulosic non-starch polysaccharides.

[2]CS = corn starch diet.

[3]Linear reduction ($P < 0.05$) for inclusion of 15 or 30% canola meal, corn germ meal, sugar beet pulp, or wheat middlings.

[4]Linear increase ($P < 0.05$) for canola meal or wheat middlings but linear reduction ($P < 0.001$) for corn germ meal or sugar beet pulp with inclusion of 15 or 30% of ingredient.

[5]Linear reduction ($P < 0.001$) for canola meal or wheat middlings but linear increase ($P < 0.05$) for corn germ meal or sugar beet pulp with inclusion of 15 or 30% of ingredient.

[6]Linear reduction ($P < 0.001$) for canola meal or wheat middlings but linear increase ($P < 0.001$) for sugar beet pulp with inclusion of 15 or 30% of ingredient.

[7]Linear reduction ($P < 0.05$) for canola meal but linear increase ($P < 0.001$) for sugar beet pulp with inclusion of 15 or 30% of ingredient.

[8]Linear increase ($P < 0.001$) for inclusion of 15 or 30% of corn germ meal.

Table 6.8. (cont.)

[9]Linear increase ($P < 0.001$) for sugar beet pulp but linear reduction ($P < 0.001$) for wheat middlings with inclusion of 15 or 30% of ingredient.

[10]Linear increase ($P < 0.001$) for canola meal or sugar beet pulp but linear reduction ($P < 0.05$) for wheat middlings with inclusion of 15 or 30% of ingredient.

Table 6.9. Apparent total tract digestibility (ATTD) of dry matter and nutrients in ingredients at 15 or 30% inclusion rate [1]

	Canola meal			Corn germ meal			Sugar beet pulp			Wheat middlings		
Item[2], %	15%	30%	SEM	15%	30%	SEM	15%	30%	SEM	15%	30%	SEM
DM	69.4	71.5	3.8	71.9	82.4	2.9*	78.6	83.4	3.3	70.1	81.3	3.2*
OM	73.2	75.7	3.6	75.0	84.7	2.5*	81.5	86.0	3.5	73.5	83.6	3.2*
CP	79.0	82.4	3.1	64.4	61.2	4.7	26.0	18.2	20.1	71.6	76.0	7.6
AEE	61.7	64.1	11.0	-69.0	4.2	18.7*	-105.5	-82.5	12.1	44.8	60.8	16.2
NDF	36.1	40.0	4.1	74.3	76.0	3.2	77.3	79.4	3.4	46.6	51.1	4.1
ADF	28.8	29.2	3.5	68.2	70.6	3.6	80.8	83.3	2.3	3.2	16.5	5.5*
TDF	55.8	54.9	5.0	72.2	77.0	2.8	84.5	88.3	2.0	51.0	57.5	3.4
IDF	56.6	55.3	4.7	73.5	75.7	2.8	81.9	86.2	2.4	52.9	57.4	3.3
SDF	21.2	49.2	24.8	44.4	91.6	8.4*	103.5	99.5	2.3	-100.0	63.3	32.5*
Cellulose	48.1	50.6	3.4	77.1	75.9	3.1	90.5	91.0	2.4	14.5	26.1	6.2
Ins. Hemi.	54.3	69.2	10.9	78.1	79.3	4.8	69.3	70.8	6.5	62.6	64.2	4.1
NSP	72.5	73.8	6.3	75.5	79.3	3.8	88.7	91.4	2.1	56.9	62.4	3.6
Ins. NSP	74.1	75.6	5.9	77.0	78.1	3.7	86.9	90.0	2.5	59.0	62.5	3.5

Table 6.9. (cont.)

NC NSP	93.7	95.7	10.0	74.8	80.8	4.7	87.4	91.9	2.4	67.0	70.5	3.2

[*]15% and 30% values differ ($P < 0.05$).

[1]Data are means of 8 observations per treatment except for the diet with 15% sugar beet pulp where only 7 observations were used.

[2]AEE = acid hydrolyzed ether extract; TDF = total dietary fiber; IDF = insoluble dietary fiber; SDF= soluble dietary fiber; Ins. Hemi = insoluble hemicelluloses; NSP = non-starch polysaccharides; Ins. NSP = insoluble non-starch polysaccharides; NC NSP = non-cellulosic non-starch polysaccharides.

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CHAPTER 7: EFFECTS OF INCLUSION RATE OF HIGH FIBER DIETARY INGREDIENTS IN MIXED DIETS ON AMINO ACID DIGESTIBILITY IN INGREDIENTS BY GROWING PIGS

ABSTRACT: An experiment was conducted to determine effects of inclusion rate of ingredients with varying concentrations of soluble and insoluble fiber on the apparent ileal digestibility (AID) of AA by growing pigs. Twenty pigs (BW: 30.64 ± 2.09 kg) were fitted with a T-cannula in the distal ileum and were allotted to a replicated 10 × 4 incomplete Latin Square design with 10 diets and 4 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) was formulated. 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. Diets were fed to pigs in an amount equal to 3 times the ME requirement for maintenance and ileal digesta were collected on d 22 and 23 of each period. Results indicated a linear reduction ($P < 0.05$) in AID of CP and all indispensable AA with addition of canola meal, corn germ meal, sugar beet pulp, or wheat middlings to the corn starch diet. There was a reduction ($P < 0.05$) in AID of CP and all AA except Arg in canola meal as inclusion rate increased in the diet. There was also a reduction ($P < 0.05$) in AID of CP, Lys, Asp, Pro, and Ser in corn germ meal as inclusion rate of this ingredient increased in the diet. However, there were no effects of inclusion rate of sugar beet pulp or wheat middlings on AID of CP and AA. In conclusion, calculated values for AID of CP and AA in canola meal and corn

germ meal depend on inclusion rate in the diet, and therefore, inclusion rate of the test ingredient needs to be considered when determining AA digestibility.

Key words: amino acid, digestibility, fiber, inclusion rate, pigs

INTRODUCTION

If the direct procedure is used to determine apparent ileal digestibility (**AID**) of CP and AA, a semi-synthetic diet using corn starch may be formulated so that the test ingredient is the sole source of AA in the diet (Gabert et al., 2001). However, the difference procedure is used if the test ingredient cannot supply all the AA or if it cannot be included at high concentrations in the diet due to low palatability (Kil et al., 2013). This method assumes there are no interactions between ingredients and that values for AID of AA obtained in individual ingredients are additive in mixed diets (Gabert et al., 2001). In this case, the test ingredient is included at the highest inclusion rate possible to minimize the error contributed by the basal diet (Fan and Sauer, 1995). A single digestibility coefficient for an AA in a feed ingredient is typically used when formulating diets, but the inclusion level of this ingredient may not necessarily be similar to the inclusion rate used when AA digestibility was determined in this ingredient. The concentration of DE and ME in an ingredient included at 15% is not different from values generated if it is included at 30% (Navarro et al., 2018). However, it is not known if values for AA digestibility are affected by inclusion levels of a high fiber test ingredient. Therefore, the objective of this experiment was to determine the AID of AA in canola meal, corn germ meal, sugar beat pulp, and wheat middlings included at 15 and 30% in the diet. The hypothesis was that inclusion of increasing concentrations of high fiber dietary ingredients results in a linear reduction in the AID

of CP and AA in mixed diets, but AID values in ingredients are not affected by their inclusion rate in the diet.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocol for this experiment. Pigs were the offspring of Line 359 boars mated to Camborough females (Pig Improvement Company, Hendersonville, TN).

Animals and Experimental Design

Twenty ileal-cannulated pigs (initial 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. Experimental diets, feeding, data recording, and sample collection were discussed in detail by Navarro et al. (2018).

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 was considered an adaptation period to the diet. An energy digestibility experiment was conducted from d 15 to d 21 (Navarro et al., 2018). 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 minutes or whenever full and replaced with a new bag. Digesta were stored at – 20°C immediately after collection. At the conclusion of the experiment, ileal digesta samples were thawed and mixed within animal and diet, and a subsample was collected, lyophilized, and ground through a 1-mm screen in a Wiley mill (model 4; Thomas Scientific, Swedesboro, NJ) prior to chemical analysis.

Chemical Analysis

All samples were analyzed in duplicates. Diets, ingredients, and ileal digesta samples were analyzed for DM (Method 930.15; AOAC Int., 2007). The concentration of N in all samples 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 × 6.25. Amino acids were analyzed in diets, ingredients, and ileal digesta samples on an Amino Acid Analyzer (model L8800, Hitachi High Technologies America Inc., Pleasanton, CA) using ninhydrin for postcolumn derivatization and norleucine as the internal standard. Before analysis, samples were hydrolyzed with 6*N* HCl for 24 h at 110°C [Method 982.30 E(a); AOAC, 2007]. Methionine and Cys were analyzed as Met sulfone and cysteic acid after cold performic acid oxidation overnight before hydrolysis [Method 982.30 E(b); AOAC, 2007]. Tryptophan was determined after NaOH hydrolysis for 22 h at 110°C [Method 982.30 E(c); AOAC, 2007]. The concentration of titanium in diets and ileal digesta samples were measured following the procedure of Myers et al. (2004). Diets and ingredients were also analyzed for ADF, NDF, ADL, IDF, and SDF using standard procedures described by Navarro et al. (2018).

Calculations and Statistical Analysis

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

$$AID = [1 - \{(AA_d/AA_f) \times (TiO_{2f}/ TiO_{2d})\}] \times 100 \quad \textbf{[1]}$$

where AID is the apparent ileal digestibility value of an AA (%), AA_d is the analyzed AA of the ileal digesta DM, AA_f is the analyzed AA 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 AID of CP and AA in ingredients were calculated using the difference procedure (Kong and Adeola, 2014).

Homogeneity of the variances was confirmed using the UNIVARIATE procedure in PROC MIXED in SAS (SAS Institute Inc., Cary, NC). The BOXPLOT procedure of SAS was used to check for outliers. Analysis of variance was used with the MIXED procedure. Diet was the fixed effect and period, replicate, and pig within replicate were random effects. Least squares means were calculated using a Least Significant Difference test and effects of adding 15 or 30% of each fiber source to the corn-SBM-corn starch basal diet were analyzed using orthogonal contrasts. Two-independent-sample t-tests were conducted using the TTEST procedure to compare response variables between 15 and 30% inclusion rate within each ingredient. The pig was the experimental unit and results were considered significant at $P < 0.05$.

RESULTS

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 from this pig in period 4. Therefore, there were only 7 observations for the diet containing 15% sugar beet pulp.

Apparent Ileal Digestibility of CP and AA in Diets

The AID of CP and all indispensable AA decreased (linear, $P < 0.05$) with addition of canola meal, corn germ meal, sugar beet pulp, or wheat middlings to the corn starch diet (Table 7.3). There was also a reduction (linear, $P < 0.05$) in the AID of most dispensable AA with inclusion of the test ingredients in the corn starch diet with the exception that the AID of Gly was

not affected by canola meal or wheat middlings and the AID of Pro was not influenced by the addition of sugar beet pulp or wheat middlings.

Apparent Ileal Digestibility of CP and AA in Ingredients

Determined values for the AID of CP and all AA except Arg were less ($P < 0.05$) if 30% canola meal was used compared with 15% (Table 7.4). The AID of CP, Lys, Asp, Pro, and Ser in corn germ meal also decreased ($P < 0.05$) as inclusion level of this ingredient increased in the diet. However, inclusion rate in the diet did not affect the AID of CP or AA in sugar beet pulp or wheat middlings.

DISCUSSION

At 15% inclusion rate in the diet, AID of all indispensable AA in canola meal concur with previous estimates, but AID of most dispensable AA were less than reported values (Berrocoso et al., 2015). The AID of most AA in corn germ meal was slightly less than reported data (Gutierrez et al., 2014). The AID of most AA in wheat middlings was less and the AID of most AA except Ile, Lys, Ala, Gly, Pro, and Tyr in sugar beet pulp was very close to values reported by the NRC (2012) and by Sauvant et al. (2004). The differences between determined AID values and values from the literature may mainly be due to differences in sources used and diet formulation.

The reason the AID of some AA in diets was reduced with increased inclusion of test ingredients may be that dietary fiber reduces the digestibility of CP and AA (Gutierrez et al., 2013; Navarro et al., 2017) because of increased secretion of mucin and epithelial cell turnover, which results in greater endogenous loss of AA (Montagne et al., 2004; Morita et al., 2008). Dietary fiber increases secretion of pancreatic enzymes that may escape reabsorption before the

end of ileum and also may contribute to endogenous losses of AA (Langlois et al., 1987; Dierick et al., 1989). Elevated levels of mucin may also impair the rate of AA absorption due to increased resistance of the unstirred water layer, which is mainly composed of mucin (Satchithanandam et al., 1990). This fiber-induced reduction in CP and AA digestibility may also be influenced by an increase in transit time in the hindgut, resulting in less time for enzymatic digestion, nutrient absorption, and for the digesta to be fermented (Morel et al., 2006; Wilfart et al., 2007). However, there were no differences in the time it took for digesta to first appear at the end of the ileum between experimental diets (Navarro et al., 2018), indicating that rate of passage was not responsible for the reduced AID of AA in this experiment.

Reduction in AA digestibility was not observed for sugar beet pulp or wheat middlings due to high variance among pigs, which may be a consequence of the low concentration of AA in these ingredients. It is also possible that differences in AA digestibility were observed because digestibility values were not corrected for basal endogenous losses to generate standardized ileal digestibility (**SID**) values. The contribution of endogenous AA to the total ileal output of AA is greater at low levels of dietary AA (Fan et al., 1994), and therefore, low concentrations of AA in the diet will generate low AID values. However, the values for AID of AA that differed between inclusion rates of canola meal or corn germ meal were greater at 15% inclusion compared with 30% indicating that the effect of fiber was greater than the influence of endogenous losses of AA on the AID of AA in these ingredients.

CONCLUSION

The AID of CP and some AA in canola meal and corn germ meal were different between inclusion rates, and therefore, inclusion rate needs to be considered when determining AA

digestibility in these ingredients. Digestibility coefficients of AA in high fiber ingredients may need to be determined at different inclusion levels in the diet. It may be more valuable to compare SID values among inclusion rates of a test ingredient to minimize the influence of endogenous AA on the calculated digestibility values of AA. Further investigation is warranted to determine if AA digestibility is also influenced by inclusion rate of ingredients with low fiber content.

TABLES

Table 7.1. Ingredient composition of experimental diets (as-fed basis)

			Canola meal		Corn germ meal		Sugar beet pulp		Wheat middlings	
Ingredient, %	Basal	CS[1]	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[2]	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Titanium dioxide	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Analyzed values										
DM, %	87.19	87.70	87.49	87.74	87.91	87.63	88.03	87.84	87.58	87.29
CP, %	22.84	15.65	17.97	21.72	20.47	22.79	16.83	17.90	17.51	19.74

Table 7.1. (cont.)

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
TDF[3], %	11.14	8.25	11.34	12.74	13.17	19.29	15.77	26.70	13.36	19.79
IDF[3], %	10.55	7.64	10.92	12.07	12.56	17.64	13.54	21.62	13.03	18.80
SDF[3], %	0.59	0.60	0.42	0.67	0.61	1.64	2.23	5.08	0.32	0.99
Indispensable AA, %										
Arg	1.69	1.18	1.37	1.43	1.37	1.53	1.23	1.31	1.24	1.42
His	0.66	0.46	0.55	0.59	0.54	0.61	0.50	0.54	0.49	0.57
Ile	1.12	0.78	0.91	0.94	0.87	0.95	0.85	0.91	0.81	0.91
Leu	2.09	1.46	1.66	1.71	1.68	1.86	1.56	1.66	1.50	1.71
Lys	1.50	1.05	1.25	1.32	1.16	1.22	1.16	1.30	1.07	1.22
Met	0.34	0.24	0.32	0.39	0.28	0.32	0.25	0.28	0.25	0.30
Phe	1.27	0.88	1.00	1.00	1.01	1.11	0.95	1.02	0.91	1.05
Thr	0.97	0.67	0.85	0.90	0.78	0.87	0.73	0.80	0.69	0.79
Trp	0.33	0.26	0.30	0.31	0.27	0.30	0.26	0.25	0.28	0.29

Table 7.1. (cont.)

Val	1.26	0.88	1.08	1.16	1.06	1.21	0.98	1.06	0.94	1.10
Mean	11.23	7.86	9.29	9.75	9.02	9.98	8.47	9.13	8.18	9.36
Dispensable AA, %										
Ala	1.18	0.83	0.97	1.00	1.01	1.18	0.89	0.96	0.88	1.01
Asp	2.66	1.82	2.01	1.88	2.02	2.15	1.94	2.10	1.84	2.08
Cys	0.34	0.24	0.36	0.44	0.27	0.31	0.26	0.28	0.27	0.33
Glu	4.61	3.21	3.86	4.07	3.61	3.89	3.40	3.61	3.46	4.05
Gly	1.02	0.72	0.93	1.02	0.88	1.03	0.78	0.85	0.79	0.93
Pro	1.33	0.94	1.19	1.21	1.08	1.16	0.98	1.10	1.01	1.17
Ser	1.17	0.80	0.95	0.96	0.95	1.05	0.88	0.95	0.84	0.97
Tyr	0.78	0.55	0.59	0.60	0.62	0.65	0.59	0.62	0.56	0.62
Mean	13.09	9.11	10.86	11.18	10.44	11.42	9.72	10.47	9.65	11.16
Total AA	24.32	16.97	20.15	20.93	19.46	21.40	18.19	19.60	17.83	20.52

[1]CS = corn starch diet.

[2]The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kilogram of complete

Table 7.1. (cont.)

diet: Vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 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 B_{12}, 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.

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

Table 7.2. Analyzed nutrient composition of corn, soybean meal, canola meal, corn germ meal, sugar beet pulp, and wheat middlings, as-fed basis

Item	Corn	Soybean meal	Canola meal	Corn germ meal	Sugar beet pulp	Wheat middlings
DM, %	84.52	90.19	88.90	88.24	92.48	87.53
CP, %	4.78	49.33	40.52	23.70	7.27	14.30
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
TDF[1], %	8.27	14.38	26.42	35.89	48.54	34.65
IDF[1], %	7.86	12.98	25.44	33.41	44.57	33.68
SDF[1], %	0.41	1.40	0.98	2.48	3.97	0.96
Indispensable AA, %						
Arg	0.30	3.69	2.31	1.59	0.28	1.04
His	0.19	1.32	1.01	0.68	0.23	0.43
Ile	0.23	2.39	1.46	0.88	0.29	0.53
Leu	0.74	3.96	2.67	1.88	0.49	1.00
Lys	0.24	3.24	2.11	0.97	0.47	0.70

Table 7.2. (cont.)

Met	0.11	0.67	0.73	0.44	0.16	0.22
Phe	0.31	2.61	1.52	1.08	0.29	0.65
Thr	0.23	1.97	1.56	0.92	0.35	0.51
Trp	0.05	0.77	0.53	0.22	0.07	0.18
Val	0.34	2.63	1.86	1.44	0.43	0.79
Mean	2.74	23.25	15.76	10.10	3.06	6.05
Dispensable AA, %						
Ala	0.46	2.18	1.66	1.50	0.37	0.74
Asp	0.43	5.67	2.55	1.73	0.56	1.06
Cys	0.12	0.64	0.90	0.34	0.09	0.31
Glu	1.13	9.44	6.66	3.39	0.74	3.14
Gly	0.26	2.11	1.92	1.32	0.33	0.81
Pro	0.54	2.46	2.34	1.13	0.32	0.95
Ser	0.29	2.42	1.36	1.06	0.34	0.63
Tyr	0.16	1.75	1.07	0.60	0.25	0.37

Table 7.2. (cont.)

Mean	3.39	26.67	18.46	11.07	3.00	8.01
Total AA	6.13	49.92	34.22	21.17	6.06	14.06

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

Table 7.3. Apparent ileal digestibility (AID) of CP and AA in experimental diets[1]

Item, %			Canola meal		Corn germ meal		Sugar beet pulp		Wheat middlings		Pooled
	Basal	CS[2]	15%	30%	15%	30%	15%	30%	15%	30%	SEM
CP[3]	77.0	79.6	76.8	70.1	73.6	66.6	74.6	70.0	74.9	71.0	2.2
Indispensable AA											
Arg[3]	91.3	91.8	89.5	85.1	87.9	83.6	89.5	88.5	88.8	85.3	1.5
His[3]	86.0	86.7	85.3	79.3	80.2	73.9	83.2	81.9	83.9	80.6	1.9
Ile[3]	83.0	84.1	82.0	72.9	77.8	71.5	80.1	78.8	80.6	77.9	1.7
Leu[3]	83.4	85.0	83.0	74.9	78.9	73.5	81.2	80.3	81.3	78.8	1.7
Lys[3]	84.3	86.7	83.3	75.0	79.9	72.4	80.5	78.5	81.8	77.9	1.6
Met[3]	85.3	87.0	85.8	81.8	80.5	74.5	82.4	83.6	82.8	81.1	1.5
Phe[3]	83.8	85.1	83.3	74.6	79.3	73.6	81.5	80.6	81.2	78.8	1.8
Thr[3]	76.6	77.4	77.3	66.6	70.4	64.0	70.9	69.4	72.0	70.2	2.2
Trp[3]	82.7	86.1	85.8	79.5	79.8	75.7	81.2	78.3	81.8	78.5	1.7
Val[3]	79.7	80.6	79.3	70.3	73.5	67.4	75.2	73.7	76.1	74.2	2.0
Mean[3]	83.9	85.2	83.3	75.6	79.1	73.3	80.8	79.5	81.3	78.5	1.7

Table 7.3. (cont.)

Dispensable AA											
Ala[3]	75.8	78.5	78.5	69.1	70.9	63.5	71.0	69.6	73.0	69.3	2.5
Asp[3]	80.1	84.1	81.6	73.5	76.7	67.1	77.6	77.6	78.0	74.0	1.6
Cys[3]	68.2	74.6	76.1	67.6	61.4	52.5	66.7	63.0	69.5	65.5	2.9
Glu[3]	81.3	87.1	86.4	78.6	79.1	71.3	81.8	80.5	83.0	78.5	2.0
Gly[4]	67.1	68.9	73.2	60.9	58.5	49.4	61.0	55.3	64.1	61.8	4.1
Pro[5]	83.0	80.1	80.8	70.5	77.0	71.5	71.4	75.2	78.2	79.5	2.4
Ser[3]	83.9	85.1	83.1	75.6	79.9	74.2	80.1	79.9	80.7	79.5	1.2
Tyr[3]	83.9	85.4	83.5	74.8	80.0	74.1	79.8	78.3	81.7	78.7	1.5
Mean[3]	79.6	82.9	82.3	73.5	75.6	67.6	76.5	75.7	78.4	75.0	1.9
Total AA[3]	81.6	84.0	82.8	74.5	77.2	70.2	78.5	77.5	79.7	76.6	1.8

[1]Data are means of 8 observations per treatment except for the diet with 15% sugar beet pulp where only 7 observations were used; AID = 1 – (CP or AA in digesta/CP or AA in feed) × (Ti in feed/Ti in digesta) × 100%.

[2]CS = corn starch diet.

[3]Linear reduction ($P < 0.05$) for inclusion of 15 or 30% canola meal, corn germ meal, sugar beet pulp, or wheat middlings.

[4]Linear reduction ($P < 0.05$) for inclusion of 15 or 30% corn germ meal or sugar beet pulp.

[5]Linear reduction ($P < 0.05$) for inclusion of 15 or 30% canola meal or corn germ meal.

Table 7.4. Apparent ileal digestibility (AID) of CP and AA in canola meal, corn germ meal, sugar beet pulp, and wheat middlings fed to pigs at 15 or 30% inclusion rate[1]

Item, %	Canola meal			Corn germ meal			Sugar beet pulp			Wheat middlings		
	15%	30%	SEM	15%	30%	SEM	15%	30%	SEM	15%	30%	SEM
CP	76.3	64.6	4.7*	60.1	43.7	7.4*	43.6	18.6	24.0	63.2	47.9	19.7
Indispensable AA												
Arg	83.8	77.6	4.0	72.3	64.5	4.1	39.4	44.3	21.0	71.8	59.6	15.4
His	83.0	71.2	5.1*	55.2	46.8	9.1	51.0	51.3	13.8	70.6	55.4	16.2
Ile	77.7	61.8	5.1*	48.1	37.7	7.8	26.7	36.2	21.5	56.9	49.6	18.6
Leu	80.4	64.8	4.8*	56.5	47.9	6.7	35.7	44.0	24.6	61.0	53.3	18.4
Lys	80.3	65.8	5.5*	49.2	30.3	8.4*	24.0	35.1	20.3	54.9	44.2	17.1
Met	86.3	78.9	3.1*	64.6	55.7	5.0	56.4	73.4	9.8	66.3	64.1	12.8
Phe	80.2	63.2	5.1*	55.5	46.0	7.4	33.2	42.2	23.8	58.1	53.0	18.4
Thr	77.8	57.7	5.4*	42.5	33.3	8.9	-2.2	20.6	21.2	32.6	39.6	18.3
Trp	91.7	76.3	3.6*	59.7	50.8	8.2	40.0	24.7	27.1	72.7	58.9	16.9
Val	76.9	61.0	4.8*	49.3	42.3	6.5	14.5	28.8	21.5	49.9	51.5	15.5

Table 7.4. (cont.)

Mean	80.7	66.6	4.6*	55.5	46.0	6.5	27.9	38.5	18.6	58.9	52.2	16.4
Dispensable AA												
Ala	83.7	61.5	6.5*	54.3	41.2	7.3	-0.8	19.0	31.4	51.7	42.4	21.0
Asp	87.0	62.8	7.1*	54.8	22.0	7.6*	26.1	46.6	28.2	58.2	36.9	21.7
Cys	86.7	66.4	4.7*	32.9	16.9	13.8	41.1	16.8	46.7	78.3	57.6	17.8
Glu	98.4	75.0	5.3*	66.5	40.7	16.2	98.7	65.3	40.4	95.4	67.2	15.4
Gly	85.8	54.9	9.2*	35.1	18.3	18.2	-10.0	-26.5	58.6	53.1	42.9	23.0
Pro	78.6	61.9	4.1*	58.3	39.2	8.1*	-126.4	4.3	93.0	57.3	64.5	8.6
Ser	80.1	65.9	4.0*	61.3	50.3	4.7*	19.8	46.3	14.7	55.9	60.0	11.0
Tyr	81.5	65.4	4.7*	57.8	45.1	7.2	22.3	36.2	14.0	61.2	51.5	15.8
Mean	88.7	66.8	5.5*	56.6	35.4	10.2	19.9	33.4	31.0	72.2	55.6	15.7
Total AA	85.0	66.8	5.0*	56.1	40.5	8.2	24.0	36.0	24.1	66.5	54.1	15.9

*15% and 30% values differ ($P < 0.05$).

[1]Data are means of 8 observations per treatment except for the diet with 15% sugar beet pulp where only 7 observations were used.

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CHAPTER 8: CONCLUDING REMARKS

The overall objective of this research was to identify underlying mechanisms behind the negative effects of inclusion of high-fiber ingredients on nutrient and energy digestibility in mixed diets fed to growing pigs. The fundamental issues in fiber research are: 1) the definition of fiber is still inconclusive and, 2) our current inability to conduct a complete characterization of fiber components in the feed. A better understanding of energy contribution from fermentation and adverse effects on digestibility is essential to developing strategies that utilize the abundance of fibrous co-products that may be fed to pigs.

Energy is the single most expensive component in swine diets. A complete and accurate evaluation of feedstuff is, therefore, the main impediment to improving efficiency in animal production. A complete analysis of chemical components in feed ingredients is challenging and values presented in feed composition tables usually do not add to 100%, which indicates that not all nutrients or energy-contributing components are accounted for and may result in erroneous prediction equations. However, it may be possible to predict the energy in ingredients with greater accuracy if all energy-containing components in feed ingredients are accounted for and data from this research indicate that this is possible for some, but not all, feed ingredients if traditional analyses are complemented by additional analyses that primarily aim at analyzing soluble carbohydrates.

Characterization of fiber is often a tedious and an ambiguous task. Crude fiber, acid detergent fiber (**ADF**), and neutral detergent fiber (**NDF**) have traditionally been used to quantify fiber fractions in a feed ingredient. In recent years, insoluble dietary fiber (**IDF),** soluble dietary fiber (**SDF**), and total dietary fiber (**TDF**) analyses have been the preferred method for describing fiber fractions in feed ingredients. The stronger correlation between IDF and TDF and

in vitro apparent ileal digestibility (**IVAID**) and *in vitro* apparent total tract digestibility (**IVATTD**) of DM and OM than the correlations between NDF and ADF and IVAID and IVATTD indicates that measuring IDF and TDF in fiber results in an improved prediction of the digestibility of GE compared with values for NDF and ADF. Furthermore, the stronger correlation between TDF and DE and ME than the correlations between ADF and NDF and DE and ME indicates that TDF is a better measure for estimating the concentration of DE and ME in a feed ingredient. The relatively strong correlation between the IVAID or the IVATTD of DM and the concentration of DE and ME as well as the apparent total tract digestibility (**ATTD**) of DM indicates that the *in vitro* procedure may be used to estimate digestibility of DM and energy.

Physical characteristics of fiber, such as bulk density, water binding capacity, swelling, and viscosity, was hypothesized to have a negative influence on digestibility of energy and nutrients. However, physical characteristics of feed ingredients were not correlated with IVAID or IVATTD of DM or OM, which indicates that these parameters do not influence digestibility of DM or OM in feed ingredients. Physical characteristics of feed ingredients were also not correlated with the concentration of DE and ME in feed ingredients. It is likely that because of the relatively high concentration of water in the small intestine of pigs, physical characteristics of feed ingredients do not result in measurable changes to nutrient and energy digestibility. It is also likely that a lack of a correlation between viscosity and energy digestibility or concentration of DE and ME is because pigs are less susceptible to negative effects of viscosity compared with poultry. However, the positive correlations between swelling capacity, WBC, or viscosity and ATTD of several fiber fractions indicates that these physical characteristics may be used to evaluate the digestibility of fiber *in vivo*. Bulk density of the diet was positively correlated with ATTD of GE and the concentration of DE and ME, which is likely a result of the negative

correlation between bulk density and the concentration of fiber fractions. This implies that a decrease in bulk density may result from more fiber in the diet, which has less available energy compared with protein, fat, and digestible carbohydrates.

Due to the negative effects of fiber on digestibility, it is necessary to determine if inclusion rate of high fiber dietary ingredients influences the calculated values for digestibility of nutrients and concentration of energy in feed ingredients. We hypothesized 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. It was determined that inclusion of high-fiber ingredients negatively influences 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. This observation gives support to the method used by the industry and in research that directly determines the concentration of DE and ME in feed ingredients and uses these values in diet formulation regardless of the inclusion rate of the ingredients.

The stimulating effect of dietary fiber on passage rate of digesta in the gastrointestinal tract is theorized to be the main cause for the decreased performance of pigs fed high-fiber diets. However, the time from feed ingestion to first appearance of digesta at the end of the ileum was not different among pigs fed experimental diets. In contrast, the time of first appearance of digesta in the feces was reduced as inclusion of fiber in the diets increased, indicating reduced transit time in the hindgut of pigs fed high-fiber diets. This may explain the reduction in ATTD

of GE in diets that was observed as the fiber-rich ingredients were added, resulting in a decrease in transit time in the hindgut and, therefore, less time for the digesta to be fermented. However, this had no impact on values for DE and ME or ATTD of GE in ingredients. Thus, it appears that the effect on transit time is dependent on the source of fiber and a reduction in transit time is more evident in the hindgut than in the small intestine of pigs.

The hypothesis that increasing concentrations of high-fiber ingredients results in no difference in the apparent ileal digestibility (**AID**), apparent hindgut disappearance (**AHD**), and ATTD of DM and nutrients in ingredients between 15 and 30% inclusion rates was also evaluated. It was expected that dietary fiber negatively influences the digestibility of DM and nutrients in the diet, the extent to which is dependent on the concentration and the source of fiber. Inclusion of high fiber dietary ingredients in the diet increases the flow of DM and nutrients into the hindgut of the pig, resulting in greater fermentation of these nutrients. Although there is degradation of some fiber fractions before the end of the small intestine, the majority of fermentation takes place in the hindgut. The AID, AHD, and ATTD of most nutrients measured at 15% inclusion of ingredients is not different when measured at 30% inclusion, indicating that the inclusion rate of high fiber dietary ingredients only influences digestibility of a few nutrients. A high digestibility of IDF was consistently observed throughout this research, indicating that a significant amount of fiber may be fermented by microbes inhabiting the intestinal tract. However, caution is warranted in interpreting this data as current methods for determination of fiber fractions were developed for food and feedstuff and it is not known if these procedures are also applicable to ileal digesta and fecal samples.

A single digestibility coefficient for an AA in a feed ingredient is typically used when formulating diets, but the inclusion level of this ingredient in the diet may not necessarily be

similar to the inclusion rate used when AA digestibility was determined in this ingredient. We hypothesized that values for AID of AA are not affected by inclusion rate of high-fiber ingredients in mixed diets. However, the AID of CP and some AA in canola meal and corn germ meal were different between inclusion rates and, therefore, inclusion rate needs to be considered when determining AA digestibility in these ingredients. Digestibility coefficients of AA in high-fiber ingredients may need to be determined at different inclusion levels in the diet. It also may be more valuable to compare standardized ileal digestibility values among inclusion rates of a test ingredient to minimize the influence of endogenous AA on the calculated digestibility values of AA, especially in high-fiber ingredients with lower concentrations of AA.

Overall, results presented in this dissertation demonstrated the complexity of fiber nutrition and the interactions between fiber and other nutrients in a mixed diet. As an example, physical characteristics of high-fiber ingredients, such as viscosity and water binding capacity, have been speculated to reduce nutrient digestibility in pigs. However, measurable physical characteristics of fiber had no influence on the calculated DE and ME in feed ingredients and, therefore, these parameters cannot be used to evaluate energy digestibility in feed ingredients, but swelling, WBC, and viscosity may be used to predict digestibility of fiber. Determination of the energy content in feed ingredients using animal trials is not always possible or economical, so it is recommended that TDF and IDF be used instead of ADF and NDF when estimating the concentration of DE and ME using prediction equations. The inclusion rate is inconsequential when determining the concentration of DE and ME or digestibility of DM and nutrients in high-fiber ingredients, but it is recommended to use the greatest inclusion rate possible to minimize error contributed by the basal diet. However, further research is warranted to determine if it is

necessary to have AA digestibility values corresponding to the inclusion level of the ingredient in the diet.