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Quantification of digestive utilization of dietary fiber from corn co-products in growing pigs

by

Néstor Augusto Gutiérrez Céspedes

A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Nutritional Sciences

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DEDICATION

With love to my newborn son, Sebastián.

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NOMENCLATURE

AA	amino acid(s)
ADF	acid detergent fiber
ADFI	average daily feed intake
ADG	average daily gain
AEE	acid hydrolyzed ether extract
AID	apparent ileal digestibility
ANOVA	analysis of variance
AOAC	association of official analytical chemists
Arg	arginine
Asp	aspartate
ATP	adenosine triphosphate
ATTD	apparent total tract digestibility
BW	body weight
cal	calorie
CB	corn bran
CB-S	corn bran with solubles
CoA	coenzyme A
CGmM	corn germ meal
CGnM	corn gluten meal
CP	crude protein
Cu	copper
CV	coefficient of variation
Cys	cysteine
d	day(s)
DDG	distillers dried grains

DDGS	distillers dried grains with solubles
DDGS-CV	conventional distillers dried grains with solubles
DDGS-RO	low fat distillers dried grains with solubles
DDGS-BPX	uncooked distillers dried grains with solubles
DE	digestible energy
DM	dry matter
DMI	dry matter intake
EE	ether extract
Eq.	equation(s)
Exp.	experiment
Fe	iron
g	gram
G:F	gain-to-feed ratio
GE	gross energy
GLM	general linear model
Glu	glutamate
Gly	glycine
h	hour(s)
HCl	hydrochloric acid
His	histidine
HP-DDG	high protein distillers dried grains
Ile	isoleucine
Ingred	main effect of ingredient
Leu	leucine
Lys	lysine
ME	metabolizable energy

Met	methionine
min	minute(s)
Mn	manganese
n	sample size
N	Nitrogen
Na	sodium
NDF	neutral detergent fiber
NE	net energy
NRC	National Research Council
P	probability
PPAR	peroxisome proliferator-activated receptor
Pro	proline
SAS	Statistical Analysis System
SBM	soybean meal
SBO	soybean oil
SEM	standard error of the mean
Ser	serine
ST	starch
TDF	total dietary fiber
Thr	threonine
Trp	tryptophan
Val	valine
VFA	volatile fatty acid(s)
wk	week(s)
wt	weight

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ABSTRACT

In vivo digestibility experiments using the cannulated pig model were used to study the digestion of fiber from diets formulated with high concentrations of corn co-products and fed to growing pigs. Experiment 1 was conducted to measure the effect of increasing levels of insoluble-low fermentable fiber from corn in the diet, using corn bran with solubles from the corn-ethanol distillation industry (**CB-S**), on digestibility of energy, fiber, and AA, and hindgut fermentation of fiber in diets fed to growing pigs. Results indicated that increasing fiber from corn lowered ($P < 0.01$) the apparent ileal digestibility (**AID**) of GE, DM, CP, and all indispensable amino acids except Arg, but did not affect ($P > 0.05$) the AID of neutral detergent fiber (**NDF**) or total dietary fiber (**TDF**). Increased fiber from corn also reduced the apparent total tract digestibility (**ATTD**) of GE, DM, CP, NDF, and TDF ($P < 0.01$). A decrease ($P < 0.01$) in hindgut fermentability of NDF (19.6 to 6.4%) and TDF (21.9 to 9.7%) was observed with the dietary inclusion of CB-S. Two subsequent 28-d growth trials were conducted in Exp. 2 to measure the effects of increasing dietary fiber from CB-S in 2 sets of 7 diets formulated either with declining (growing phase: 2,387 to 2,133 kcal NE/kg; finishing phase: 2,499 to 2,209 kcal NE/kg) or constant dietary NE (growing phase: approximately 2,390 kcal NE/kg; finishing phase: approximately 2,500 kcal NE/kg), on growth performance and apparent total tract ATTD of energy in 70 growing (BW = 48.9 kg; n = 10) and 70 finishing (BW = 102.0 kg; n = 10) pigs. Results showed that increasing fiber with declining diet NE lowered BW, ADG, and G:F ($P < 0.05$) in growing and in finishing pigs. When NE was held constant, as fiber increased, BW and ADG were unaffected ($P > 0.05$) in growing and finishing pigs, and G:F was unaffected in finishing pigs but improved in growing pigs ($P < 0.05$) with increasing dietary fiber. In both growing and finishing pigs, ADFI was not affected ($P > 0.05$) by the increased fiber from corn,

regardless of the NE content of diets. Experiment 3 was conducted to determine the effects of addition of reduced oil distillers dried grains with solubles (**DDGS-RO**) and soybean oil (**SBO**) on dietary Lys, acid hydrolyzed ether extract (**AEE**), and NDF digestibility in corn-based diets fed to growing pigs. Results showed that the AID of Lys was not affected by SBO concentration ($P > 0.05$), but DDGS-RO inclusion showed a quadratic effect ($P < 0.001$). An interaction between DDGS-RO and SBO on the AID ($P = 0.003$; $R^2 = 0.68$) and ATTD ($P = 0.004$; $R^2 = 0.79$) of AEE, as well as on the AID ($P = 0.037$; $R^2 = 0.53$) and ATTD ($P = 0.004$; $R^2 = 0.36$) of NDF was observed. It was concluded that DDGS-RO increased the digestibility of AEE, and decreased the digestibility of NDF, but the effect was modulated by SBO. Soybean oil increased the digestibility of AEE but the effect was modulated by DDGS-RO, and increased the AID of NDF in diets without DDGS-RO. The AID of Lys decreased with DDGS-RO and was not affected by addition of SBO. Experiment 4 was conducted to determine a best fitting dietary fiber component to estimate the effect of dietary fiber concentration on the digestibility of energy, fiber, and AA, and energy value of 9 corn co-products. It was observed that the arabinoxylan and NSP xylose residue were the dietary fiber components that best explained variation due to dietary fiber concentration and, with the exception of AID of Lys, can be used to predict the digestibility of energy and dietary fiber, and the DE and ME values in corn co-products. In conclusion, dietary fiber from corn co-products has an intermediate digestibility and does not affect digestibility of the other nutrients in the diet. The ability of pigs to digest fiber from corn origin is modulated by the fat concentration of the diet. The xylose and arabinoxylan concentrations in corn co-products better explain the variation in digestibility of dietary fiber and energy than most of the commonly used fiber procedures.

Key words: non-starch polysaccharides, ileal digestibility, cannulated pig, best fit.

CHAPTER 1: LITERATURE REVIEW

Dietary fiber from corn co-products in swine feeding

Corn co-products from the biofuel industry: Overview

Several co-products from the bio-ethanol production have been commonly used to feed animals for over 50 years already (Shurson et al., 2012). The two main types of ethanol production from maize are dry milling and wet milling. The wide range of co-products that are produced differ substantially in composition and nutritional values (Gutierrez, et al., 2014). Corn gluten meal, corn gluten feed, condensed fermented corn extractives, corn germ meal, and corn oils are co-products from the wet milling process. Co-products from the dry milling process include wet distillers grains, condensed distillers solubles, modified wet distillers grain, distillers dried grains (**DDG**), and distillers dried grains with solubles (**DDGS**). Advances in the ethanol industry increase the efficiency of starch and oil extraction from the corn grain, concentrating the fiber and protein component of the co-product therefore new products such as high protein or reduced oil distillers dried grains enter the market. Distillers dried grains with solubles are a by-product of the corn-ethanol distillation process where entire grain kernels are ground, cooked (premixing at 40-60 °C and cooking at 90-165 °C) and enzymatically hydrolyzed (thermo stable amylases, at 60 °C, > 30 min), after which yeast are added to ferment sugars to ethanol (de Vries, 2014). After distillation, solids and solubles are separated by centrifugation. Solubles are concentrated by condensation and added back to the solids, to a maximum of 25% of the total product. The resulting DDGS is dried using rotary drum driers (250-600 °C, product temperature approximately 100 °C, typically < 1 h) and in some cases pelleted (de Vries, 2014).

Distillers dried grains with solubles may substitute for corn and soybean meal in the diet because DDGS has similar concentrations of DE and ME as corn, and contains highly digestible P (Stein and Shurson, 2009). However, one of the main challenges of using DDGS, and many other corn co-products, is that they often have high concentrations of dietary fiber. Dietary fiber is mainly composed of sugar polymers that cannot be digested by the pig's gastrointestinal enzymes. In spite the impossibility of enzymatic digestion, the pig may obtain energy from dietary fiber by microbial fermentation in the hindgut, producing volatile fatty acids (**VFA**) that can be absorbed and used by the pig to produce ATP or stored as fatty acids in adipose tissue (Bach Knudsen, 2001). The energy contribution from VFA is not as efficient as the energy contribution obtained form enzymatic hydrolysis of simple sugars, fat, and proteins in the small intestine (Black, 1995).

Carbohydrates in plants

A categorization of the carbohydrate constituent of plants is necessary because swine diets consist almost exclusively of feedstuffs of plant origin, which contain mostly carbohydrates, and supply the majority of the dietary energy. Plant carbohydrates can be divided into 2 components: the cell wall and non-cell wall contents (Jaworski, 2012).

The plant non-cell wall carbohydrates include starch, disaccharides, oligosaccharides, fructan polysaccharides, and resistant starch. The plant cell wall carbohydrates include cellulose, hemicellulose, β-glucans, pectins and gums, and lignin (Cervantes-Pahm, 2011; NRC, 2012).

Carbohydrates can also be divided into digestible and non-digestible carbohydrates (Bach Knudsen et al., 2012). Digestible carbohydrates are those that the pig can digest through

the secretion of endogenous enzymes and the term refers to sugars (glucose, fructose, sucrose, lactose, and maltose), certain oligosaccharides, and starch (Bach Knudsen et al., 2012). Non-digestible carbohydrates are those that are not digested by the end of the small intestine due to enzymatic action and must be fermented in the hindgut (Bach Knudsen et al., 2012). Non-digestible carbohydrates consist of non-digestible oligosaccharides, resistant starch, and NSP (Bach Knudsen et al., 2012). Most non-digestible carbohydrates, as well as plant cell wall carbohydrates, may also be included in the term dietary fiber, which is commonly defined as "all plant polysaccharides and lignin that are resistant to hydrolysis by human digestive secretions" (Trowell, 1976).

The dietary fiber concept

Swine diets consist almost exclusively of feedstuffs of plant origin, which contain varying levels of plant cell wall material. Seventy to 90% of plant cell walls are non-starch polysaccharides (**NSP**), which are interconnected and associated with proteins and lignin via covalent and non-covalent linkages (Back Knudsen, 2001; de Vries, 2014). Although the chemical constitution of these cell wall fractions varies widely, they can be considered alike from a nutritional point o view, as they are not enzymatically digested and exert similar physiological properties (de Vries, 2014). Hence, often a physiological based definition is used to describe the fraction of feed resistant to enzymatic digestion (de Vries, 2004). This fraction, which is mostly constituted of plant cell wall components, is usually referred to as fiber or dietary fiber.

There are numerous definitions of dietary fiber, but most of them either define dietary fiber as a group of compounds that are identified in analytical methods or as a group of compounds that have specific physiological functions (Food and Nutrition Board-IOM, 2001; Urriola, 2010). In the 19th century, the Weende procedure defined crude fiber as the organic residue that is insoluble in acid and alkaline treatments (Mertens, 2003), became an official AOAC method in 1980, and was used to measure the indigestible organic matter of food in feed. This portion of the diet was considered the *de facto* definition of dietary fiber and without real value to the animal, because although is a robust method to analytical variation it recovers only part of the fiber fraction (AACC, 2001; Urriola, 2010).

The concept of dietary fiber was first introduced by Hipsley (1953) to denote non-digestible constituents that make up the plant cell wall. Burkitt and Dennis adopted the term dietary fiber in conjunction with a number of health-related benefits, and referred to it as the "dietary fibre hypotheses" (Bach Knudsen, 2001). These conclusions triggered interest in dietary fiber, but it became clear that dietary fiber is a heterogeneous group of chemical components with multiple physiological functions and, therefore, difficult to define (Carpenter, 2003; Urriola, 2010). Trowell (1974) defined dietary fiber as "the skeletal remains of plant cells in the diet, which are resistant to hydrolysis by the digestive enzymes of man", but the definition excluded polysaccharides added to the diet such as food additives (e.g. plant gums, modified cellulose) and was later expanded to include "all polysaccharides and lignin, which are not digested by the endogenous secretions of the human digestive tract" (Trowell et al., 1976; Bach Knudsen, 2001). The definition of dietary fiber has been debated continuously and no universal agreement has yet been reached, and most researchers use either a physiological or a chemical definition. According to Theander et al., (1994) the physiological definition of dietary fiber refers to "the

dietary components resistant to degradation by mammalian enzymes", while the chemical definition of dietary fiber refers to the "sum of NSP and lignin".

It is now accepted that a more accurate definition of fiber must include the physiological effects of fiber (IOM, 2006), and that an important part of the definition is that dietary fiber consists of carbohydrates that are indigestible by mammalian enzymes (AACC, 2001; IOM, 2006). In this line, and as outlined by Urriola (2010), the current definition of dietary fiber from the American Association of Cereal Chemist includes the following:

1. It is an indigestible portion of the diet.
2. It consists of carbohydrates and lignin.
3. It originates from plants.
    a. It has physiological effects that increase laxation and reduce blood cholesterol and/or blood glucose.

A more chemical definition currently used by AOAC is: "Dietary fiber consists of the remnants of edible plant cells, polysaccharides, lignin, and associated substances resistant to digestion by the alimentary enzymes of humans" and includes oligosaccharides, pectic polysaccharides, hemicellulose, cellulose, lignin, gums, and some minor associated plant cell wall substances (de Vries, 2014).

The term NSP is related to dietary fiber, but does not cover all components that can be classified as dietary fiber, because it excludes chemical entities such as oligosaccharides and lignin, which were included in the definition of dietary fiber by the AOAC and AACC (Urriola, 2010). The use of the term NSP may not be an accurate description of fiber in feed ingredients because dietary fiber is not limited to NSP or plant cell walls (Cho et al., 1997; Urriola, 2010).

Urriola (2010) listed several different issues that need to be addressed in the definition of dietary fiber, specifically chemical entities from the diet or chemical modifications due to processing of feed ingredients, that may not be analytically detected by the dietary fiber chemical assay but is considered part of dietary fiber, or chemical entities that may not be considered part of the dietary fiber component but are detected analytically in the dietary fiber assay. These chemical entities include chitosan and mucopolysaccharides, lignin, products of Maillard reactions, fatty derivates (e.g. cutin), oligosaccharides, and special mono-disaccharides.

Chemical Composition of Dietary Fiber

Dietary fiber derives mostly from plant cell walls, and consists of polysaccharides associated, or substituted, with proteins and phenolic compounds, together with the phenolic polymer lignin (Theander et al., 1989; Bach Knudsen, 2001). As cited by Bach Knudsen (2001) the building blocks of the cell wall polysaccharides are pentoses (arabinose and xylose), hexoses (glucose, galactose, and mannose), 6-deoxyhexoses (rhamnose and fucose), and uronic acids (glucoronic and galacturonic acids). The main polysaccharides of plant cell walls are cellulose, arabinoxylans, and mixed linked D-glucans, xyloglucans, rhamnogalacturonans, arabinogalactans (Bacic et al., 1998; Selvendran, 1984; Theander et al., 1989). The other major component of the cell wall is lignin, which can be described as very branched networks build up by phenylpropane units. Lignin serves two main functions; it cements and anchors the cellulose microfibrils and other matrix polysaccharides and, as it associates with non-cellulosic polysaccharides, stiffens the walls thus preventing biochemical degradation and physical damage of the cell walls (Liyama et al., 1994; Bach Knudsen, 2001).

Chemistry societies separate carbohydrates in three groups: monosaccharides, oligosaccharides (including disaccharides), and polysaccharides (Nelson and Cox, 2008). Monosaccharides and disaccharides, however, are often grouped together as sugars and oligosaccharides are defined as compounds between 3 and 9 monosaccharides while polysaccharides contain more than 10 (Cummings and Stephen, 2007; Urriola, 2010).

According to Bach Knudsen (2001), the physical and chemical location of polysaccharides within the plant cell wall has a large influence on the physicochemical properties of cell wall polysaccharides and on its effects on the gastrointestinal tract. Cellulose form microfibrils that are highly ordered and form a rigid skeleton, whereas the amorphous region (constituted of non-cellulosic polysaccharides and glycoproteins) is less ordered (Fig. 1.1; Bach Knudsen, 2001). While the nature of cellulose varies little between plants, the composition of the amorphous matrix usually shows considerable variation from tissue e to tissue within the plant and between plants (Bach Knudsen, 2001). In cereals such as corn and corn co-products the main cell wall NSP of the whole grain are arabinoxylans, cellulose, and β-glucan with some variation between the cereals. Cereals are pectin free, but pectin polysaccharides are common in dicotyledonous plants (Bacic et al., 1988; Selvendran, 1984). The chemical composition of the plant cell wall varies not only among plant species, but also varies with the maturity of the plant organ at harvest.

Physicochemical Properties of Dietary Fiber

Dietary fiber can also be classified according to its physicochemical properties, which includes: 1) hydration properties such as swelling capacity, solubility, water holding capacity,

and water binding capacity 2) viscosity 3) cation exchange capacity (Kritchevsky, 1988). Only hydration properties and viscosity will be considered in the present review. The physicochemical properties are linked to the type of polymers that make up the cell wall and their intermolecular association (McDougall et al., 1996).

Prior to the solubilisation of polymers, incoming water swells the dietary fiber to a variable extent, spreading the macromolecules until they are extended and dispersed for solubilization (Thibault et al., 1992). The solubility of a polysaccharide depends not on the monosaccharide, but on the links among them (Cho et al., 1997). Solubilisation is not possible in the case of polysaccharides that adopt regular ordered structures such as cellulose or arabinoxylans, where the linear structure increases the strength of the non-covalent bonds, stabilizing the ordered conformation (Bach Knudsen, 2001). Corn and its co-products are rich in cellulose and arabinoxylans, therefore its dietary fiber is mostly insoluble. Soluble polysaccharides such as β(1-6)-glucans are easier to access by microbes, facilitating fermentation (Oakenfull, 2001). Separation of dietary fiber into soluble and insoluble fractions was the initial step in understanding fiber (Cho et al., 1997). Soluble fiber influences the absorption of lipids and glucose, while insoluble influences bowel movement and is less fermented in the large intestine than soluble fiber (Cho et al., 1997; Serena et al., 2008; Urriola 2010).

The water holding capacity and water binding capacity refer to the ability of a dietary fiber source to retain water within its matrix (Bach Knudsen, 2001). Although the terms have been used interchangeably, they are not the same because water binding capacity refers to the amount of water retained in the dietary fiber matrix after stress (e.g. centrifugation, pH changes, and particle size reduction) has been applied (Cho et al., 1997). It is therefore that during passage through the gut, dietary fiber may swell to a variable extent. Although soluble and insoluble fiber

can both retain water, the water binding capacity id determined by the physicochemical structure of the molecules, and by the pH and electrolyte concentration of the surrounding fluid (Bach Knudsen, 2001). Dietary fiber from cereals tends to have lower water binding capacity than fiber sources with a high concentration of pectins (Serena and Bach Knudsen, 2007).

When dissolved in water the majority of polysaccharides produce viscous solutions (Morris, 1992; Bach Knudsen, 2001). Viscosity is the relationship between the flow of matter and the force that moves it (Dikeman and Fahey, 2006). The viscosity is dependent on the molecular weight of the polymer and the concentration, and large molecules increase the viscosity of a diluted solution because of the volume they occupy (Bach Knudsen, 2001). Absorption of glucose and other nutrients may be reduced by highly viscous dietary fiber (Nyman, 2003).

Differences in the degree of fermentability by microbes of the gastrointestinal tract exist between sources of dietary fiber (Gallager, 2006). The available energy from VFA that the pig obtains from dietary fiber increases with a greater fermentability of dietary fiber (McBurney and Sauer, 1993). The fermentability of dietary fiber depends on the access of bacterial enzymes to their substrate, chemical composition of the substrates, solubility, water holding capacity, and porosity of the dietary fiber (Cho et al., 1997, Gallager, 2006; Guillon et al., 2006; Urriola, 2010).

Analytical Methods to Measure Dietary Fiber

All analytical methods to determine the dietary fiber content of human food, animal feed, and feed ingredients include two basic steps; first, digestion of carbohydrates and other non-fiber

components of the diet (e. g. protein, fat, water, minerals) and, second, quantification of the undigested residue (Urriola, 2010). The digestion procedure can use chemical compounds (e. g. alkali, acid, and detergents) or use enzymes (amylase, amyloglucosidases, and proteases) (Urriola, 2010). Measurement of the indigestible residue can be accomplished y weighing the residue (gravimetric) of by measuring chemical compounds in the residue using chromatography, gas liquid chromatography, and high performance liquid chromatography (Urriola, 2010).

The analytical method that is most commonly used to measure fiber in feed ingredients is the crude fiber method (Bach Knudsen, 2001). It's a chemical-gravimetric method developed at the Agricultura Experimental Station in Weende, Germany (Grieshop et al., 2001). It employs sequential extraction with diluted acid and alkali, followed by gravimetric determination of the residue after drying (Bach Knudsen, 2001). Because of the solubilisation of the structural polysaccharides and lignin, this method only measures a small and variable fraction of the fiber components (Bach Knudsen, 2001). Hence there is no relationship between crude fiber and any definition of dietary fiber (Mertens, 2003) because the recovery of cellulose (40-100%), hemicelluloses (15 to 20%), and lignin (5 to 90%) is not complete (Grieshop et al., 2001; Mertens, 2003; Urriola, 2010).

The detergent methods developed by Van Soest and co-workers is a chemical-gravimetric procedure that empirically relates the value from the analysis to the physiological properties of dietary fiber, and measure the fraction of the fiber that is insoluble in neutral detergents (**NDF**) and acid detergents (**ADF**; Van Soest et al., 1991). The NDF measure hemicellulose, cellulose and lignin, while ADF measure cellulose and lignin, allowing for the calculation of hemicellulose by difference (Bach Knudsen, 2001). The NDF and ADF, however, do not recover soluble dietary fiber such as pectins, mucilages, gums, and β-glucans (Grieshop et al., 2001). In

cereal grains such as corn and co-products where dietary fiber is mostly insoluble, the lack of recovery of soluble dietary fiber components are less concerning (Johnston et al., 2003; Urriola et al., 2010). Other problems with the detergent procedure include the possible contamination of the residue with starch, and that hemicellulose may be left in the ADF fraction (Mertens, 2003).

The two main approaches used to develop more robust and reproducible dietary fiber methods have been the enzymatic- or non-enzymatic gravimetric AOAC procedures (Method 985.29; Prosky et al., 1985) and the enzymatic-chemical from Uppsala (Theander et al., 1994). In the enzymatic-gravimetric approach, often called total dietary fiber (**TDF**), all non-fiber components are removed from the sample by extraction of low-molecular weight sugars and lipids and enzymatic degradation (e.g., amylase, glucoamylase, and protease) of protein and starch, the residue is weighed and corrected for ash and protein (Bach Knudsen, 2001). The TDF has been modified to determine soluble and insoluble dietary fiber (AOAC Official Method 991.43; AOAC Int., 2007). The TDF procedure is more time consuming and less reproducible than the crude fiber and detergent methods (Mertens, 2003).

In the enzymatic-chemical approach, often called Uppsala TDF, the dietary fiber constituents are determined directly after extraction of low-molecular weight sugars, enzymatic removal of starch, acid hydrolysis of dietary fiber polysaccharides and determination of their monosaccharide residues by gas-liquid chromatography, high-performance liquid chromatography or colorimetry (Bach Knudsen, 2001). The Uppsala method calculates TDF as the sum of amylase-resistant polysaccharides, uronic acids, and Klason lignin (AOAC Int., 2007; Grieshop et al., 2001). The enzymatic-chemical methods yield information on the monomeric composition of the NSP and divide it into soluble and insoluble fractions by 80% ethanol, which gives a general view of the functional properties of the fiber (Bach Knudsen, 2001).

The concentration of dietary fiber of a diet or a feed ingredient can also be estimated indirectly, or by difference. The underlying assumption of this method are that all other nutrients have relative low analytical errors and that all values are additive (Urriola, 2012). The dietary fiber concentration is equivalent to the calculation of indigestible carbohydrates, which is achieved by analyzing the substrate for starch and sugars along with protein, fat, and water (de Lange, 2008) as follows, Eq [1]:

Indigestible carbohydrates, g = DM, g – (ash + starch + sugars + protein + fat) [1]

One of the limitations of calculating indigestible carbohydrates by difference is that it includes the cumulative errors from all other analytical procedures (e. i. protein, fat, ash, DM). Other dietary components such as polyols, alcohol, and organic acids are not included. It is therefore that the value is not reliable and should be discouraged (Urriola, 2010).

Fermentability and Utilization of Dietary Fiber by Growing Pigs

The effect of dietary fiber on gastric emptying and has been extensively studied in human nutrition, and a strong relationship has been established between reduced rate of gastric emptying and delayed absorption of nutrients, causing a reduction in the post-prandial peripheral glucose and insulin responses to carbohydrate meals. The importance in pigs is that a reduction in the rate of gastric emptying may limit intake of nutrients and growth. It is however an advantage for sows, since it may induce satiety, decreasing the sensation of hunger and improving in turn the wellbeing of animals in commercial conditions (Vestergaard, 1997; Bach Kndusen, 2001). Reports of the effects of dietary fiber on gastric emptying in the literature are, however,

contradictory and most likely caused by differences among studies in the form in which the dietary fiber has been included.

As summarized by Urriola (2010), fermentative microorganisms conserve energy by transferring electrons from redox reactions to part of the substrate from which energy is derived. During fermentation the substrate is only partially oxidized and only a small amount of energy is conserved for microbial growth (Müller, 2008). During fermentation of dietary fiber in the pig intestine, microbes start breaking down polysaccharides into smaller polysaccharides or the constituent carbohydrates (Müeller, 2008). The monomers then are absorbed into the microbial cell and channeled into the pathways of central metabolism (White, 2000). The products of fermentation are excreted from the microbial cell into the intestinal lumen. The products of microbial fermentation can also be used as substrate for another microbe, excreting in turn a second product (anaerobic food chain). Finally the pig absorbs some of the end products of fermentation of carbohydrates, mainly VFA.

Absorption of VFA

Each of the VFA is readily absorbed from all segments of the lower digestive tract, in a very efficient process that shares similarities with processes occurring in the rumen of herbivores. The VFA absorption appears to be mostly passive and increases linearly with corresponding decreases in pH or increases in concentration (Bergman, 1990). However, unlike the rumen, individual VFA are probably absorbed at comparable rates rather than in the ascending order of acetate<propionate<butyrate (Bergman, 1990). Absorption is proposed to occur following 3 main mechanisms: 1) diffusion of protonated VFA 2) anion exchange (Wong

et al., 2006), and 3) transporter mediated (Kirat and Kato, 2006). Diffusion of protonated VFA is likely the least important, because at physiological pH, only 1% of all VFA in the intestinal lumen is protonated (Cook and Sellin, 1998). If anion exchange is used, VFA are taken up into the enterocyte and $HCO3^-$ is released to the intestinal lumen (Cook and Sellin, 1998). More recent studies have documented the existence of active transport of VFA. Active transporters of VFA belong to the monocarboxilate family and MCT-1 is the transporter present in the intestine of pigs (Welter and Claus, 2008). Another transporter expressed in human colonocytes is the sodium-coupled nomocarboxylate transporter or SLC5A8 that may be implicated in absorption of VFA, especially butyrate (Thangaraju et al., 2008). The MCT1 transporter has been identified in pig intestinal cells, but is not clear if the SLC5A8 is also present in pig colonocytes.

Absorption of VFA also facilitates absorption of other nutrients from the diet. Water and sodium are absorbed along with VFA (Yen, 2001). Plant lignans, diphenolic compounds similar to endogenous steroid hormones are also co-transported by VFA (Bach Knudsen et al., 2006). Inulin improves the bioavailability of iron in corn and soybean meal diets in young anemic piglets (Yasuda et al., 2006). It is not clear if inulin increases absorption of Fe by increasing production of VFA and thereby VFA increase absorption of Fe, or if SFCA reduce luminal pH and increase solubility of Fe, or if VFA increase the expression of the Fe transporters (Tako et al., 2008).

Metabolism of VFA

Approximately 60% of the initial energy is retained in VFA arising from the colonic fermentation. Colonic microbes use the remaining 40% of the potential energy contained

originally in the dietary fiber substrate for growth of is lost as hydrogen and methane (Fleming and Arce, 1986; Miller and Wolin, 1979). The concentration and molar proportions of VFA in portal and arterial blood is different from that in intestinal digesta, suggesting that VFA are metabolized in the intestinal cells and liver (Table 1.1; Argenzio et al., 1974; Bergman, 1990; Marsono et al., 1993). The typical VFA molar proportions in intestinal content of pigs are 65:25:10 (acetate:propionate:byturate). From Table 1.1 is clear that total VFA concentrations as well as individual molar proportions in the cecum and colon are close to those found in the rumen. The concentrations and proportions of VFA in the blood also show some similarities among the several species. Portal blood has a higher total VFA concentration than hepatic or arterial blood because of direct absorption of VFA through the gut epithelium and because hepatic and peripheral metabolism has not yet had a chance to occur (Bergman, 1990). The molar proportions of the individual VFA in blood do not parallel those found in the rumen or gut contents. In pigs, a change in the ratio of VFA after absorption and passage through liver to 90:10:0 in hepatic circulation demonstrates selective metabolism of VFA in enterocytes and in liver (Robertson, 2007). This change clearly indicates that each of the individual VFA is metabolized to different extents by the gut epithelium. Similar metabolic patterns occur in the liver, since much lower amounts of propionate and butyrate are found in hepatic, arterial, or peripheral venous blood than in portal blood. The liver must therefore remove a large proportion of the remaining propionate and butyrate and a smaller proportion of acetate (Bergman, 1990). In all species acetate comprises >90% of the VFA in arterial or peripheral blood and is therefore the main VFA made available for use by muscle or adipose tissue (Bergman, 1990).

Volatile fatty acids are therefore used in 3 ways: 1) by colon cells that use them as an energy source, 2) by the liver that use propionate for gluconeogenesis, and 3) by adipose tissue

and muscle (Wong et al., 2006). Propionate and butyrate are metabolized by the intestinal epithelium and by the liver. Butyrate, however, is largely removed by the gut epithelium, whereas the liver takes up most of the propionate. For both VFA only little escapes to peripheral circulation. In the cecum of rats, approximately 12% of the butyrate is converted to ketone bodies and free amino acids (Remesy and Demigne, 1976). In addition to ketone bodies, butyrate is readily oxidized to CO2 in the colonic wall of pigs (Imoto and Namioka, 1978) and thus acts as an important respiratory fuel or energy source for the colon. Glutamine is also used as a respiratory fuel for the colon of most animal species, but the evidence indicates that butyrate is probably preferentially utilized over glutamine and all other metabolites as an energy source for the colonic epithelial cells (Kritchevsky, 1988; Elia and Cummings, 2007). Butyrate metabolism by liver involves conversion to butyryl-CoA by the enzyme butyryl-CoA synthetase (Bergman, 1990). After this initial reaction, it is rapidly converted to acetyl-CoA, longer chain fatty acids, or ketone bodies. Although the vast majority of butyrate is taken up by epithelial tissues of the gastrointestinal tract and by the liver, trace amounts can enter the general blood circulation (Bergman, 1990). Nearly all tissues of the body have the ability to metabolize butyrate, where is rapidly oxidized or used in lipogenesis, and ruminants and non-ruminants share similar pathways of butyrate metabolism. Butyrate is also effectively removed by the mammary gland mainly for milk fat synthesis (Annison et al., 1963). Butyrate is not only an energy source; it may also regulate cell proliferation and differentiation, which in turn may contribute to prevention of colorectal cancer and other diseases (Cook and Sellin, 1999; Wong et al., 2006).

Propionyl-CoA synthetase activity is high in the liver of rats as well as ruminants, and greatly exceeds that of acetyl-CoA synthetase (Ash and Baird, 1973; Demigne et al., 1985). As a result, most of the propionate is removed from the portal blood by the liver. The usual pathway

for propionate metabolism thus is to enter the tricarboxylic acid (TCA) cycle as oxaloacetate, and, in liver, large amounts are converted to glucose (Fig. 1.2; Bergman, 1990). Propionate is the only VFA that can be a major source of glucose. Acetate, butyrate, or longer chain VFA with even numbers of carbon atoms cannot contribute to a net synthesis of carbohydrate. This is because the only pathway for these VFA to be converted to glucose is through acetyl-CoA and the TCA cycle. When an acetyl-CoA molecule enters the cycle, two carbon atoms are lost as CO2, no net gain of oxaloacetate occurs, and a net synthesis of glucose is impossible (Bergman, 1990). The glucogenicity of propionate in nonruminant animals is less clear. One study in ponies using the isotope dilution principle and transfer quotient calculation concluded that approximately 7% of the total glucose production was derived from propionate produced in the cecum (Gibson et al., 1976), but further studies in other species need to be made, in spite that non-ruminants obtain far more glucose from simple sugars in the digestive tract than ruminants do, and thus do not need to rely on gluconeogenesis from dietary fiber.

Most of the acetate is believed to be transported to the adipose tissue and skeletal muscle where it is used in the synthesis of fatty acids or oxidized and used for synthesis of ATP (Elia and Cummings, 2007). However, substantial use of acetate by the gut has been previously reported in ruminants (Pethick et al., 1981), but is probably used mostly by smooth muscle in the gut wall and adipose tissue in the omentum rather than by epithelial tissues (Bergman, 1990). In ruminants, only the liver utilizes a small proportion of absorbed acetate, because acetyl-CoA synthetase activity is low in the liver compared with adipose tissue or muscle, and similarly lipogenesis is known to occur almost entirely in adipose tissue rather than in liver (Bergman, 1990).

The energy absorbed as VFA accounted for 67 to 74% of the total energy absorbed in the hindgut of pigs fed high fiber diets (Anguita et al., 2006), and the energy from VFA provided 7.1 to 17.6% of the total available energy. In some cases up to 82% of the energy infused inside the cecum as VFA was retained as body energy (Jørgensen et al., 1997).

The effects of VFA on metabolism of fatty acids and fat distribution are not fully understood (Robertson, 2007), but it is suggested that VFA, and especially propionate, may change adipose tissue lipolysis, change adipocyte size and differentiation, an change body fat distribution. Especially, VFA appear to stimulate PPARϒ, acetyl-CoA carboxylase, and fatty acid synthase (Lee and Hossner, 2002).

Effects of dietary fiber in the gastrointestinal tract

The solubility of dietary fiber has been thought to determine the effects of dietary fiber on processes of digestion and absorption of nutrients. Soluble dietary fiber, for example, has been associated with a reduction in absorption of nutrients from the small intestine through its effect on luminal viscosity, which may reduce the rate of nutrient absorption (Rainbird et al., 1984). In contrast non-viscous insoluble dietary fiber from wheat bran or cellulose affected glucose absorption only partially (Low et al., 1986).

The effect of dietary fiber in the small intestine has been reported previously, and is accepted that dietary fiber reduces the digestibility of dry matter and energy because of its resistance to digestion with endogenous enzymes secreted into the small intestine (Bach Knudsen and Hansen, 1991; Graham et al., 1986). The effect on dietary nutrients is, however, more variable and influenced by the type of dietary fiber. Dierick et al. (1983) reported a reduction of

the digestibility of nitrogen and amino acids with pectin and sugar beet pulp, but the effect of cellulose was marginal. In some cases, it has also been found that the cell wall encloses intracellular protein and fat and prevents their digestion in the small intestine (Bach Knudsen et al., 1993; Bach Knudsen, 2001). The intake of soluble or insoluble dietary fiber has also been reported to have no effect on the digestibility of starch (Bach Knudsen, 2001).

The reported average digestibility of dietary fiber at the end of the ileum is 20% (Bach Knudsen, 2001). However, the digestibility of dietary fiber at the end of the ileum is influence by the type of dietary fiber. For example, results obtained with cereal diets show a higher digestibility of soluble ß-glucans, with values in the range of 17 to 73% in oats (Bach Knudsen and Hansen, 1991; Bach Knudsen et al., 1993) and 70 to 97% in barley (Fadel et al., 1988, 1989; Graham, 1986; Bach Knudsen, 2001). In contrast, branched-chain arabinoxylans showed ileal digestibilities ranging from 10 to 12% in wheat products (Bach Knudsen and Hansen, 1991).

The most important difference between fermentation in the small and large intestine of pigs is the type of digestion and the retention time (Bach Knudsen, 2001). The transit time is longer through the large intestine (20-40 h) than through the stomach and the small intestine (Bach Knudsen, 2001). The most active fermentation compartments are the cecum and the proximal colon, where most of the carbohydrates disappear (Bach Knudsen et al., 1993; Bach Knudsen, 2001). The types of polysaccharides that reach the hindgut have significant implications for the site of its degradation. The main NSP degraded in the cecum are soluble NSP (ß-glucan, pectin, soluble arabinoxylans, etc; Bach Knudsen et al., 1993; Canibe and Bach Knudsen, 1997). For other soluble NSP, the swelling and high water binding capacity results in an increased surface area of the cell wall residues to the microflora, which facilitate colonization and degradation of substrate (Bach Knudsen, 2001). In contrast, cellulose, arabinoxylans, and

xylans, when present in lignified tissues are more resistant to degradation in the large intestine (Glitsø et al., 1999).

An increased intake of dietary fiber influence bowel movement, because of the stimulation of microbial growth and VFA, but also because of mechanical action and water holding properties (Bach Knudsen, 2001). The consequence is increased bulk in colon and feces and a reduction of transit time (Glitsø et al., 1999). The effect of dietary fiber on transit time is however associated with the type of dietary fiber being offered. Therefore, polysaccharides that are almost completely degraded in the large intestine will only increase the fecal dry mass due to microbial matter, while the increase will be much greater with more resistant fiber sources (Bach Knudsen, 2001).

In conclusion, utilization of dietary fiber is an important issue in swine nutrition because an increasing amount of high fiber ingredients are being fed to pigs. Current methods to measure dietary fiber do not measure all components that are defined as dietary fiber, but procedures such as TDF appear to be the most accurate available. Fermentation of fiber depends on factors inherent to the diet and factors inherent to the pig. Soluble dietary fiber is much more fermentable than insoluble dietary fiber, and the energy value of fiber in feed ingredients fed to pigs increase with the concentration of soluble fiber.

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Table 1.1. Volatile fatty acids molar proportions and concentrations in digestive tract and blood of different mammalian species

		Molar Proportions of VFA, %		
	Total VFA, mM	Acetic	Propionic	Butyric
Sheep rumen	106	68	19	13
Portal vein	1.60	86	12	2
Hepatic vein	1.39	98	1.4	0.4
Artery	0.77	98	1.5	0.5
Rabbit cecum	74	73	9	18
Portal vein	5.31	74	10	16
Hepatic vein	2.51	91	4	5
Artery	1.77	88	6	6
Pig colon	210	55	34	11
Portal vein	0.75	63	29	8
Artery	0.17	90	6	4
Human colon	124	60	19	21
Portal vein	0.36	69	23	8
Hepatic vein	0.15	78	14	8
Arm vein	0.08	89	6	5
Human portal vein	0.16	73	20	7
Arm vein	0.04	89	5	6

Bergman (1990)

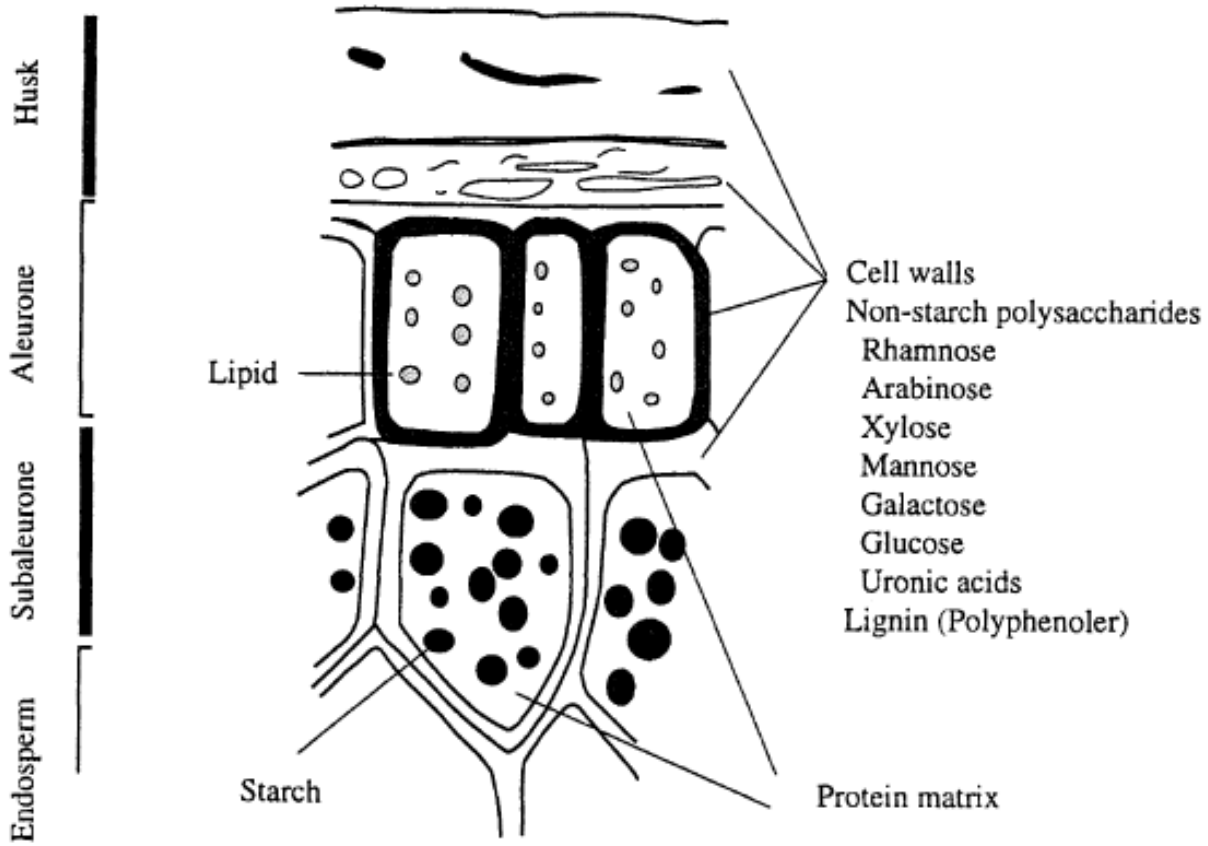

Fig. 1.1 Example of cell wall materials from oats; Bach Knudsen (2001)

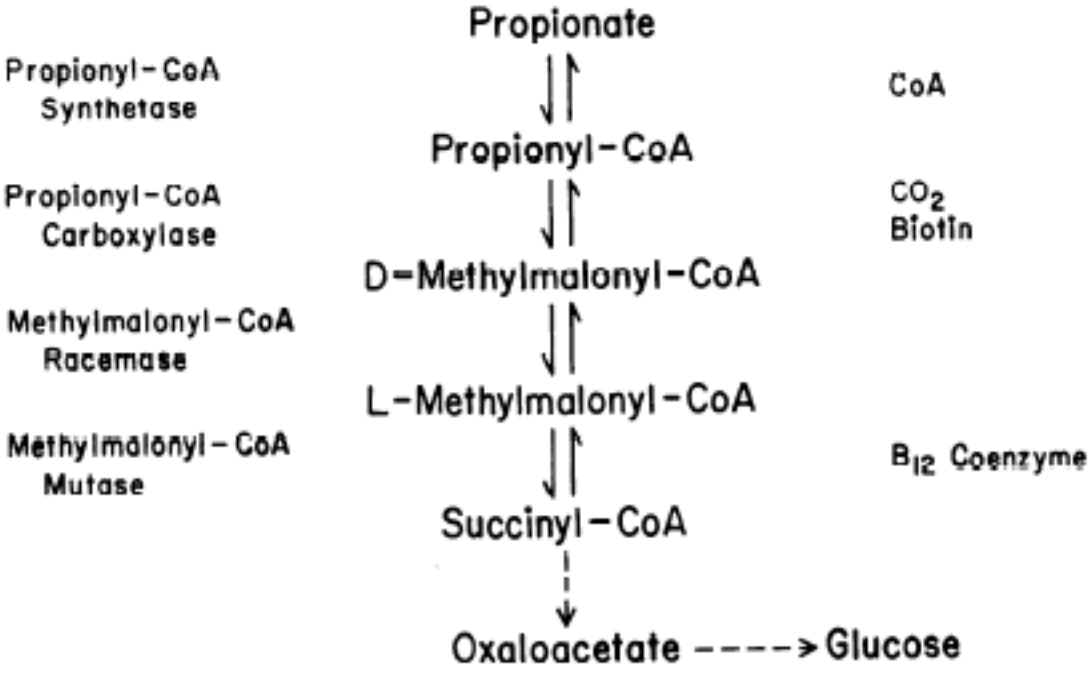

Fig. 1.2 Major pathway for propionate metabolism in liver; Bergman (1990)

CHAPTER 2: EFFECT OF INSOLUBLE-LOW FERMENTABLE FIBER FROM CORN-ETHANOL DISTILLATION ORIGIN ON ENERGY, FIBER, AND AMINO ACID DIGESTIBILITY, HINDGUT DEGRADABILITY OF FIBER, AND GROWTH PERFORMANCE OF PIGS[1]

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ABSTRACT

Extensive use of corn co-products in swine diets increases the concentration of dietary fiber, raising concerns on energy and nutrient digestibility and, ultimately, pig performance. A digestion trial was conducted to determine the effect of increasing levels of insoluble-low fermentable fiber from corn in the diet, using corn bran with solubles from the corn-ethanol distillation industry (**CB-S**), on digestibility of energy, fiber, and AA, and hindgut fermentation of fiber in diets fed to growing pigs. Fifteen growing pigs (BW = 28.7 kg) arranged in a 3-period incomplete block design, and fitted with a T-cannula in the distal ileum, were provided 5 diets (n = 9) containing either a corn-casein basal or the basal diet with 10, 20, 30, or 40% CB-S. Fecal and ileal digesta samples were collected. Two subsequent 28-d growth trials determined the effects of increasing dietary fiber from CB-S in 2 sets of 7 diets formulated either with declining (growing phase: 2,387 to 2,133 kcal NE/kg; finishing phase: 2,499 to 2,209 kcal NE/kg) or constant dietary NE (growing phase: approximately 2,390 kcal NE/kg; finishing phase: approximately 2,500 kcal NE/kg), on growth performance and apparent total tract digestibility (**ATTD**) of energy in 70 growing (BW = 48.9 kg; n = 10) and 70 finishing (BW = 102.0 kg; n = 10) pigs. Results indicated that increasing fiber from corn lowered ($P < 0.01$) the apparent ileal digestibility (**AID**) of GE, DM, CP, and all indispensable amino acids except Arg, but not NDF or total dietary fiber (**TDF**). Increased fiber from corn also reduced ATTD of GE, DM, CP, NDF, and TDF ($P < 0.01$). Increasing fiber with declining diet NE lowered BW, ADG, and G:F ($P < 0.05$) in growing and in finishing pigs. When NE was held constant, as fiber increased, BW and ADG were unaffected in growing and finishing pigs, and G:F was unaffected in finishing pigs but improved in growing pigs ($P < 0.05$) with increasing dietary fiber. In both growing and finishing pigs, ADFI was unaffected by the increased fiber from corn, regardless of the NE

content of diets. In conclusion, the dietary level of insoluble-low fermentable dietary fiber from corn origin decreased the digestibility of dietary AA, and the ability of the growing pig to ferment corn dietary fiber. In spite of the reduction in digestibility of energy and nutrients with insoluble-low fermentable fiber level from corn, growth performance was not impaired when the energy supply is adequately balanced in the diet using the NE system.

Key words: amino acids, digestibility, energy, fiber, hindgut fermentation, pig

INTRODUCTION

Corn and its co-products are used extensively in swine diets because of their availability, cost, and nutrient composition. The inclusion of corn distillers dried grains with solubles (**DDGS**) increases the concentration of dietary fiber in corn-soybean diets as a result of its high fiber content (NRC, 2012). Fiber in corn and its co-products is largely insoluble because of its content of arabinoxylans, cellulose, and lignin, and is mostly resistant to hindgut fermentation (Bach Knudsen, 1997; Choct, 2002). Addition of insoluble fiber to swine diets may also decrease the digestibility of dietary energy, Lys, and fiber (Noblet and Le Goff, 2001; Urriola and Stein, 2010). The inclusion of corn DDGS in commercial swine diets has been reported to decrease ADG and ADFI, although this may be a reflection of an incorrect nutrient profile used in diet formulation (Whitney et al., 2006; Linneen et al., 2008).

The apparent ileal digestibility (**AID**) and apparent total tract digestibility (**ATTD**) of fiber is, however, different among sources of corn DDGS (Urriola et al., 2010), which may contribute to differences in digestibility of energy in DDGS and subsequently in diets containing DDGS. Corn bran with solubles (**CB-S**), obtained after adding solubles remaining from the corn-

ethanol distillation process to corn bran, is a good research model to evaluate the effects of corn fiber in swine diets because it has a lower concentration of starch and a greater concentration of fat and fiber than in whole corn grain (Bach Knudsen, 1997). The first objective of this study was to test the hypothesis that inclusion of insoluble-low fermentable fiber from corn decreases the digestibility of energy, fiber, and AA, and reduces the hindgut fermentation of fiber in growing pigs. A second objective was to test the hypothesis that the increase of dietary fiber from corn, in diets with declining or constant NE, reduces growth performance and ATTD of energy in growing and finishing pigs.

MATERIALS AND METHODS

The experimental protocols for the digestion and growth trials were reviewed and approved by the Institutional Animal Care and Use Committee of Iowa State University.

Digestion Trial

Fifteen growing barrows (progeny of 337 sires × C-22 dams; PIC, Hendersonville, TN) were housed in individual pens of 1.2 × 1.2 m equipped with a feeder, a cup waterer, and a half concrete slatted floor surface in an environmentally controlled building. All pigs were surgically fitted with a T-cannula in the distal ileum following procedures described by Stein et al. (1998). Pigs were allowed to recover from surgery for 7 d and fed a standard corn-soybean meal diet ad libitum.

Dietary treatments included a corn-casein basal diet that was formulated to meet the nutrient requirements of growing pigs, as recommended by the NRC (1998). Four additional dietary treatments were obtained by replacing the basal diet with CB-S (Table 2.1) in 4 equally

spaced steps: 10, 20, 30, and 40% (Table 2.2). Because of the high total dietary fiber (**TDF**) concentration in CB-S, the resulting TDF content of dietary treatments was 7.3, 8.7, 9.1, 11.4, and 14.7% (as-fed basis). Corn or CB-S were the only sources of dietary fiber, and standardized ileal digestible (**SID**) Lys:ME was maintained at 2.6 g/Mcal ME across treatments. Diets also contained TiO_2 at 0.45% (as-fed basis) as an inert marker. The portion of the diet including limestone, monocalcium phosphate, L-Trp, TiO_2, vitamin and trace mineral premixes, and zinc sulfate, and NaCl was maintained constant (3.8%) across all experimental diets.

After recovery from surgery, pigs were weighed (initial BW = 28.7 ± 2.1 kg) and randomly allotted to 5 dietary treatment groups in a 3-period incomplete block design, totaling 9 experimental units per treatment. Pigs did not repeat dietary treatments across periods. Each collection period involved 9 d adaptation to dietary treatments followed by 2 d of feces sub-sample collection and 3 d of ileal digesta sub-sample collection.

All pigs received the same daily amount of feed, which was provided at a level of approximately 90% of predicted ad libitum intake of the basal diet. Ad libitum intake was calculated as: DE intake (kcal/d) = 13.162 x $(1\text{-}e^{-0.0176BW})$, where BW was average BW (NRC, 1998).

To convert ad libitum DE intake to ME units, the efficiency of utilization of dietary DE for ME was assumed to be 0.96 (Noblet et. al., 1994) with the ME of the basal diet estimated to be 3,411 kcal/kg. Feed intake was then adjusted to 90% of this predicted value, and all pigs were offered the same daily amount. During the trial, the daily feed allowance was divided into 2 equal meals provided at 0700 and 1600 h. At the end of each collection period, all animals were weighed and daily feed allowance was adjusted.

After 9 d adaptation to the diet, feces were collected via grab sampling on d 10 and 11 and stored at -20°C. On d 12, 13, and 14, ileal digesta samples were collected for 8 h and stored following the procedures for collection and storage of ileal digesta reported by Cervantes-Pahm and Stein (2008).

At the conclusion of each experimental period, frozen ileal and fecal samples were allowed to thaw at room temperature and pooled within animal, with a sub-sample collected for chemical analysis. Ileal sub-samples were lyophilized prior to chemical analysis. Fecal sub-samples were oven dried in a convection oven at 65°C to constant weight (Jacobs et al., 2011). After drying, ileal and fecal sub-samples were ground through a 1-mm screen prior to chemical analysis.

Samples of CB-S, diets, ileal digesta, and feces were analyzed for DM (Method 930.15; AOAC Int., 2007), ether extract (**EE**; Method 920.39; AOAC Int., 2007), starch (**ST**; Method 996.11; AOAC Int., 2007), ADF (Goering and Van Soest, 1970), NDF (van Soest et al., 1979), TDF (Method 985.29; AOAC Int., 2007), and N (Method 968.06; AOAC Int., 1990). Crude protein was calculated as N × 6.25 and Gly was used as the standard for calibration. Samples were also analyzed for GE by bomb calorimetry (Parr 6200 calorimeter, Parr Instruments Co., Moline, IL) and benzoic acid was used as the standard for calibration. Samples of CB-S, diets, feed ingredients, and ileal digesta were analyzed for AA with an AA analyzer (Model No. 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 determined as Met sulfone and cysteic acid after cold performic acid oxidation overnight before hydrolysis [Method 982.30 E(c); AOAC Int., 2007]. Tryptophan was

determined after NaOH hydrolysis for 22 h at 110°C [Method 982.30 E(c); AOAC Int., 2007]. Titanium dioxide concentrations of diets, ileal digesta, and fecal sub-samples were determined according to the procedure of Leone (1973).

For each dietary treatment, the AID of GE, DM, N, AA, NDF, and TDF were calculated following the procedures outlined by Stein et al. (2007). The ATTD of GE, DM, NDF, and TDF in each diet were calculated following the procedures of Oresanya et al. (2008). The amount of dietary components reaching the terminal ileum and excreted in feces were calculated relative to the indigestible marker (TiO_2) as described by Urriola and Stein (2010). The net disappearance of DM, N, NDF, and TDF in the hindgut was calculated by subtracting the amount (g) of ileal digested dietary component from the amount (g) of total tract digested dietary component. Fermentation of energy was calculated by subtracting the amount (kcal) of ileal digested energy from the amount (kcal) of total tract digested energy (Högberg and Lindberg, 2004).

Growth Trials

In two subsequent trials, in both the growing and the finishing phases, 35 barrows and 35 gilts (337 sires × C-22 dams; PIC) were housed individually in pens of 1.2 × 1.2 m equipped with a feeder, a cup waterer, and half concrete slatted floor surface. The average initial BW was 31.2 ± 1.4 kg for growing and 85.4 ± 4.7 kg for finishing pigs.

In each growth phase, pigs were allotted based on BW to 7 dietary treatments with 10 experimental units per treatment. In the 2 growth phases, treatments included a basal corn-soybean meal diet, formulated to meet all nutrient requirements as recommended by the NRC (1998), and 6 experimental diets formulated with 3 levels of added CB-S (7.5, 15, and 22.5% CB-S for growing pigs or 8, 16, and 24% CB-S for finishing pigs) with added soybean oil (**SBO**;

2, 4, or 6%) or without added SBO, to create a set of treatments with a constant NE and another set of treatments with a declining NE as CB-S increased (Tables 2.3 and 2.4). The maximum dietary inclusion level of CB-S was selected to maintain constant NE with a maximum of 6% added fat. After establishing upper added CB-S and fat levels, equally spaced intermediate levels were selected for both. The CB-S used to increase the dietary fiber level came from the same batch as in the digestion trial. Net energy for diets were calculated based on ingredient composition libraries (Sauvant et al., 2004). Constant SID Lys:NE ratios (3.85 and 2.33 g/Mcal NE for growing and finishing pigs, respectively) were maintained across treatments. Diets were formulated to contain TiO_2 as an inert marker at 0.40% (as-fed basis). Pigs had free access to feed and water, and individual BW and ADFI were recorded weekly for a period of 28 d.

Individual fecal samples were collected weekly by grab sampling and stored at -20°C. Pens were scraped clean prior to collection. Feed samples were also collected weekly and stored at -20°C. At the conclusion of the experiment, fecal samples were allowed to thaw at room temperature and pooled within animal with a sub-sample collected for chemical analysis. Fecal sub-samples were then oven dried in a convection oven at 65°C to constant weight. After drying, fecal sub-samples were ground through a 1-mm screen prior to chemical analysis. Diets and fecal sub-samples were subsequently analyzed for GE, DM, N, and TiO_2 according to procedures described previously. Samples of diets were also analyzed for EE, ST, ADF, NDF, and TDF according to procedures described previously.

For the growing and the finishing phase, ADG, ADFI, and G:F were calculated, and the ATTD of energy, DM, and N of each dietary treatment were determined following the procedures outlined by Oresanya et al. (2008). The NE content of diets was estimated using the following equation:

$$NE\ (kcal/kg\ DM) = 0.7 \times DE + 1.61 \times EE + 0.48 \times ST - 0.91 \times CP - 0.87 \times ADF$$

where DE was the measured DE content of the diet (kcal/kg DM), and values of EE, ST, CP, and ADF are expressed as grams per kilogram of DM (Noblet et al., 1994).

Statistical Analyses

For the digestion and growth trials, normality and independence of the error were verified using the UNIVARIATE procedure of SAS (SAS Inst. Inc., Cary, NC). Homogeneity of the error was verified using the Levene's test of the GLM procedure. In the MIXED procedure, the repeated statement with the group option was used for a model with unequal variances. Outliers were identified using the boxplot of the UNIVARIATE procedure, and an observation was considered to be an outlier if the observed value was greater than 3 inter quartile range away from the error mean. All data were analyzed using the MIXED procedure of SAS with the individual pig as the experimental unit.

In the digestion trial, dietary treatment was considered a fixed effect. Period and pig were included in the model as random effects. Linear and quadratic effects of dietary treatments were determined. In the growth trials, the set of treatments with the constant NE were analyzed separate from the set of treatments with the declining NE. A repeated measures model with dietary treatment as fixed effect was used. The interaction of sex and dietary treatment was not significant and was excluded from the model. Block and sex were included in the model as random effects, and initial BW as a covariate. Differences among treatments were determined using ANOVA, and means were separated using the LS means statement and the PDIFF option with adjustment for the Tukey-Kramer test. An α-value of 0.05 was used to assess significance among treatment means.

RESULTS

Digestion Trial

All pigs were successfully cannulated at the distal ileum and recovered from surgery without complications. The NDF and TDF content of the CB-S used in this study was 22.74 and 25.15%, respectively. The addition of CB-S increased the dietary content of NDF and TDF from 6.76 to 14.01% and 7.27 to 14.73%, respectively (Table 2.2). Although dietary GE increased, the calculated ME and NE decreased across diets with CB-S inclusion.

With the exception of Arg, which showed a quadratic decrease ($P = 0.03$), the AID of all other indispensable AA decreased linearly ($P < 0.001$) as CB-S increased from 0 to 40% in the diet (Table 2.5). Similarly, a decrease in AID of dispensable Asp, Glu, and Tyr (linear, $P < 0.01$) was observed. A trend for a quadratic decrease in the AID of His ($P = 0.07$), Gly ($P = 0.06$), and Pro ($P = 0.08$) was also observed. The mean AID of indispensable AA decreased (linear, $P < 0.01$) while the mean AID of dispensable AA showed a tendency to decrease (quadratic, $P = 0.06$) as dietary fiber increased.

Results showed that the AID and ATTD of GE, DM, and CP decreased (linear, $P < 0.01$) as dietary fiber level increased (Table 2.6). The AID of NDF and TDF was not affected but the ATTD digestibility of NDF and TDF declined (linear, $P < 0.01$), resulting in a linear decline ($P < 0.01$) in hindgut fermentation of NDF (19.6, to 5.9%) and TDF (21.9 to 9.7%) as dietary fiber content increased. Dietary fiber level, however, had no effect on hindgut fermentation of GE, DM, and CP.

The amount of DM, CP, NDF, and TDF reaching the terminal ileum and at the fecal level showed a linear increase ($P < 0.01$) in response to increased dietary fiber concentrations (Table 2.7). Similarly, the amount of GE at the terminal ileum (939 to 1,278 kcal/kg DMI) and at the fecal level (645 to 1,061 kcal/kg DMI) increased (linear, $P < 0.01$) as the dietary inclusion of fiber increased.

Growth Trials

In growing and finishing pigs, the dietary NDF and TDF content increased with the addition of CB-S. The basal diet offered to growing and finishing pigs had less GE and EE than diets containing CB-S, with GE and EE slightly increasing with the increasing inclusion of CB-S. The calculated NE in the set of diets with no SBO added declined with inclusion of CB-S, but the calculated NE content in the set of diets with SBO added remained constant as CB-S inclusion increased in the diet (Tables 2.3, and 2.4).

In each growth phase, the ATTD of DM, CP, and GE of the diet decreased (linear, $P < 0.01$) in pigs fed treatments with both increasing levels of CB-S with or without constancy of NE (Table 2.8). The measured DE content of the set of diets formulated for declining NE, however, was not affected by CB-S inclusion in both growth phases, but there was a linear tendency to decrease ($P = 0.07$) in the DE content of diets fed to finishing pigs. Additionally, the determined NE content of these diets decreased linearly in the growing (2,382 to 2,317 kcal/kg; $P < 0.01$) and the finishing (2,552 to 2,442 kcal/kg; $P < 0.01$) phase as CB-S was increased in the diets. Conversely, in both growing and finishing pigs fed diets formulated for constant NE, a linear increase ($P < 0.01$) in the dietary content of DE (3,055 to 3,391 kcal/kg in growing and 3,194 to 3,513 kcal/kg in finishing pigs) and NE (2,382 to 2,573 kcal/kg in growing and 2,552 to 2,672

kcal/kg in finishing) was observed when CB-S was increased in the diet. In finishing pigs, a quadratic increase ($P < 0.01$) of DE and NE content was also observed as CB-S increased in diets originally formulated for constant NE.

Growth performance results from growing and finishing pigs are presented in Table 2.9. The set of diets formulated with declining NE, and fed to growing pigs showed a decrease in G:F ($P = 0.01$) from 0.46 to 0.43, with a tendency to decrease BW ($P = 0.10$) and ADG ($P = 0.06$). When declining NE diets were fed to finishing pigs, a decrease in BW (from 102.8 to 99.4 kg; $P = 0.03$), ADG (from 1.02 to 0.84 kg; $P = 0.01$), and G:F (from 0.33 to 0.28; $P < 0.01$) was observed. Average daily feed intake, daily DE intake, and daily NE intake were not affected by CB-S inclusion level in diets formulated for declining NE and fed to growing and finishing pigs. In growing and finishing pigs BW, ADG, ADFI, daily DE intake, and daily NE intake were not affected 0.05) by CB-S level and constant NE. Gain to feed ratio, however, increased ($P < 0.01$) in growing pigs from 0.46 to 0.49 with dietary CB-S level in diets formulated for constant NE, but was not affected in finishing pigs.

DISCUSSION

Corn bran is composed mainly from the pericarp of the corn grain, which contains a lower concentration of starch and a greater concentration of insoluble arabinoxylans, cellulose, and lignin compared to whole corn grain (Bach Knudsen, 1997; Choct, 2002). The concentration of NDF and TDF in corn bran is, therefore, greater than corn. Because solubles remaining from the corn-ethanol distillation process were added to the corn bran, the EE content in CB-S is approximately double, and the NDF or TDF content is half of previously reported values for corn

bran without solubles (Sauvant et al., 2004; Anderson et al., 2012). As a result of the addition of solubles, the TDF content of CB-S is also lower than the TDF content of DDGS (Urriola et al., 2010; Anderson et al., 2012). The source of CB-S used in this experiment was the same and had similar chemical composition as reported previously (Anderson et al., 2012).

In the digestion and growth trials, the addition of CB-S to the basal diet resulted in an increase of the dietary NDF and TDF content. In both experiments, the maximum dietary TDF content reached with CB-S inclusion was, however, lower than the TDF content of a corn-soybean meal diet containing 30% of DDGS and fed to growing pigs (Urriola et al., 2010; Urriola and Stein, 2010). Most of the TDF in dietary treatments is insoluble because corn and CB-S were the only source of dietary fiber in the digestion trial and the main source in the growth trials, and the non-starch polysaccharides (**NSP**) of corn and its co-products have been previously reported as insoluble (Bach Knudsen, 1997; Choct, 2002).

In the digestion trial, the observed increased amount of CP reaching the terminal ileum and the reduced AID of CP and most AA, resulting from the dietary increase of insoluble fiber, has been previously reported (Schultze et al., 1994; Noblet and Le Goff, 2001; Owusu-Asiedu et al., 2006). Urriola and Stein (2010) observed a decrease in AID of Lys with 30% inclusion of DDGS in a corn-soybean meal diet fed to growing pigs. The increase in CP reaching the terminal ileum and reduction of AID of most AA may be the result of a combination of an increased amount of endogenous N excretion, and a decreased absorption of endogenous and exogenous N (Libao-Mercado et al., 2006).

Dietary fiber is considered an important contributor to the increase in the excretion and loss of endogenous protein (Souffrant, 1991, 2001; Moughan, 2003). Endogenous losses of AA

can be classified into basal or minimum quantities of AA that are inevitably lost in all diets, and specific losses influenced by diet ingredient composition (Leterme et al., 1996; Stein et al., 2007). Low AID of some AA might reflect the effect of higher intestinal specific endogenous losses, which can increase as insoluble dietary fiber increases in the diet. Langlois et al. (1987) observed an increase in the secretion of pancreatic juice and protein after pigs were fed diets with 40% wheat bran, a source of insoluble fiber. An increased mucosa enzyme activity and mucin content has also been observed in pigs fed diets with high insoluble fiber (Hedemann, et al., 2006). Leterme et al. (2000) reported an increase of ileal endogenous N losses in piglets when insoluble fiber from barley endosperm increased in the diet. The presence of insoluble fiber in the diet has also been reported to impair the AID of N (Schulze et al., 1994). Huisman et al. (1985) observed a decrease in AID of CP and most AA with the inclusion of insoluble dietary fiber from straw meal. Drying and addition of solubles to corn bran may also reduce the AID of Lys in CB-S. During DDGS production, the formation of biologically unavailable Maillard reactions products from excessive heat, and the addition of solubles, have been previously suggested to lower AID of Lys in DDGS (Pahm et al., 2008; Stein and Shurson, 2009).

Because fiber in corn and its co-products is mostly insoluble, and in the NDF analysis soluble carbohydrates are not included, the expected values of NDF and TDF content of ingredients and diets are relatively similar. In growing pigs, Urriola et al. (2010) reported a strong relationship between the ATTD of TDF and of NDF in corn-soybean meal diets containing 30% DDGS, a source of insoluble fiber. Corn and CB-S were the only source of fiber in the dietary treatments, and a similar pattern for digestibility of NDF and TDF was, therefore, expected. Results showed that insoluble fiber from corn and CB-S have no effect on the ileal digestion of dietary fiber, which has also been demonstrated previously using different sources of

insoluble dietary fiber (Graham et al., 1986; Urriola and Stein, 2010). For all dietary treatments, approximately 24 and 17% of the ingested NDF and TDF, respectively, was digested before the end of the ileum. Schulze et al. (1994) observed that level of insoluble fiber did not affect ileal digestibility of NDF, and 17% of ingested NDF from wheat bran was digested before the end of the ileum. Similarly, the addition of wheat bran to a basal cereal-based diet did not affect the AID of NSP, and approximately 11% of the NSP in the wheat bran containing diet were fermented before reaching the hindgut (Graham et al., 1986). Fermentation of soluble and insoluble dietary fiber in the small intestine has been previously reported by other researchers (Jørgensen et al., 1996; Urriola et al., 2010; Urriola and Stein, 2010). Because pigs do not possess the enzymes necessary to hydrolyze dietary fiber, microbial fermentation is responsible for the disappearance of dietary fiber before the end of the ileum. Results from the digestion trial indicated that ileal fermentation of dietary fiber was not affected by level of insoluble dietary fiber, indicating that microbial fermentation before the end of the ileum was not affected by the amount of substrate present. In contrast, the amount of soluble dietary fiber in the diet has been reported to affect the degree of fermentation prior to the end of the ileum, and the importance and extent of fermentation of dietary fiber in the small intestine is related directly to the proportion of soluble dietary fiber (Graham et al., 1986).

In pigs, the largest portion of ingested dietary fiber is fermented by the microorganisms of the hindgut (Noblet and Le Goff, 2001). The ATTD of NDF and TDF, however, decreased with level of inclusion of insoluble dietary fiber from corn, which agrees with previous reports that ATTD of NDF and TDF decreases after 30% DDGS is added to a basal corn-soybean meal diet (Urriola and Stein, 2010). This observation may be attributed to a low ATTD of fiber in corn bran, because fiber in corn is largely insoluble and composed of cellulose and arabinoxylans,

polysaccharides that are partially resistant to microbial degradation (Choct, 2002; Guillon et al., 2007). The lower degradability of dietary fiber in the hindgut, as a consequence of level of insoluble fiber in the diet, resulted in an increase in fecal output of dietary fiber. Digestibility in the hindgut is a function of hydrolysis or fermentation and digesta transit time, and a rapid passage of digesta may decrease the time that substrates are subjected to fermentation and decrease degradability in the large intestine (Morel et al., 2006; Wilfart et al., 2007a). In growing pigs, low digestibility of fiber seems mainly due to the high rate of passage when feeding fiber-rich diets (Le Goff et al., 2002), but a decrease in the microbial capacity of the hindgut to ferment the increased flow of ingested insoluble dietary fiber may have also contributed to this effect.

The amount and the physicochemical composition of dietary fiber present in the diet may also influence energy and nutrient digestion, and growth performance. The observed increase in ileal and total tract amounts of GE and DM, and concomitant decrease in AID and ATTD, was a direct result of gradually replacing highly digestible starch in the diet with low digestible insoluble dietary fiber from CB-S. Energy digestibility has been previously reported to decrease linearly with dietary NDF content (Noblet and Perez, 1993; Lindberg and Pedersen, 2003). In growing pigs, each 1% increase in NDF content of the diet reduces the energy digestibility by 0.9% (Le Goff and Noblet, 2001). Similar effects on ileal and total tract digestibility of DM have been previously reported after insoluble dietary fiber was included at the expense of a highly digestible source of carbohydrates (Newton et al., 1983; Graham et al., 1986; Schulze et al., 1994; Le Goff and Noblet, 2001; Wilfart et al., 2007b). Because fiber has an energy diluting effect in the diet, the extent of the decline in dietary energy is such that fiber fermentation may contribute little to the overall energy supply to the animal (Le Goff and Noblet, 2001; van

Milgen, 2006). Energy contribution from short chain fatty acids produced during fiber fermentation in the gastrointestinal tract of the growing pig, however, maybe offset by an increase in endogenous secretions, or by a reduction in the availability of other dietary nutrients, so that the net contribution from fermentation of dietary fiber to the overall energy supply is close to zero (Le Goff and Noblet, 2001; van Milgen, 2006). In diets containing CB-S or DDGS, the high EE content of the feedstuff, may attenuate the negative effects on dietary energy supply from dietary fiber content. This advantage may be lost when DDGS is manufactured with reduced EE content because of better extraction of EE from the solubles, resulting in a more concentrated fiber and lower NE content.

In the growth trials, calculated NE of diets during formulation of dietary treatments differ from NE estimated from observed DE and dietary chemical composition (Noblet et al., 1994) in growing and finishing pigs. This outcome may originate from the underestimation of the NE of CB-S used for diet formulation, and obtained from feed composition libraries available (Sauvant et al., 2004). Solubles added back to the corn bran are rich in EE, and may increase the NE content of corn bran. The rich content of EE in CB-S resulted in the dietary increase of EE with CB-S level, leading to an increase of observed NE with CB-S level. Dietary treatments intended for constant NE, therefore, showed an increase (191 and 120 kcal/kg for growing and finishing pigs, respectively) in the observed NE content, possibly from the underestimation of NE in CB-S used during formulation.

Surprisingly, in growing and finishing pigs, ADFI was not affected by dietary treatments. In pigs under thermo-neutral conditions, a decrease in energy density of the diet is commonly associated with an increase in ADFI, to compensate for required energy intake to support maintenance and growth (Henry, 1985). Energy density of the diet influences ADFI, but the

absence of this adjustment when dietary energy is diluted may be the consequence of physical factors related to gut fill (Henry, 1985). Gut fill caused by excessive bulkiness of a high-fiber diet may limit short-term response in feed intake when energy density is low, and in some extreme cases, may exert a depressive effect in feed intake. During dietary energy dilution, the ability of the pig to compensate for an increased feed intake may be enhanced, however, after a period of adaptation to a high-fiber diet (Kyriazakis and Emmans, 1995). In both growth trials, the underestimation of the NE content of CB-S during formulation of dietary treatments, resulting in a greater than expected NE density in treatments with high amounts of CB-S, may have explained the absence of differences in ADFI and average daily energy intake across treatments, in both growing and finishing pigs.

A reduction in growth performance was expected in both growing and finishing pigs because of a decreased availability of dietary energy and AA, resulting from the previously reported negative effects of dietary fiber from corn on digestibility of energy and nutrients. In the current experiment, decreased growth performance was observed in growing and finishing pigs fed diets formulated for declining NE. In contrast, growth rate was maintained in growing and finishing pigs fed diets formulated for constant NE, and in growing pigs actually improved feed efficiency. Although observed NE increased in diets formulated to remain constant, in growing and finishing pigs the NE intake of this set of diets was similar, which validates the original intention of supplying the animal with equal amounts of usable energy, by applying the NE system. Baird et al. (1975) reported that dietary fiber content has no effect on growth performance, indicating the pig can tolerate quite a wide range of dietary fiber, provided dietary energy density is adequate. Beaulieu et al. (2009) confirmed these findings. In pigs fed constant NE diets, growth performance was maintained by an equal supply of NE from digestion and

absorption of starch and lipids (specially in the high-fiber diets), if availability of AA is not a limiting factor. In pigs fed diets formulated for declining NE, on the other hand, the energy from fermentation of dietary fiber did not compensate the decrease in energy supply from highly available carbohydrates replaced by insoluble dietary fiber. Additionally, in diets formulated for constant NE, dietary energy digestibility at the ileal level may have not been reduced by level of dietary fiber. This is not uncommon and has been reported in previous experiments, which used different sources of insoluble dietary fiber, where a minimal effect on ileal digestibility and absorption of energy and nutrients was reported (Wang et al., 2002; Serena et al., 2008). The greater content of EE in diets with constant NE may have also reduced digesta transit time and may improve fiber degradation because high-fat digesta moves slower through the intestinal tract (Cervantes-Pahm and Stein, 2008), exposing the fiber for microbial fermentation for a longer period of time.

In conclusion, results of this research indicate that increasing the amounts of insoluble and low fermentable fiber from corn reaching the hindgut may reduce the ability of growing pigs to ferment the fiber component of the diet, and may also decrease the digestibility of dietary AA. In addition, a balanced supply of highly available energy in the form of starch, specially lipids, overcomes the detrimental effects of increased fiber from corn on growth performance. In spite of the reduction in digestibility of energy and nutrients with insoluble and low fermentable fiber level from corn, growth performance was not affected when energy was balanced in the diet.

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Table 2.1. Analyzed composition of corn bran with solubles (as-fed basis)[1]

Composition	Corn bran with solubles
DM, %	95.27
GE, kcal/kg	4,581
Ether extract, %	8.30
Starch, %	24.07
ADF, %	5.89
NDF, %	22.74
TDF, %	25.15
CP, %	13.02
Indispensable AA, %	
Arg	0.78
His	0.53
Ile	0.67
Leu	2.00
Lys	0.65
Met	0.31
Phe	0.81
Thr	0.70
Trp	0.12
Val	0.88
Dispensable AA, %	
Ala	1.28
Asp	1.19
Cys	0.35
Glu	2.82

Table 2.1. (continued)

Gly	0.71
Pro	1.38
Ser	0.83
Tyr	0.61
All AA, %	16.62

[1]Corn bran with solubles (Poet Nutrition, Glenville, MN). TDF = total dietary fiber.

Table 2.2. Ingredient and composition (as-fed basis) of experimental diets for the digestion trial[1]

	CB-S, %				
Item	0	10	20	30	40
Ingredient, %					
Ground corn	84.00	75.30	66.50	57.80	49.10
Corn bran	-	10.00	20.00	30.00	40.00
Casein	10.00	9.00	7.90	6.90	5.80
Soybean oil	2.20	2.00	1.70	1.50	1.30
Limestone	1.24	1.24	1.24	1.24	1.24
Monocalcium phosphate	1.20	1.20	1.20	1.20	1.20
L–Trp	0.01	0.01	0.01	0.01	0.01
Titanium dioxide	0.45	0.45	0.45	0.45	0.45
Vitamin premix[2]	0.15	0.15	0.15	0.15	0.15
Trace mineral premix[3]	0.10	0.10	0.10	0.10	0.10
Zinc oxide[4]	0.05	0.05	0.05	0.05	0.05
NaCl	0.60	0.60	0.60	0.60	0.60
Energy and nutrients[5]					
GE, kcal/kg	3,853	3,884	3,969	4,081	4,140
ME, kcal/kg	3,411	3,229	3,046	2,864	2,681
NE, kcal/kg	2,393	2,273	2,153	2,033	1,914
Ether extract, %	4.04	4.69	4.84	5.50	6.08
Starch, %	57.07	54.11	49.75	46.21	44.07
ADF, %	2.35	2.64	2.93	3.22	3.51
NDF, %	6.76	8.56	10.79	11.32	14.01
TDF, %	7.27	8.69	9.11	11.41	14.73

Table 2.2. (continued)

CP, %	15.8	15.7	15.6	15.5	15.3
SID Lys, %	0.91	0.86	0.81	0.76	0.71
Met + Cys, %	0.44	0.41	0.46	0.51	0.53
Thr, %	0.54	0.49	0.55	0.59	0.62
Trp, %	0.16	0.16	0.16	0.17	0.15

[1]CB-S = corn bran with solubles (Poet Nutrition, Sioux Falls, SD). 0 = basal diet; 10 = diet containing 10% CB-S; 20 = diet containing 20% CB-S; 30 = diet containing 30% CB-S; and 40 = diet containing 40% CB-S.

[2]Provided per kilogram of complete diet: 6,614 IU vitamin A; 827 IU vitamin D; 26 IU vitamin E; 2.6 mg vitamin K; 29.8 mg niacin; 16.5 mg pantothenic acid; 5.0 mg riboflavin; and 0.023 mg vitamin B_{12}.

[3]Provided per kilogram of complete diet: 165 mg Fe as $FeSO_4$; 39 mg Mn as $MnSO_4$; 17 mg Cu as $CuSO_4$; 0.3 mg I as $Ca(IO_3)_2$; and 0.3 mg Se as Na_2SeO_3.

[4]Zinc oxide = 72% Zn.

[5]TDF = total dietary fiber and SID = standard ileal digestible; values for ME and SID Lys were calculated from NRC (1998); values for NE of diets were calculated from Sauvant et al. (2004); all other values were analyzed.

Table 2.3. Composition (as-fed basis) of experimental diets for growing pigs[1]

	Basal	Declining NE			Constant NE		
Item CB-S, %:	0	7.5	15	22.5	7.5	15	22.5
Ingredient, %							
Ground corn	72.24	67.02	62.06	56.5	63.24	54.29	45.50
Corn bran	-	7.50	15.00	22.50	7.50	15.00	22.50
Soybean meal, 46.5% CP	24.00	21.75	19.30	17.54	23.50	23.00	22.29
Soybean oil	-	-	-	-	2.00	4.00	6.00
Limestone	1.20	1.20	1.20	1.30	1.20	1.30	1.30
Monocalcium phosphate	1.15	1.10	1.00	0.75	1.15	1.00	1.00
L–Lys≅HCl	0.18	0.19	0.20	0.19	0.18	0.18	0.18
L–Thr	0.03	0.03	0.03	0.01	0.03	0.03	0.03
L–Trp	-	0.01	0.01	0.01	-	-	-
Titanium dioxide	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin premix[2]	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Trace mineral premix[3]	0.14	0.14	0.14	0.14	0.14	0.14	0.14
NaCl	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Energy and nutrients[4]							
GE, kcal/kg	3,719	3,788	3,832	3,918	3,897	4,097	4,270
DE, kcal/kg	3,282	3,161	3,042	3,297	3,253	3,226	3,197
NE, kcal/kg	2,387	2,301	2,218	2,133	2,387	2,388	2,389
Ether extract, %	2.31	2.65	2.91	3.32	4.28	6.79	9.56
Starch, %	42.97	45.68	44.72	39.78	39.59	39.05	33.80
ADF, %	3.56	3.67	3.78	3.91	3.68	3.79	3.90
NDF, %	9.38	10.54	11.71	12.89	10.36	11.34	12.31

Table 2.3. (continued)

TDF, %	10.06	10.60	11.54	13.62	10.51	12.07	12.66
CP, %	16.8	14.1	15.3	14.1	16.9	15.7	15.9
SID Lys, %	0.92	0.89	0.86	0.82	0.92	0.92	0.92
Met + Cys, %	0.52	0.51	0.50	0.49	0.52	0.52	0.51
Thr, %	0.57	0.56	0.54	0.51	0.58	0.58	0.58
Trp, %	0.17	0.17	0.16	0.15	0.17	0.17	0.16
Ca, %	0.75	0.74	0.71	0.71	0.75	0.76	0.76
Bioavailable P, %	0.26	0.26	0.25	0.22	0.27	0.25	0.26

[1]CB-S = corn bran with solubles (Poet Nutrition, Sioux Falls, SD). Basal = basal diet containing 0% CB-S and 0% soybean oil (SBO); declining NE = diets containing 7.5, 15, or 22.5% of CB-S and no SBO added; and constant NE = diets containing 7.5, 15, or 22.5% of CB-S and 2, 4, or 6% of SBO.

[2]Provided per kilogram of complete diet: 6,614 IU vitamin A; 827 IU vitamin D; 26 IU vitamin E; 2.6 mg vitamin K; 29.8 mg niacin; 16.5 mg pantothenic acid; 5.0 mg riboflavin; and 0.023 mg vitamin B_{12}.

[3]Provided per kilogram of complete diet: 165 mg as Zn $ZnSO_4$; 165 mg Fe as $FeSO_4$; 39 mg Mn as $MnSO_4$; 17 mg Cu as $CuSO_4$; 0.3 mg I as $Ca(IO_3)_2$; and 0.3 mg Se as Na_2SeO_3.

[4]TDF = total dietary fiber and SID = standardized ileal digestible; values for SID Lys, Ca, and bioavailable P in diets were calculated from NRC (1998); values for NE of diets were calculated from Sauvant et al. (2004); all other values were analyzed.

Table 2.4. Composition (as-fed basis) of experimental diets for finishing pigs[1]

	Basal	Declining NE			Constant NE		
Item CB-S, %:	0	8	16	24	8	16	24
Ingredient, %							
Ground corn	86.12	79.72	73.62	67.21	76.72	67.42	58.22
Corn bran	-	8.00	16.00	24.00	8.00	16.00	24.00
Soybean meal, 46.5% CP	11.00	9.50	7.60	6.00	10.40	9.70	9.00
Soybean oil	-	-	-	-	2.00	4.00	6.00
Limestone	0.80	0.80	0.90	1.00	0.80	0.90	0.90
Monocalcium phosphate	0.80	0.70	0.60	0.50	0.80	0.70	0.60
L–Lys≅HCl	0.15	0.15	0.15	0.15	0.15	0.15	0.15
L–Trp	0.01	0.01	0.01	0.02	0.01	0.01	0.01
Titanium dioxide	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin premix[2]	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Trace mineral premix[3]	0.11	0.11	0.11	0.11	0.11	0.11	0.11
NaCl	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Energy and nutrients[4]							
GE, kcal/kg	3,633	3,793	3,825	3,896	3,874	4,053	4,206
DE, kcal/kg	3,302	3,176	3,047	2,917	3,265	3,228	3,195
NE, kcal/kg	2,499	2,403	2,307	2,209	2,492	2,487	2,484
Ether extract, %	2.28	3.21	3.45	4.07	4.53	6.77	9.60
Starch, %	54.94	52.83	50.39	50.05	52.25	45.62	43.04
ADF, %	3.12	3.27	3.40	3.55	3.24	3.36	3.49
NDF, %	9.39	10.64	11.88	13.11	10.44	11.50	12.56
TDF, %	9.85	10.96	10.60	11.82	10.08	10.44	12.68

Table 2.4. (continued)

CP, %	11.1	10.8	10.1	9.9	10.7	10.8	11.1
SID Lys, %	0.58	0.56	0.54	0.52	0.58	0.58	0.58
Met + Cys, %	0.41	0.40	0.39	0.39	0.40	0.40	0.40
Thr, %	0.38	0.37	0.36	0.36	0.38	0.38	0.38
Trp, %	0.12	0.11	0.10	0.10	0.11	0.11	0.11
Ca, %	0.50	0.48	0.50	0.51	0.50	0.52	0.50
Bioavailable P, %	0.19	0.18	0.17	0.17	0.20	0.19	0.18

[1]CB-S = corn bran with solubles (Poet Nutrition, Sioux Falls, SD). Basal = basal diet containing 0% CB-S and 0% soybean oil (SBO); declining NE = diets containing 8, 16, or 24% of CB-S and no SBO added; and constant NE = diets containing 8, 16, or 24% of CB-S and 2, 4, or 6% of SBO.

[2]Provided per kilogram of complete diet: 6,614 IU vitamin A; 827 IU vitamin D; 26 IU vitamin E; 2.6 mg vitamin K; 29.8 mg niacin; 16.5 mg pantothenic acid; 5.0 mg riboflavin; and 0.023 mg vitamin B_{12}.

[3]Provided per kilogram of complete diet: 165 mg Zn as $ZnSO_4$; 165 mg Fe as $FeSO_4$; 39 mg Mn as $MnSO_4$; 17 mg Cu as $CuSO_4$; 0.3 mg I as $Ca(IO_3)_2$; and 0.3 mg Se as Na_2SeO_3.

[4]TDF = total dietary fiber and SID = standardized ileal digestible; values for SID Lys, Ca, and bioavailable P of diets were calculated from NRC (1998); Values for NE of diets were calculated from Sauvant et al. (2004); all other values were analyzed.

Table 2.5. Effects of increasing dietary fiber from corn bran with solubles on apparent ileal digestibility of AA in growing pigs (digestion trial)[1,2]

	CB-S, %						*P*-value[3]	
Item	0	10	20	30	40	SEM	L	Q
Indispensable AA, %								
Arg	83.4	77.9	80.8	79.5	80.6	1.1	0.22	0.03
His	87.0	80.8	82.4	79.0	80.5	1.7	<0.01	0.07
Ile	80.9	78.4	77.3	75.9	75.4	1.1	<0.01	0.35
Leu	88.2	86.6	85.8	84.7	84.4	0.8	<0.01	0.44
Lys	85.2	82.5	79.5	79.8	75.8	2.2	<0.01	0.92
Met	89.7	87.8	86.4	85.3	84.3	0.8	<0.01	0.43
Phe	87. 6	85.7	84.6	83.3	82.6	0.9	<0.01	0.53
Thr	73.3	70.2	69.8	66.6	68.2	1.5	<0.01	0.24
Trp	83.4	82.7	81.1	78.6	75.9	1.3	<0.01	0.27
Val	80.3	77.2	76.2	74.9	74.3	1.2	<0.01	0.29
Mean	84.3	81.5	80.8	79.4	78.9	0.9	<0.01	0.28
Dispensable AA								
Ala	76.3	74.7	75.6	74.6	76.5	1.4	0.96	0.33
Asp	77.6	74.1	73.4	69.9	71.1	1.3	<0.01	0.19
Cys	65.0	62.0	62.6	60.7	65.2	2.1	0.86	0.11
Glu	86.4	83.4	83.8	81.4	82.2	0.9	<0.01	0.18
Gly	53.9	49.5	52.2	48.2	53.5	3.1	0.41	0.06
Pro	77.9	55.5	74.8	76. 6	76.2	4.0	0.16	0.08
Ser	73.0	68.7	73.2	68.2	72.0	1.5	0.60	0.24
Tyr	87.4	85.8	85.2	83.8	82.8	0.8	<0.01	0.88

Table 2.5. (continued)

Mean	79.6	72.4	77.0	74.9	75.9	1.4	0.25	0.06
All AA	81.8	76.6	78.7	77.0	77.3	1.1	0.02	0.90

[1]CB-S = corn bran with solubles (Poet Nutrition, Sioux Falls, SD). 0 = basal diet; 10 = diet containing 90% of the basal diet and 10% of corn bran with solubles (CB-S); 20 = diet containing 80% of the basal diet and 20% of CB-S; 30 = diet containing 70% of the basal diet and 30% of CB-S; and 40 = diet containing 60% of the basal diet and 40% CB-S.

[2]Data are least squares means (n = 9).

[3]*P*-values for linear (L) and quadratic (Q) effects.

Table 2.6. Effects of increasing dietary fiber from corn bran with solubles on apparent ileal digestibility, apparent total tract digestibility, and hindgut disappearance of DM, energy, CP, NDF, and total dietary fiber (TDF) in growing pigs (digestion trial)[1,2]

	CB-S, %						*P*-value[3]	
Item	0	10	20	30	40	SEM	L	Q
Apparent ileal digestibility, %								
DM	79.8	76.1	75.7	71.9	71.2	1.1	<0.01	0.49
GE	78.8	75.1	74.6	72.5	72.2	1.3	<0.01	0.19
CP	77.9	75.5	72.4	69.2	67.9	1.5	<0.01	0.70
NDF	23.0	25.1	24.3	23.3	25.2	3.0	0.76	0.96
TDF	14.9	17.5	16.5	15.9	19.9	2.8	0.15	0.62
Apparent total tract digestibility, %								
DM	87.7	85.8	82.7	80.4	79.0	0.7	<0.01	0.33
GE	85.4	83.3	80.6	78.2	76.9	0.9	<0.01	0.36
CP	85.2	82.5	79.7	75.7	74.0	1.4	<0.01	0.87
NDF	42.6	41.6	41.9	29.3	30.5	2.3	<0.01	0.28
TDF	36.6	34.4	33.5	26.4	29.1	2.2	<0.01	0.66
Hindgut disappearance, %								
DM	7.8	9.7	7.1	8.4	7.8	1.0	0.68	0.77
GE	6.5	8.1	5.9	5.7	4.8	1.0	0.07	0.43
CP	7.4	7.0	7.5	6.4	5.9	1.9	0.54	0.79
NDF	19.6	16.5	17.8	6.4	5.5	3.5	<0.01	0.52
TDF	21.9	16.4	16.8	10.8	9.7	3.0	<0.01	0.81

[1]CB-S = corn bran with solubles (Poet Nutrition, Sioux Falls, SD). 0 = basal diet; 10 = diet containing 90% of the basal diet and 10% of corn bran with solubles (CB-S); 20 = diet

containing 80% of the basal diet and 20% of CB-S; 30 = diet containing 70% of the basal diet and 30% of CB-S; and 40 = diet containing 60% of the basal diet and 40% CB-S.

[2]Data are least squares means (n = 9).

[3]*P*-values for linear (L) and quadratic (Q) effects.

Table 2.7. Effects of increasing dietary fiber from corn bran with solubles (CB-S) on the amount (g/kg or kcal/kg of DMI) of energy, DM, CP, NDF, and total detry fiber (TDF) in ileal effluent and feces from growing pigs fed the experimental diets (digestion trial)[1,2]

	CB-S, %						*P*-value[3]	
Item	0	10	20	30	40	SEM	L	Q
Ileal								
DM	205	248	246	281	293	11	<0.01	0.47
GE	939	1,103	1,140	1,246	1,278	56	<0.01	0.27
CP	40	44	49	53	55	3	<0.01	0.61
NDF	71	81	94	106	115	4	<0.01	0.86
TDF	79	85	102	117	127	3	<0.01	0.39
Total tract								
DM	132	151	182	203	218	7	<0.01	0.44
GE	645	741	872	990	1,061	39	<0.01	0.54
CP	27	31	36	42	44	3	<0.01	0.73
NDF	53	63	72	97	107	3	<0.01	0.12
TDF	59	67	81	102	113	3	<0.01	0.31

[1]CB-S = corn bran with solubles (Poet Nutrition, Sioux Falls, SD). 0 = basal diet; 10 = diet containing 90% of the basal diet and 10% of corn bran with solubles (CB-S); 20 = diet containing 80% of the basal diet and 20% of CB-S; 30 = diet containing 70% of the basal diet and 30% of CB-S; and 40 = diet containing 60% of the basal diet and 40% CB-S.

[2]Data are least squares means (n = 9).

[3]*P*-values for linear (L) and quadratic (Q) effects.

Table 2.8. Effects of increasing dietary fiber from corn bran with solubles, in diets formulated with declining or constant NE on apparent total tract digestibility of DM, GE, CP and on the DE and NE content of diets fed to growing and finishing pigs[1,2,3]

		Declining NE					*P*–value[5]		Constant NE					*P*–value[6]	
Item	CB-S,[4] %:	0	7.5/8	15/16	22.5/24	SEM	L	Q	0	7.5/8	15/16	22.5/24	SEM	L	Q
Growing pigs															
	ATTD of DM,[7] %	84.2	81.8	80.7	79.8	0.4	<0.01	0.07	84.2	84.5	80.9	80.2	0.5	<0.01	0.28
	ATTD of GE, %	82.2	79.6	78.3	77.7	0.5	<0.01	0.04	82.2	82.7	79.7	79.4	0.5	<0.01	0.41
	ATTD of CP, %	79.0	71.5	72.7	69.7	0.7	<0.01	<0.01	79.1	80.3	73.8	74.5	0.9	<0.01	0.71
	DE, kcal/kg	3,055	3,014	3,002	3,044	17	0.13	0.83	3,055	3,224	3,266	3,391	22	<0.01	0.31
	NE,[8] kcal/kg	2,382	2,327	2,300	2,317	13	<0.01	0.07	2,382	2,491	2,504	2,573	16	<0.01	0.23
Finishing pigs															
	ATTD of DM, %	89.9	88.0	85.9	84.2	0.5	<0.01	0.93	89.9	88.3	87.5	84.2	0.4	<0.01	0.03
	ATTD of GE, %	87.9	86.0	83.7	81.8	0.6	<0.01	0.93	87.8	86.5	86.2	83.0	0.5	<0.01	0.04
	ATTD of CP, %	84.5	80.1	75.7	72.1	1.0	<0.01	0.70	84.6	81.2	79.5	74.9	0.9	<0.01	0.38

Table 2.8 (continued)

DE, kcal/kg	3,194	3,261	3,201	3,189	22	0.07	0.85	3,194	3,353	3,495	3,513	18	<0.01	<0.01
NE, kcal/kg	2,552	2,536	2,465	2,442	17	<0.01	0.86	2,552	2,632	2,719	2,677	15	<0.01	<0.01

[1]CB-S = corn bran with solubles (Poet Nutrition, Sioux Falls, SD), and ATTD = apparent total tract digestibility. Declining NE = diets containing CB-S and no soybean oil (SBO) added; and constant NE = diets containing CB-S and 2, 4, or 6% of SBO.

[2]Data are least squares means (n = 10).

[3]Dietary treatment x sex, $P > 0.05$.

[4]Fed diets containing 0, 7.5, 15, or 22.5% CB-S to growing pigs and diets containing 0, 8, 16, or 24% CB-S to finishing pigs.

[5]*P*-values for linear (L) and quadratic (Q) effects are for the effects of declining NE with CB-S inclusion.

[6]*P*-values for L and Q effects are for the effects of constant NE with CB-S inclusion.

[7]ATTD = Apparent total tract digestibility.

[8]Values of NE of diets were calculated from Noblet et al. (1994) and expressed as-fed basis.

Table 2.9. Effects of increasing dietary fiber from corn bran with solubles in diets formulated with declining or constant NE on growth performance and energy intake in growing and finishing pigs[1,2,3]

		Declining NE						Constant NE					
Item	CB-S,[4] %:	0	7.5/8	15/16	22.5/24	SEM	*P*–value	0	7.5/8	15/16	22.5/24	SEM	*P*–value
Growing pigs													
BW, kg		49.5	49.1	48.8	47.0	0.7	0.10	49.4	49.6	49.5	48.6	0.7	0.78
ADG, kg		1.04	1.02	1.01	0.92	0.04	0.06	1.04	1.07	1.07	1.02	0.03	0.65
G:F		0.46^{a}	0.44^{b}	0.44^{b}	0.43^{b}	0.01	0.01	0.46^{b}	0.47^{ab}	0.48^{a}	0.49^{a}	0.01	<0.01
ADFI, kg		2.29	2.35	2.30	2.15	0.07	0.26	2.29	2.28	2.23	2.09	0.07	0.14
DE intake, kcal/d		6,998	7,092	6,896	6,554	216	0.33	6,988	7,347	7,277	7,078	211	0.61
NE intake, kcal/d		5,456	5,474	5,285	4,990	166	0.16	5,449	5,677	5,578	5,370	163	0.56
Finishing pigs													
BW, kg		102.8^{a}	101.7^{a}	101.3^{ab}	99.4^{b}	0.8	0.03	103.0	103.0	102.4	102.5	0.9	0.94
ADG, kg		1.02^{a}	0.97^{ab}	0.94^{bc}	0.84^{c}	0.04	0.01	1.03	1.02	0.99	0.99	0.04	0.90
G:F		0.33^{a}	0.32^{ab}	0.31^{b}	0.28^{c}	0.01	<0.01	0.33	0.34	0.34	0.34	0.01	0.67
ADFI, kg		3.08	3.07	3.02	2.94	0.10	0.70	3.09	2.93	2.89	2.91	0.10	0.43
DE intake, kcal/d		9,847	9,995	9,653	9,412	293	0.53	9,888	9,846	10,113	10,278	309	0.77
NE intake, kcal/d		7,871	7,773	7,433	7,208	227	0.16	7,902	7,728	7,869	7,833	249	0.96

[a-c]Within a row and declining or constant NE, means without a common superscript differ, $P < 0.05$.

[1]CB-S = corn bran with solubles (Poet Nutrition, Sioux Falls, SD). Declining NE = diets containing CB-S and no soybean oil (SBO) added; and constant NE = diets containing CB-S and 2, 4, or 6% of SBO.

[2]Data are least squares means (n = 10).

[3]Effect of week, $P < 0.05$; dietary treatment x sex, $P > 0.05$; and dietary treatment and week, $P > 0.05$.

[4]Fed diets containing 0, 7.5, 15, or 22.5% CB-S to growing pigs and diets containing 0, 8, 16, or 24% CB-S to finishing pigs.

CHAPTER 3: EFFECTS OF REDUCED OIL DISTILLERS DRIED GRAINS WITH SOLUBLES AND SOYBEAN OIL ON DIETARY FAT, FIBER, AND AMINO ACID DIGESTIBILITY IN CORN BASED DIETS FED TO GROWING PIGS

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ABSTRACT

The use of corn co-products increases the concentration of fiber and often the use of supplemental fat in swine diets, which may affect energy and nutrient digestibility. An experiment was conducted to determine the effects of reduced oil distillers dried grains with solubles (**DDGS-RO**) and soybean oil (**SBO**) on dietary Lys, acid hydrolyzed ether extract (**AEE**), and neutral detergent fiber (**NDF**) digestibility in corn-based diets fed to growing pigs. Eighteen growing pigs (BW = 33.8 ± 2.2 kg) were surgically fitted with a T-cannula in the distal ileum and allocated to 1 of 6 dietary treatment groups in a 3-period incomplete latin square design, with 9 observations per treatment. Six dietary treatments were obtained by adding 0, 20, and 40% DDGS-RO to corn-casein diets formulated with 2 and 6% SBO. Ileal digesta and fecal samples were collected and the apparent ileal (**AID**) and total tract digestibility (**ATTD**) of AEE and NDF and the AID of Lys were determined. Results showed that the AID of Lys was not affected by SBO concentration ($P > 0.05$), but DDGS-RO inclusion showed a quadratic effect ($P < 0.001$). The AID of Lys was highly predictable ($R^2 = 0.69$) from the DDGS-RO and dietary SBO level. An interaction between DDGS-RO and SBO on the AID ($P = 0.003$; $R^2 = 0.68$) and ATTD ($P = 0.004$; $R^2 = 0.79$) of AEE was observed, where the AID and ATTD of AEE increased with SBO. The AID (72.5 to 79.1%) and ATTD (62.6 to 71.6%) of AEE increased with DDGS-RO at 2% SBO, but no effect was observed at 6% SBO. An interaction between DDGS-RO and SBO on the AID ($P = 0.037$; $R^2 = 0.53$) and ATTD ($P = 0.004$; $R^2 = 0.36$) of NDF was observed, where the AID (46.4 to 22.4%) and ATTD (52.0 to 40.9%) of NDF decreased with DDGS-RO at 6% SBO, but no effect was observed at 2% SBO. The AID of NDF increased (32.5 to 46.4%) with SBO at 0% DDGS-RO, but no effect was observed at 20 or 40% DDGS-RO. In conclusion, DDGS-RO increased the digestibility of AEE, and decreased the

digestibility of NDF, but the effect was modulated by SBO. Soybean oil increased the digestibility of AEE but the effect was modulated by DDGS-RO, and increased the AID of NDF in diets without DDGS-RO. The AID of Lys decreased with DDGS-RO and was not affected by addition of SBO.

Keywords: Cannulation, response surface, regression, endogenous losses, pig

INTRODUCTION

Corn co-products are rich in dietary fiber and its inclusion in swine diets dilutes the traditionally starch-based dietary energy. Dietary fiber from corn and its co-products is only partially fermented in the gastrointestinal tract of pigs because it is rich in insoluble non-starch polysaccharides, such as cellulose, arabinoxylans, and lignin (Bach Knudsen, 1997; Jaworski, 2012). Dietary energy digestibility declines linearly with fiber content (Noblet and Perez, 1993); the extent of this decline is such that, due to the limited fermentability of fiber from corn and its co-products, increasing fiber in the diet may contribute little to the overall energy supply of the growing pig (Le Goff and Noblet, 2001; van Milgen, 2006). Furthermore, advances in the ethanol industry increase the efficiency of starch and oil extraction from the corn grain, leading to a higher concentration of the fiber component of the co-products, resulting in the necessity to add greater quantities of fat to the diet to maintain an acceptable concentration of energy in the final diet. Added fat to swine diets typically originate from either intact fat in feed ingredients such as distillers dried grains with solubles (**DDGS**) or supplemented extracted fat such as choice white grease or any number of vegetable oils (Azain, 2001).

The addition to the diet of DDGS with low fat content, and subsequent increase of dietary fiber, may decrease the digestibility of energy, dietary fiber, and nutrients in swine diets (Farrell, 1973; Noblet and Perez, 1993; Souffrant, 2001). Yet, the effects of fiber rich corn co-products on the digestion of dietary fiber and of nutrients is not available when fat is added to the diet.

The objective of the present study was to test the hypothesis that the digestibility of AA, acid hydrolyzed ether extract (**AEE**), and neutral detergent fiber (**NDF**) decrease with an increase in dietary fiber and fat from reduced oil distillers dried grains with solubles (**DDGS-RO**) and soybean oil (**SBO**).

MATERIALS AND METHODS

The experimental protocol was reviewed and approved by the Institutional Animal Care and Use Committee at Iowa State University (12-13-7686-S).

Animals, Housing, and Experimental Design

Eighteen growing barrows (progeny of sire line 337 × dam line C-22, PIC, Hendersonville, TN) were housed in individual pens (1.2 × 1.2 m) equipped with a feeder, a cup waterer, and a half-slatted concrete floor in an environmentally controlled building. All pigs were surgically fitted with a T-cannula in the distal ileum following procedures described by Stein et al. (1998). After recovery from surgery, pigs were weighed (initial BW = 33.8 ± 2.2 kg) and randomly allocated to 1 of 6 dietary treatments groups in a 3-period incomplete latin square design, resulting in 9 observations per treatment. Pigs were not allowed to repeat dietary treatments across periods. Each collection period involved 9 d of adaptation to dietary treatments followed by 2 d of feces sub-sample collection and 3 d of ileal digesta sub-sample collection.

Dietary Treatments

Six dietary treatments were obtained by adding 0, 20, and 40% reduced oil distillers dried grains with solubles (**DDGS-RO**) to corn-casein diets formulated with 2% and 6% soybean oil (**SBO**; Table 3.1). A corn-casein diet with 2% SBO was formulated to meet or exceed the nutrient requirements of growing pigs (NRC, 2012), and 5 additional dietary treatments were obtained by adding DDGS-RO and SBO at the expense of corn. Casein and the portion of the diet including limestone, monocalcium phosphate, salt, vitamin and trace mineral premixes were maintained constant. Diets also contained 0.5% Cr_2O_3 as an inert marker. All pigs received the

same daily amount of feed, which was provided at a level of approximately 90% of predicted ad libitum intake of the diet formulated with 2% SBO and no DDGS-RO. The daily feed allowance was divided into 2 equal meals provided at 0700 and 1600 h. At the end of each collection period, all pigs were weighed and daily feed allowance for the next collection period was adjusted.

Sample Collection

After 9 d of adaptation to the diet, feces were collected via grab sampling on d 10 and 11, and stored at -20°C. On d 12, 13, and 14, ileal digesta samples were collected for 8 h by attaching a 207-mL plastic bag (Whirl-Pak, Nasco, Fort Atkinson, WI) to the opened cannula with a cable tie. Bags were removed whenever they were filled with digesta or at least every 30 min, and stored at -20°C to prevent bacterial degradation. At the conclusion of each experimental period, frozen ileal and fecal samples were allowed to thaw at room temperature and pooled within animal, with a sub-sample collected for chemical analysis. Ileal sub-samples were lyophilized before chemical analysis. Fecal sub-samples were oven-dried in a convection oven at 65°C to constant weight (Jacobs et al., 2011). After drying, feed, ileal, and fecal sub-samples were finely ground in a Wiley Mill (Variable Speed Digital ED-5 Wiley Mill; Thomas Scientific, Swedesboro, NJ) through a 1-mm screen and stored in desiccators to maintain a constant percentage of DM.

Chemical Analysis and Calculations

Samples of diets were analyzed for DM (method 930.15; AOAC Int., 2007), GE by a bomb calorimeter (Model 6200; Parr Instrument Co., Moline, IL) with benzoic acid as a standard (6,318 kcal GE/kg of benzoic acid; Parr Instrument Co., Moline, IL), acid hydrolyzed ether

extract (**AEE**; Sanderson, 1986; Soxtec 2050, FOSS North America, Eden Prairie, MN), starch (method 996.11; AOAC Int., 2007), acid detergent fiber (**ADF**; Goering and Van Soest, 1970), neutral detergent fiber (NDF; Van Soest and Robertson, 1980), total dietary fiber (**TDF**; method 985.29; AOAC Int., 2007), and nitrogen using the combustion method (method 990.03: AOAC International, 2007) with a Trumac apparatus (Leco Corporation, St. Joseph, MI) with EDTA for calibration (9.58 ± 0.01% nitrogen; Leco Corporation, St. Joseph, MO). Crude protein was calculated as nitrogen × 6.25. Ileal digesta and fecal samples were also analyzed for DM, GE, NDF, and AEE. Diets and ileal digesta were analyzed for AA (University of Missouri Agriculture Experiment Station Chemical Laboratories, Columbia, MO) according to method 982.30 E (a, b, c; AOAC Int., 2007). Chromium was determined in diets, ileal digesta, and fecal sub-samples using the method of Fenton and Fenton (1979) and absorption was measured at 440 nm using a spectrophotometer (Synergy 4, BioTek, Winooski, VT). Chromic oxide standard samples were assayed to confirm the accuracy of the analytical procedure, and a recovery of 100.8 ± 1.95% was attained.

For each dietary treatment, the AID and ATTD of DM, GE, NDF, and AEE, and the AID of AA were calculated using the index method (Oresanya et al., 2008). The DE value was determined by multiplying the GE by the observed ATTD of GE of the ingredient, and the ME was estimated from the calculated DE and CP of the ingredient (Noblet and Perez, 1993).

Statistical Analyses

Univariate Analysis and Normality Test. The data were analyzed in a mixed model including the fixed effects of DDGS-RO, SBO, their interaction and the covariate initial BW, and the random effects of Period (3 levels) and Group (6 levels with 3 pigs per group).

Studentized residuals from each analysis were and used to test normality. Outliers were removed until the Shapiro-Wilk's test reached $P>0.05$ and Studentized residual fell within $\pm 3\sigma$. Least squares means for DDGS-RO and interaction between DDGS-RO and SBO were compared using Tukey-Kramer adjustment. Effects and multiple comparison differences were deemed significant at $\alpha \leq 0.05$.

Response Surface Model. Orthogonal polynomial contrasts were used to test the linear and quadratic effects of DDGS-RO and SBO, when possible. Linear effects tested were: DDGS-RO (L_DDGS-RO), SBO (L_SBO), and interaction L_SBO*L_DDGS-RO. Quadratic effects tested were: Q_DDGS-RO and the interaction L_SBO*Q_DDGS-RO.

Depending on the significance ($P<0.05$) of the contrasts, response surface models were generated to predict response according to the levels of DDGS-RO and SBO. A hierarchical model selection was used to construct the response surface models. Models were only constructed when both DDGS-RO and SBO were significant ($P<0.05$), regardless of the orthogonal polynomial effect (linear or quadratic). If the quadratic effect of Q_DDGS-RO was significant ($P<0.05$), the linear effect of L_DDGS-RO was kept in the model. Similarly, if the interaction L_SBO*Q_DDGS-RO was significant ($P<0.05$), the interaction L_SBO*L_DDGS-RO was kept in the model, as well as all other effects (L_SBO, L_DDGS-RO, and Q_DDGS-RO), since these effects are part of the interaction effect of L_SBO*Q_DDGS-RO. Since SBO had only two levels (2 and 6%), we could only test the linear effect (L_SBO and interactions).

RESULTS

All pigs successfully recovered from surgery, remained healthy and readily consumed their diets throughout the experiment. The NDF and AEE of the DDGS-RO used in the present study were 39.2% and 7.1%, respectively. The analyzed nutrient composition showed that dietary inclusion of DDGS-RO increased the dietary AEE in treatments formulated with 2% SBO (4.4, 5.7, and 6.3% AEE) and 6% SBO (8.4, 9.1, and 10.1% AEE; Table 3.2). The dietary NDF also increased with DDGS-RO in treatments formulated with 2% SBO (6.9, 11.0, and 14.6% NDF) and 6% SBO (6.8, 9.7, and 14%). Dietary concentrations of GE, CP, and AA also increased with DDGS-RO at both 2% and 6% SBO. The starch concentration, however, decreased with DDGS-RO at 2% and 6% SBO.

The AID of GE and DM decreased with dietary inclusion of DDGS-RO ($P < 0.001$; Table 3.3). In contrast, the dietary inclusion of SBO increased the AID of GE ($P = 0.046$), but did not affect the AID of DM ($P = 0.325$). The ATTD of GE and DM decreased with DDGS-RO ($P < 0.001$) and were not affected by the SBO level ($P > 0.05$). Results showed that the AID of all indispensible AA decreased ($P < 0.05$) with DDGS-RO and, with the exception of the AID of Ile ($P = 0.015$) and Met ($P = 0.008$), were not affected by SBO ($P > 0.05$).

An interaction between DDGS-RO and SBO on the AID ($P = 0.011$) and ATTD ($P = 0.008$) of AEE was observed (Table 3.3), where the AID and ATTD of AEE increased with SBO across DDGS-RO levels (Fig. 3.1). The AID (72.5, 75.9, and 79.1%) and ATTD (62.6, 67.6, and 71.6%) of AEE increased with DDGS-RO at 2% SBO, but no effect was observed at 6% SBO. An interaction between DDGS-RO and SBO on the AID ($P = 0.002$) and ATTD ($P = 0.009$) of NDF was observed, where the AID (46.4 to 22.4%) and ATTD (52.0 to 40.9%) of NDF decreased with DDGS-RO at 6% SBO, but no effect was observed at 2% SBO (Fig. 3.2). The

AID of NDF increased (32.5 to 46.4%) with SBO at 0% DDGS-RO, but no effect was observed at 20 or 40% DDGS-RO.

The observed ME values of diets formulated with 2% and 6% SBO decreased ($P < 0.01$) with DDGS-RO from 3.37 to 3.17 Mcal/kg and from 3.57 to 3.35 Mcal/kg, respectively (Table 3.4). In contrast, the DE and ME values of diets increased ($P < 0.01$) by approximately 0.2 Mcal/kg of ME when SBO increased from 2% to 6% SBO in the diet.

The response surface models (Table 3.5) showed a high predictability of the AID of GE ($R^2 = 0.78$), DM ($R^2 = 0.86$), and Met ($R^2 = 0.71$) from the SBO and DDGS-RO inclusion. A high predictability of the AID and ATTD of AEE ($R^2 = 0.68$ and $R^2 = 0.79$, respectively) was observed, but the predictability of the AID and ATTD of NDF ($R^2 = 0.53$ and $R^2 = 0.36$, respectively) from the SBO and DDGS-RO inclusion was moderate.

DISCUSSION

Apparent Digestibility of Amino Acids

No interaction was observed between the effects of SBO and DDGS-RO addition on the AID of AA. The AID of AA was however negatively associated with the concentration of DDGS-RO. Similar effects from the dietary increase of co-products from the corn-ethanol distillation industry have been previously reported (Urriola and Stein, 2010; Gutierrez et al., 2013). In both cases, the decrease in AID of AA was attributed to heating and addition of solubles during the production of DDGS, which is supported by the fact that the AID of AA, such as Lys, is less in DDGS than in corn (Stein et al., 2006; Urriola et al., 2009). Although the increase of dietary fiber may reduce the digestibility of AA (Schulze et al., 1994), the effect of

insoluble dietary fiber, such as corn fiber, has only minor effects on the digestibility of dietary AA (Zhu et al., 2005) and on the basal endogenous losses of AA (Leterme et al., 1996).

Apparent Digestibility of Acid Hydrolyzed Ether Extract

An interaction between the effects of SBO and DDGS-RO addition was observed for the AID and ATTD of AEE, which was elevated with a dietary increase of extracted fat from SBO, and increased likewise with intact fat from DDGS-RO added to 2% SBO. The positive relationship between dietary increase and apparent digestibility of AEE observed in the present study agree with previously reported data from pigs (Just et al., 1980; Jørgensen et al., 1993; Kil et al., 2010).

The observed response in apparent digestibility of AEE was modulated by the source of dietary fat. This was evidenced by the response surface models, where the slopes for the effects of SBO on AID and ATTD of AEE were greater than those of DDGS-RO. Greater apparent digestibility of extracted fat than of intact fat has been reported for SBO (Agunbiade et al., 1992), palm kernel oil (Agunbiade et al., 1999), and sunflower oil (San Juan and Villamide, 2000). Therefore, greater values of AID and ATTD of AEE were observed in diets formulated with 6% SBO, where most of the AEE content is extracted fat, than in diets formulated with 2% SBO, where most of the AEE content is intact fat. Values of AID and ATTD of AEE in the present study fall within the range of values reported by Kil et al. (2010) for diets formulated with extracted or intact fat, but comparison of results between trials is difficult because diets in the present study were formulated with varying ratios of extracted to intact fat.

However, the increase in AID and ATTD of AEE with dietary intact or extracted fat may also result from the contribution of endogenous losses of fat (**ELF**) to the total fat output, which

will have a greater impact on the apparent digestibility of AEE at low levels of dietary AEE (Jørgensen et al., 1993). Fan and Sauer (1997) reported similar effects on the apparent digestibility of AA from dietary AA concentrations and endogenous AA losses.

Values of apparent digestibility of AEE were greater at the end of the ileum than over the entire intestinal tract. This observation may be the result of a net synthesis of fat in the hindgut of pigs, and is in line with previously reported data (Shi and Noblet, 1993; Bakker, 1996). The dietary fiber concentration may stimulate the synthesis of endogenous microbial fat in the hindgut of pigs, increasing the ELF in the hindgut and reducing the ATTD of fat. Kil et al. (2010) reported similar values of AID and ATTD of AEE from semipurified diets formulated with increasing levels of Solka-Floc as fiber source. Purified fiber, however, may not stimulate microbial growth and fat synthesis to the same degree as dietary fiber from feed ingredients, because is largely composed of low fermentable cellulose and lacks the more complex physicochemical structure of dietary fiber in feed ingredients (Kil et al., 2010). These results suggest that dietary fat is digested and absorbed before the end of the ileum, and that differences between values of AID and ATTD of AEE are the product of microbial synthesis of endogenous fat in the hindgut of pigs (Low, 1980; Drackley, 2000).

Corn and DDGS-RO were the main dietary fiber sources in the present study. Dietary fiber from corn is rich in cellulose, arabinoxylans, and lignin (Bach Knudsen, 1997), limiting its fermentability in the terminal ileum (Gutierrez et al., 2013). The majority of dietary fiber from corn reaches the hindgut where it is partially fermented (Gutierrez et al., 2013). As more substrate is available ELF are stimulated due to increased microbial activity and fat synthesis (Eyssen, 1973; Bach Knudsen et al., 1991), resulting in the reduction of the ATTD of AEE

relative to AID. Therefore values of AID more accurately reflect the digestibility and availability of dietary AEE than ATTD values.

In the present study, dietary NDF increased with inclusion of DDGS-RO in diets containing 2% and 6% SBO. A decrease in the apparent digestibility of fat with a dietary increase of NDF has been previously reported (Just et al., 1980; Bakker, 1996; Hansen et al., 2006), but the reduction has been associated with characteristics of dietary fiber such as solubility and viscosity, rather than its dietary concentration (Fahey et al., 1990; Bach Knudsen and Hansen, 1991; Smits and Annison, 1996). Fiber in corn and its co-products is highly insoluble and has a low viscosity (Jaworski, 2012; Gutierrez et al., 2014); therefore, the increase of dietary fiber from the dietary inclusion of DDGS-RO may not negatively affect the apparent digestibility of AEE at 2% or 6% SBO. This assumption is in line with data reported by Kil et al. (2010), who observed no effects from the dietary increase of highly insoluble and low viscous purified NDF on the apparent digestibility of AEE.

Apparent Digestibility of Fiber

The dietary AEE and NDF increased with the dietary inclusion of SBO and DDGS-RO, and an interaction between the effects of SBO and DDGS-RO inclusion on the AID and ATTD of NDF was observed. An interaction between the dietary fat and fiber concentrations on the apparent digestibility of dietary fat has been previously reported (Dégen et al., 2009). The dietary increase of DDGS-RO at 2% SBO, and the subsequent increase in dietary insoluble NDF, showed no effect on the apparent digestibility of NDF at the terminal ileum and over the entire intestinal tract. Similar results on the AID of insoluble dietary fiber have been previously reported (Graham et al., 1986; Urriola and Stein, 2010; Gutierrez et al., 2013), and AID of NDF

values observed in the present study (≈ 28% AID of NDF at 2% SBO) agree with previously reported data from corn bran (Gutierrez et al., 2013). Fermentation of dietary fiber at the terminal ileum is well documented, and the extent varies with the solubility of dietary fiber (Jørgensen et al., 1996; Noblet and Le Goff, 2001; Urriola and Stein, 2010; Gutierrez et al., 2013). Results of ATTD of NDF in the present study differ from previous reports where the increase in insoluble dietary fiber from corn origin decreased the ATTD of dietary fiber (Urriola and Stein, 2010; Gutierrez et al., 2013).

Conversely, the dietary increase of DDGS-RO at 6% SBO, and the subsequent increase in dietary insoluble NDF, resulted in a quadratic response of the apparent digestibility of NDF. The different response to DDGS-RO addition between diets with 2% and 6% SBO is possibly the consequence of the elevated dietary fat concentration in the latter set of diets, and the ability of dietary fat to increase the transit time of digesta and the time for fermentation of NDF in the intestinal tract. This effect maybe visible at 0% DDGS-RO and 6% SBO, where NDF is low but dietary AEE increased with extracted fat from SBO, and where the AID and ATTD of NDF were greatest (46.4% and 52.0%, respectively). Dietary fat may increase the transit time of digesta as previously reported in pigs (Cervantes-Pahm and Stein, 2008) and in laying hens (Mateos et al., 1982). Degradability of fiber is a function of hydrolysis and transit time of digesta, therefore a slow passage rate may increase the time that substrates are subjected to fermentation, increasing in turn the dietary fiber degradability in the terminal ileum or in the hindgut (Morel et al., 2006; Wilfart et al., 2007). However, in diets with 6% SBO the effect of fat on transit time may be offset by the increasing levels of NDF from DDGS-RO. Increase of NDF from DDGS-RO may stimulate bowel movement and reduce the transit time of digesta (Bastianelli et al., 1996; Schneeman, 1998; Bindelle et al., 2008), which agree with data from pigs fed insoluble dietary

fiber from wheat bran where a decrease in retention time of digesta was reported (Wilfart et al., 2007).

Values of apparent digestibility of NDF were greater over the entire intestinal tract than at the terminal ileum. This observation suggests that insoluble dietary fiber from corn origin is fermented to some degree at the terminal ileum but the majority is fermented in the hindgut of pigs (Urriola and Stein, 2010; Gutierrez et al., 2013). The value of ATTD of dietary fiber includes both fermentation of dietary fiber in the terminal ileum and in the hindgut, and is therefore an accurate estimate of the total fermentation of dietary fiber in pigs.

Conclusions

Results from the present experiment showed that the AID of AA was negatively associated with the concentration of DDGS-RO, and the decrease in AID of AA may be attributed to the effects of manufacture processes during the production of DDGS rather than the effect of NDF concentration in DDGS-RO. The apparent digestibility of AEE increased with dietary addition of extracted and intact fat from SBO and DDGS, respectively, but no increase was observed with addition of intact fat from DDGS-RO to diets with high concentrations of extracted dietary fat from SBO. Greater values of apparent digestibility of AEE at the end of the ileum than over the entire intestinal tract were observed, and are possibly the result of a net synthesis of endogenous fat by microbes in the hindgut of pigs. Low values of apparent digestibility of AEE observed in diets with low dietary AEE concentrations are possibly the result of the weigh of endogenous microbial fat losses on the AEE output of these diets. Addition of DDGS-RO to diets with high concentrations of extracted fat from SBO resulted in a quadratic response of the AID of NDF, and in a reduction of the ATTD of NDF. The high concentration of

extracted fat in these diets may increase the transit time of digesta, resulting in the increase of fermentation time of NDF in the gastrointestinal tract. At low concentrations of dietary fat from SBO the apparent digestibility of NDF at the terminal ileum and over the entire tract was not affected by the dietary increase of DDGS-RO.

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Table 3.1. Ingredient composition (%) of the experimental diets (as-fed basis)[1]

	SBO, %	2			6		
Item	DDGS-RO, %	0	20	40	0	20	40
Ingredient, %							
Corn		81.7	61.7	41.7	77.7	57.7	37.7
RO-DDGS		0.0	20.0	40.0	0.0	20.0	40.0
Casein		12.5	12.5	12.5	12.5	12.5	12.5
Soybean oil		2.0	2.0	2.0	6.0	6.0	6.0
Limestone		1.3	1.3	1.3	1.3	1.3	1.3
Monocalcium phosphate		1.0	1.0	1.0	1.0	1.0	1.0
Chromic oxide		0.5	0.5	0.5	0.5	0.5	0.5
Vitamin premix[2]		0.2	0.2	0.2	0.2	0.2	0.2
Trace mineral premix[3]		0.2	0.2	0.2	0.2	0.2	0.2
Salt		0.6	0.6	0.6	0.6	0.6	0.6
Energy and nutrients[4]							
ME, Mcal/kg		3.39	3.33	3.27	3.59	3.54	3.48
SID Lys, %		0.98	1.03	1.08	0.98	1.02	1.07
SID Thr, %		0.61	0.71	0.80	0.61	0.70	0.80
SID Met+Cys, %		0.60	0.70	0.80	0.59	0.69	0.78
SID Trp, %		0.20	0.22	0.23	0.20	0.21	0.23

[1]SBO = soybean oil; DDGS-RO = reduced oil distillers dried grains with solubles.

[2]Provided per kilogram of complete diet: 6,614 IU of vitamin A; 827 IU of vitamin D; 26 IU of vitamin E; 2.6 mg of vitamin K; 29.8 mg of niacin; 16.5 mg of pantothenic acid; 5.0 mg of riboflavin; 0.023 mg of vitamin B_{12}.

[3]Provided per kilogram of complete diet: Zn, 165 mg as $ZnSO_4$; Fe, 165 mg as $FeSO_4$; Mn, 39 mg as $MnSO_4$; Cu, 17 mg as $CuSO_4$; I, 0.3 mg as $Ca(IO_3)_2$; and Se, 0.3 mg as Na_2SeO_3.

[4]Values were calculated (NRC, 2012). SID = standardized ileal digestible.

Table 3.2. Analyzed nutrient composition of the experimental diets (as-fed basis)[1]

	SBO, %	2			6		
Item	DDGS-RO, %	0	20	40	0	20	40
DM, %		89.1	88.0	89.5	89.2	89.8	89.5
GE, Mcal/kg		3.98	4.08	4.18	4.18	4.33	4.42
AEE, %		4.4	5.7	6.3	8.4	9.1	10.1
Starch, %		51.1	39.2	27.2	48.6	36.7	24.7
ADF, %		2.4	3.4	4.6	2.2	3.4	4.5
NDF, %		6.9	11.0	14.6	6.8	9.7	14.0
CP		17.9	21.8	25.7	17.5	21.4	25.4
Indispensable AA							
Arg		0.7	0.8	1.0	0.6	0.8	1.0
His		0.5	0.6	0.8	0.5	0.6	0.8
Ile		0.9	1.0	1.2	0.9	1.0	1.2
Leu		2.0	2.3	2.8	1.9	2.3	2.9
Lys		1.2	1.3	1.4	1.1	1.2	1.5
Met		0.5	0.5	0.6	0.5	0.5	0.6
Phe		1.0	1.1	1.3	0.9	1.1	1.3
Thr		0.8	0.9	1.0	0.7	0.9	1.1
Trp		0.2	0.2	0.3	0.2	0.2	0.3
Val		1.1	1.3	1.5	1.1	1.2	1.5
Dispensable AA[2]							
Mean		10.1	11.6	13.3	11.2	13.5	10.1
All AA[3]		18.9	21.7	25.1	21.0	25.6	18.9

[1]SBO = soybean oil; DDGS-RO = reduced oil distillers dried grains with solubles; AEE = acid hydrolyzed ether extract; TDF = total dietary fiber.

[2]Sum of all dispensable AA.

[3]Sum of all indispensable and dispensable AA.

Table 3.3. Apparent ileal and total tract digestibility of determined traits in experimental diets[1,2]

Item	SBO, %	2			6			Pooled SEM	*P*-value		
	DDGS-RO, %	0	20	40	0	20	40		SBO	DDGS-RO	SBO x DDGS-RO
						AID, %					
	GE	80.6[a]	73.3[cb]	70.0[c]	84.0[a]	74.3[b]	70.1[c]	0.96	0.046	<0.001	0.178
	DM	80.2[a]	71.1[b]	66.1[c]	83.4[a]	71.4[b]	65.0[c]	0.96	0.325	<0.001	0.076
	NDF	32.5[b]	26.8[b]	25.3[b]	46.4[a]	21.7[b]	22.4[b]	3.12	0.389	<0.001	0.002
	AEE	72.5[c]	75.9[bc]	79.1[b]	83.5[a]	83.4[a]	83.9[a]	1.05	<0.001	0.005	0.011
						ATTD, %					
	GE	87.8[a]	84.0[b]	80.0[c]	88.3[a]	84.3[b]	80.0[c]	0.48	0.509	<0.001	0.813
	DM	88.3[a]	83.8[b]	79.0[c]	88.7[a]	83.9[b]	78.3[c]	0.46	0.892	<0.001	0.424
	NDF	47.3[ab]	48.7[ab]	45.5[bc]	52.0[a]	45.7[abc]	40.9[c]	2.28	0.451	<0.001	0.009
	AEE	62.6[d]	67.6[c]	71.6[b]	77.5[a]	77.0[a]	80.4[a]	1.30	<0.001	<0.001	0.008
						AID of AA, %					
	Arg	84.2[ab]	81.9[b]	83.2[b]	87.0[a]	82.4[b]	83.2[ab]	1.06	0.061	0.001	0.145
	His	87.1[a]	82.8[b]	83.1[b]	89.5[a]	82.6[b]	83.1[b]	0.99	0.160	<0.001	0.107
	Ile	87.6[a]	82.5[b]	81.8[b]	88.9[a]	82.9[b]	83.3[b]	0.67	0.015	<0.001	0.539
	Leu	90.1[a]	87.0[b]	87.5[b]	91.3[a]	86.9[b]	87.7[b]	0.73	0.239	<0.001	0.435
	Lys	88.9[a]	85.2[b]	84.6[b]	90.2[a]	84.3[b]	84.7[b]	0.82	0.629	<0.001	0.127
	Met	92.8[b]	90.0[c]	89.6[c]	93.7[a]	90.1[c]	90.1[c]	0.44	0.008	<0.001	0.223
	Phe	90.1[a]	86.9[b]	87.3[b]	91.2[a]	86.6[b]	87.3[b]	0.79	0.588	<0.001	0.390
	Thr	81.4[a]	75.4[b]	74.6[b]	82.8[a]	74.7[b]	75.6[b]	1.18	0.371	<0.001	0.434
	Trp	89.2[a]	84.6[b]	84.4[b]	90.7[a]	83.7[b]	84.4[b]	1.04	0.754	<0.001	0.242
	Val	86.7[a]	81.7[b]	81.7[b]	87.9[a]	81.8[b]	82.4[b]	0.86	0.191	<0.001	0.665
	Indispensable[3]	88.1[a]	84.0[b]	84.1[b]	89.4[a]	83.9[b]	84.4[b]	0.81	0.253	<0.001	0.388

Table 3.3 (continued)

Dispensable[4]	84.9[a]	80.9[b]	80.0[b]	87.5[a]	81.0[b]	80.8[b]	1.02	0.052	<0.001	0.256
All AA[5]	86.4[a]	82.4[b]	82.0[b]	88.4[a]	82.4[b]	82.5[b]	0.88	0.096	<0.001	0.274

[a,b,c,d] Means within a row lacking a common superscript letter are different ($P < 0.05$).

[1]Least squares means of 9 pigs per diet.

[2]SBO = soybean oil; DDGS-RO = reduced oil distillers dried grains with solubles; AEE = acid hydrolyzed ether extract.

[3]Average AID for all indispensable AA.

[4]Average AID for all dispensable AA.

[5]Average AID for all AA (indispensable and dispensable).

Table 3.4. Digestible and metabolizable energy value of diets[1,2]

	SBO, %	2			6				*P*-value		
Item	DDGS-RO, %	0	20	40	0	20	40	Pooled SEM	SBO	DDGS-RO	SBO*DDGS-RO
As-fed basis, Mcal/kg											
	DE	3.49^{cb}	3.43^{c}	3.34^{d}	3.69^{a}	3.65^{a}	3.53^{b}	0.020	<0.001	<0.001	0.639
	ME	3.37^{b}	3.28^{c}	3.17^{d}	3.57^{a}	3.49^{a}	3.35^{cb}	0.019	<0.001	<0.001	0.617

[a,b,c]Means within a row lacking a common superscript letter are different ($P < 0.05$).

[1] Least squares means of 9 pigs per diet.

[2]SBO = soybean oil; DDGS-RO = reduced oil distillers dried grains with solubles.

Table 3.5. Regression coefficients of the response surface models for the effects of soybean oil and reduced oil distillers dried grains with solubles on apparent digestibility and energy value of diets[1,2]

	Regression components						
Trait	Intercept	SBO	DDGS-RO	DDGS-RO^2	SBO*DDGS-RO	SBO*DDGS^2	R^2
AID							
GE	81.2908	0.3100	-0.5447	0.0057	-	-	0.78
		(0.046)	(<0.001)	(0.005)	(0.071)	(0.651)	
DM	78.9176	0.7571	-0.5133	0.0056	-0.0318	-	0.86
		(0.325)	(<0.001)	(0.005)	(0.026)	(0.629)	
NDF	24.4572	3.7063	0.5498	-0.0118	-0.3960	0.0069	0.53
		(0.389)	(<0.001)	(0.005)	(0.003)	(0.037)	
AEE	67.2575	2.7325	0.2469	$-5*10^{-5}$	-0.0425	-	0.68
		(<0.001)	(0.001)	(0.894)	(0.003)	(0.800)	
ATTD							
NDF	44.8490	1.2009	0.2205	-0.0026	-0.0722	-	0.36
		(0.451)	(<0.001)	(0.571)	(0.004)	(0.256)	
AEE	55.3292	3.5898	0.3654	-0.0002	-0.0512	-	0.79
		(<0.001)	(<0.001)	(0.413)	(0.004)	(0.153)	
AID of AA							
Met	93.0344	0.0949	-0.2458	0.0039	-	-	0.71
		(0.008)	(<0.001)	(<0.001)	(0.442)	(0.111)	
Energy concentration, as-fed basis							
DE	3.4098	0.0483	-0.0041	-	-	-	0.83
		(<0.001)	(<0.001)	(0.123)	(0.745)	(0.384)	
ME	3.2922	0.0469	-0.0053	-	-	-	0.87
		(<0.001)	(<0.001)	(0.133)	(0.670)	(0.387)	

[1]Traits included were simultaneously significant for SBO and DDGS-RO (linear or quadratic) or any of the possible interactions.

[2]*P*-values in brackets.

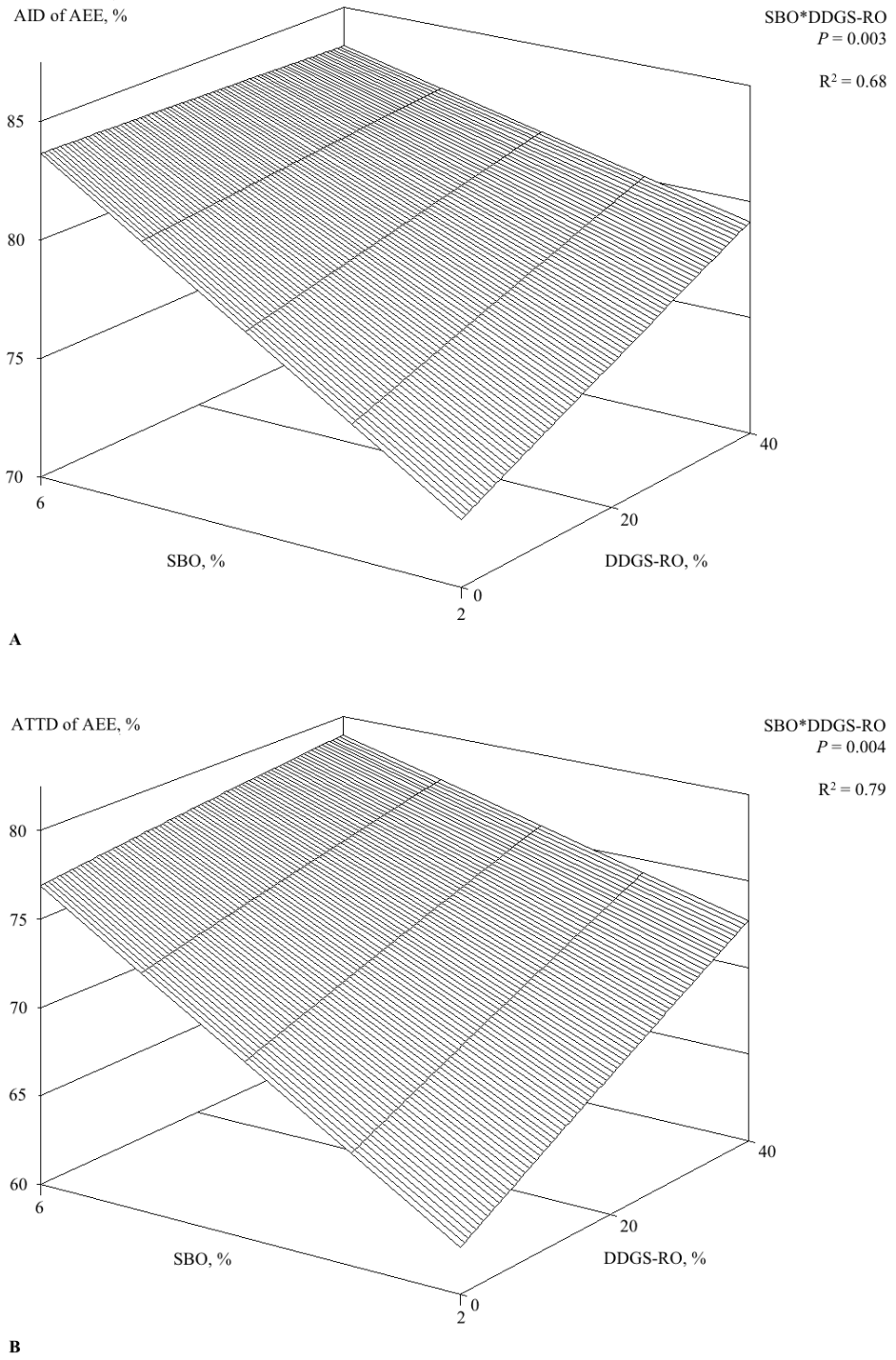

Fig. 3.1 Response surface for the effects of the dietary soybean oil (**SBO**) and reduced oil distillers dried grains with solubles (**DDGS-RO**) on the apparent ileal (**AID**; A) and total tract digestibility (**ATTD**; B) of acid hydrolyzed ether extract (**AEE**) in growing pigs (n = 9).

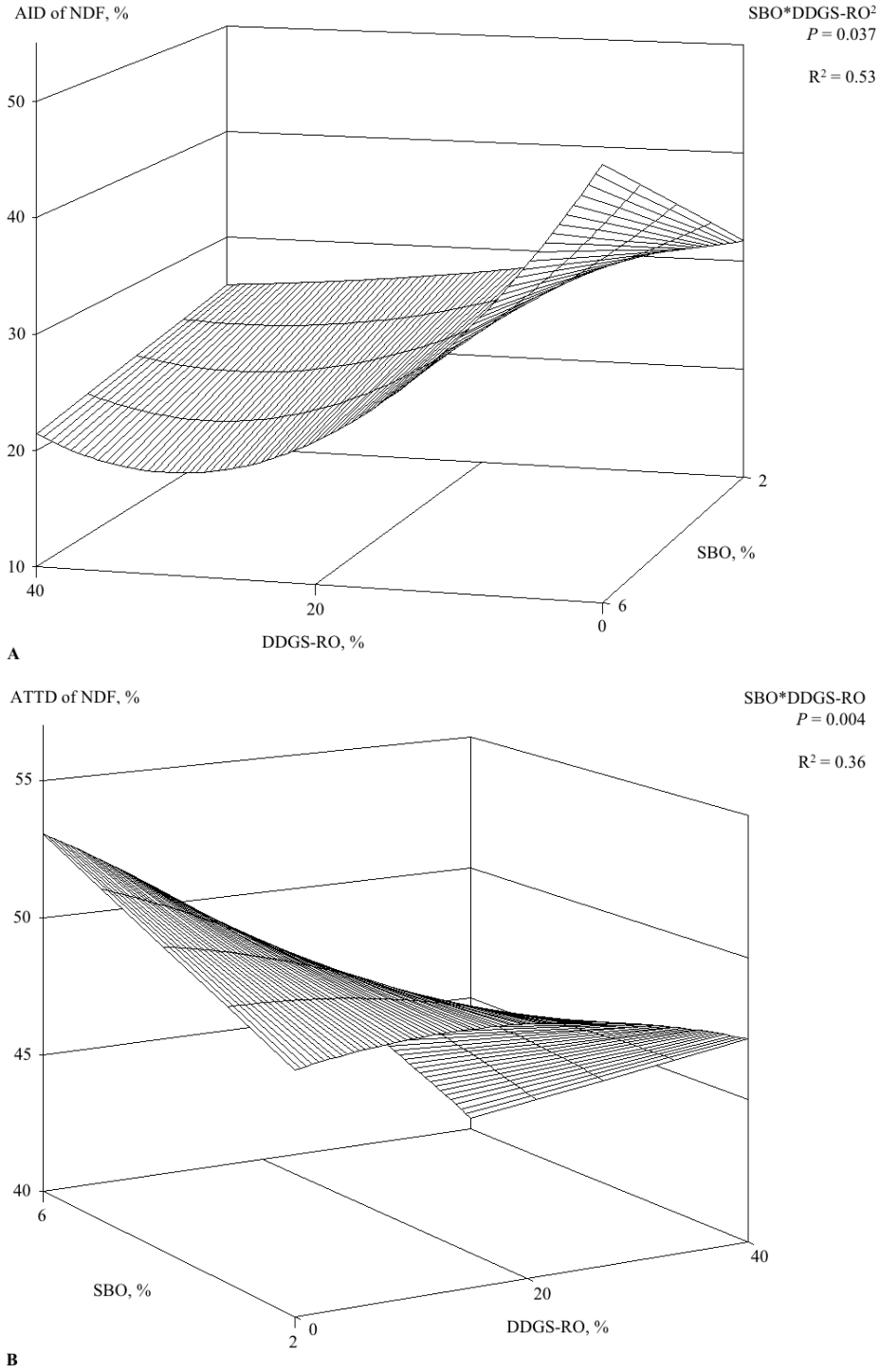

Fig. 3.2 Response surface for the effects of the dietary soybean oil (**SBO**) and reduced oil distillers dried grains with solubles (**DDGS-RO**) on the apparent ileal (**AID**; A) and total tract digestibility (**ATTD**; B) of NDF in growing pigs (n = 9).

CHAPTER 4: RELATIONSHIPS AMONG DIETARY FIBER COMPONENTS AND THE DIGESTIBILITY OF ENERGY, DIETARY FIBER, AND AMINO ACIDS, AND ENERGY CONTENT OF 9 CORN CO-PRODUCTS FED TO GROWING PIGS[1]

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ABSTRACT

An experiment was conducted to determine a best fitting dietary fiber component to estimate the effect of dietary fiber concentration on the digestibility of energy, dietary fiber, and AA, and energy value of 9 corn co-products: corn bran (**CB**; 37.0% total non-starch polysaccharides (**NSP)**), corn bran with solubles (**CB-S**; 17.1% NSP), cooked corn distillers dried grains with solubles (**DDGS-CV**; 20.4% NSP), reduced oil DDGS (**DDGS-RO**; 25.0% NSP), uncooked DDGS (**DDGS-BPX**; 22.0% NSP), high protein distillers dried grains (**HP-DDG**; 21.9% NSP), dehulled degermed corn (**DDC**; 1.1% NSP), corn germ meal (**CGmM**; 44.4% NSP), and corn gluten meal (**CGnM**; 4.9% NSP). A total of 20 growing pigs (initial BW: 25.9 ± 2.5 kg) were fitted with a T-cannula in the distal ileum and allotted to 10 dietary treatment groups in a 4-period incomplete block design with 8 observations per treatment. Treatments included a corn-soybean meal based basal diet and 9 diets obtained by mixing 70% of the basal diet with 30% of the test ingredient. In tested ingredients, 11 dietary fiber components were determined: 1) ADF; 2) NDF; 3) TDF; 4) hemicellulose; 5) total NSP; 6) NSP arabinose; 7) NSP xylose; 8) NSP mannose; 9) NSP glucose; 10) NSP galactose; 11) arabinoxylan. The apparent ileal (**AID**) and total tract digestibility (**ATTD**) of GE, DM, NDF and the AID of AA of ingredients were measured. A single best fitting dietary fiber component was assessed and ranked for each trait, showing that arabinoxylan concentration best explained variance in AID of GE (R^2=0.65; cubic, P<0.01) and DM (R^2=0.67; cubic, P<0.01). The NSP xylose residue best explained variance in ATTD of GE (R^2=0.80; cubic, P<0.01), DM (R^2=0.78; cubic, P<0.01), and NDF (R^2=0.63; cubic, P<0.01); AID of Met (R^2=0.40; cubic, P=0.02), Met+Cys (R^2=0.44; cubic, P=0.04), and Trp (R^2=0.11; cubic, P=0.04); and DE (R^2=0.66; linear, P=0.02) and ME (R^2=0.71; cubic, P=0.01) values. The AID of Lys was not predictable (P > 0.05) from the dietary

fiber concentration. In conclusion, the arabinoxylan and NSP xylose residue were the dietary fiber components that best explained variation due to dietary fiber concentration and, with the exception of AID of Lys, can be used to predict the digestibility of energy and dietary fiber, and the DE and ME values in corn co-products.

Keywords: Corn co-products, dietary fiber, digestibility, energy, pig

INTRODUCTION

Corn co-products are typically rich in dietary fiber with widely variable concentrations of starch, AA, and fat. Knowledge of the concentration and composition of dietary fiber of feed ingredients is of critical importance, because dietary fiber may reduce AA and energy digestibility (Farrell, 1973; Noblet and Perez, 1993; Souffrant, 2001). The dietary fiber in corn and co-products is highly resistant to fermentation, and is largely constituted of insoluble non-starch polysaccharides, such as cellulose, arabinoxylans, and lignin (Bach Knudsen, 1997; Jaworski, 2012). These polysaccharides are mainly polymers of hexoses (D-glucose, D-galactose, D-mannose) and pentoses (L-arabinose, D-xylose) joined through glycosidic linkages. Common assays to determine the dietary fiber concentration of a feed ingredient include crude fiber, ADF, and NDF. Classification by differences in solubility in acid and alkali, or in neutral and acid detergents lacks precision with respect to chemical composition of dietary fiber and biological function. Therefore, the nutritional relevance of values obtained using these methods in monogastric nutrition is questionable (Choct, 1997). The analysis for total non-starch polysaccharides (**NSP**), and its monosaccharide residues, may be a tool to better explain the effect of the dietary fiber concentration on the nutritional value of corn co-products.

Advances in the ethanol industry increase the efficiency of starch and oil extraction from the corn grain, resulting in continuous changes in chemical composition of corn co-products, which present a challenge to estimate their nutritional value. Fairbairn et al. (1999) reported that NDF or ADF alone accounted for 68% and 85% of the total variation in DE content of barley, respectively. However, a comprehensive analysis of the effects of dietary fiber concentration on the nutrient value of corn co-products is unavailable.

In the present study, 9 corn co-products were selected to cover a wide range in dietary fiber concentration. The objective of the study was to determine a best fitting dietary fiber component to measure the effect of dietary fiber concentration on the variation in digestibility of energy, dietary fiber, and AA, and on energy values in corn co-products.

MATERIALS AND METHODS

The experimental protocol was reviewed and approved by the Institutional Animal Care and Use Committee at Iowa State University (9-10-7024-S).

Animals, Housing, and Experimental Design

Twenty growing barrows (progeny of sire line 337 × dam line C-22, PIC, Hendersonville, TN) were housed in individual pens (1.2 × 1.2 m) equipped with a feeder, a cup waterer, and a half-slatted concrete floor in an environmentally controlled building. All pigs were surgically fitted with a T-cannula in the distal ileum following procedures described by Stein et al. (1998). After recovery from surgery, pigs were weighed (initial BW = 25.9± 2.5 kg) and randomly allotted to 10 dietary treatment groups in a 4-period incomplete block design, resulting in 8 experimental units per treatment. Pigs were not allowed to repeat dietary treatments across periods. Each collection period involved a 9 d of adaptation to dietary treatments followed by 2 d of feces sub-sample collection and 3 d of ileal digesta sub-sample collection.

Dietary Treatments

Dietary treatments included a corn-soybean meal basal diet (Table 4.1) that was formulated to meet or exceed the nutrient requirements of growing pigs (NRC, 1998). Nine additional experimental diets were obtained by mixing 70% of the basal diet and 30% of the corn co-product to be tested. Corn co-products evaluated in the experiment included corn bran with

solubles (**CB-S**; Poet Nutrition, Glenville, MN), corn bran (**CB**; Lifeline Foods, St. Joseph, MO), cooked DDGS (**DDGS-CV**; Hawkeye Renewables, Iowa Falls, IA), reduced oil DDGS (**DDGS-RO**; Hawkeye Renewables, Iowa Falls, IA), uncooked DDGS (**DDGS-BPX**; Poet Nutrition, Hanlontown, IA), high protein distillers dried grains (**HP-DDG**; Poet Nutrition, Glenville, MN), dehulled-degermed corn (**DDC**; Bunge North America, Atchison, KS), corn germ meal (**CGmM**; Cargill, Eddyville, IA), and corn gluten meal (**CGnM**; Cargill, Eddyville, IA). Diets also contained 0.55% Cr_2O_3 as an inert marker. All pigs received the same daily amount of feed, which was provided at a level of approximately 90% of predicted ad libitum intake of the basal diet. The daily feed allowance was divided into 2 equal meals provided at 0700 and 1600 h. At the end of each collection period, all pigs were weighed and daily feed allowance for the next collection period was adjusted.

Sample Collection

After 9 d of adaptation to the diet, feces were collected via grab sampling on d 10 and 11, and stored at -20°C. On d 12, 13, and 14, ileal digesta samples were collected for 8 h by attaching a 207-mL plastic bag (Whirl-Pak, Nasco, Fort Atkinson, WI) to the opened cannula with a cable tie. Bags were removed whenever they were filled with digesta or at least every 30 min, and stored at -20°C to prevent bacterial degradation. At the conclusion of each experimental period, frozen ileal and fecal samples were allowed to thaw at room temperature and pooled within animal, with a sub-sample collected for chemical analysis. Ileal sub-samples were lyophilized before chemical analysis. Fecal sub-samples were oven dried in a convection oven at 65°C to constant weight (Jacobs et al., 2011). After drying, feed, ileal, and fecal sub-samples were ground through a 1 mm screen before chemical analysis.

Chemical Analysis

Samples of diets and feed ingredients were analyzed for DM (method 930.15; AOAC Int., 2007), ether extract (**EE**; method 920.39; AOAC Int., 2007), starch (method 996.11; AOAC Int., 2007), ADF (Goering and Van Soest, 1970), NDF (van Soest et al., 1979), total dietary fiber (**TDF**; method 985.29; AOAC Int., 2007), and N (method 968.06; AOAC Int., 1990). Crude protein was calculated as N × 6.25 and Gly was used as the calibration standard (N content 18.7%, Fisher Scientific, Fair Lawn, NJ), and was determined to contain 18.7 ± 0.2% N. The 9 ingredients were analyzed for total constituent monosaccharides in NSP and insoluble NSP by GLC (Englyst and Hudson, 1987). Ileal digesta and fecal samples were also analyzed for DM, NDF, and N. The GE of diets, feed ingredients, ileal digesta, and feces was analyzed by bomb calorimetry (Parr 6200 calorimeter, Parr Instruments Co., Moline, IL). Benzoic acid (6318 kcal GE/kg; Parr Instruments, Moline, IL) was used as the standard for calibration and was determined to contain 6324 ± 9.8 kcal GE/kg. Diets, feed ingredients, and ileal digesta were analyzed for AA (University of Missouri Agriculture Experiment Station Chemical Laboratories, Columbia, MO) according to method 982.30 E (a, b, c); AOAC, 2007. Chromic oxide was determined in diets, ileal digesta, and fecal sub-samples using the method of Fenton and Fenton (1979) and absorption was measured at 440 nm using a spectrophotometer (Synergy 4, BioTek, Winooski, VT). Chromic oxide standard samples were assayed to confirm the accuracy of the analytical procedure, and a recovery of 100.8 ± 1.95% was attained.

Calculations

For each dietary treatment, the AID and ATTD of DM, GE, and NDF, and the AID of AA were calculated using the index method (Oresanya et al., 2008). The difference procedure was used to calculate the AID and ATTD of DM, GE, and NDF, and the AID of AA of each ingredient (Adeola 2001). The DE value was determined by multiplying the GE by the observed

ATTD of GE of the ingredient, and the ME was estimated from the calculated DE and CP of the ingredient (Noblet and Perez, 1993).

Effects of dietary fiber concentration in feed ingredients were determined using 11 different dietary fiber components: 1) ADF; 2) NDF; 3) TDF; 4) hemicellulose (**Hemi** = NDF-ADF); 5) total NSP; concentrations of 5 monosaccharide residues that can be detected in NSP, namely: 6) NSP arabinose; 7) NSP xylose; 8) NSP mannose; 9) NSP glucose; 10) NSP galactose; 10) arabinoxylan (Ara + Xyl); and 11) total NSP (sum of monosaccharide residue in NSP).

Traits were grouped into 4 categories to simplify statistical analysis of data as follows: 1) apparent ileal digestibility (**AID**), including AID of DM, GE, and NDF; 2) apparent total tract digestibility (**ATTD**), including ATTD of DM, GE, and NDF; 3) AID of AA, including AID of Lys, Thr, Met, Met + Cys, Trp, and average of all dispensable and all indispensable AA; and 4) energy concentration, including DE and ME values.

Statistical Analyses

Analysis of Ingredient and Normality Test. The data were analyzed in a mixed model including the fixed effect of Ingredient (**Ingred**) and the random effects of period and pig, following the model:

$$Y_{ijkl} = \mu + \tau_i + P_j + A_k + e_{ij(k)l} \quad \text{(Eq. 1)}$$

Where Y_{ijkl} is the observed values for the trait; μ is the overall mean; τ_i is the effect of the i^{th} ingredient (i = 1 to 9); P_j is the effect of the j^{th} period (j = 1 to 4, $[0,\sigma_p^2]$); A_k is the effect of the k^{th} experimental unit (k = 1 to 20, $[0,\sigma_a^2]$); and $e_{ij(k)l}$ is the random error associated with Y_{ijkl} (l = 2 to 4, $[0,\sigma_e^2]$).

Studentized residuals were generated from Eq. 1 and used to test normality. Outliers were removed until the Shapiro-Wilk's test reached $P>0.05$ and studentized residual fell within ± 3σ. The effect of Ingred was tested including the Kenward-Roger degrees-of-freedom approximation. Least squares means for Ingred were estimated and compared using the Tukey-Kramer adjustment. The effect of Ingred and multiple comparison differences were deemed significant at $P \leq 0.05$.

Analysis of Dietary Fiber Concentration in Ingredients. An alternative method was proposed by including the effect of dietary fiber concentration of the ingredient in the model. The eleven different dietary fiber components were evaluated using a modified version of Eq. 1. In this alternative model the linear, quadratic, and cubic effects of dietary fiber concentration instead of Ingred were included, following the model:

$$Y_{ijkl} = \mu + \beta_1 X_i + \beta_2 X_i^2 + \beta_3 X_i^3 + P_j + A_k + e_{ij(k)l} \qquad \text{(Eq. 2)}$$

Where Y_{ijkl},μ, P_j, A_k, and $e_{ij(k)l}$ are the same as defined in Eq. 1; β_1, β_2, and β_3 are the linear, quadratic, and cubic effects associated with the dietary fiber concentration terms X_i, X_i^2, and X_i^3, respectively.

Comparison between Fiber Models and Ingredient. The goodness-of-fit of Eq. 2 was assessed for all dietary fiber components to identify the dietary fiber component that best fits the trait categories, and then compared to the model fit using Ingred (Eq. 1). The Akaike information criterion (**AIC**) was used to measure the goodness-of-fit of these models. The AIC values were calculated using maximum-likelihood estimation in order to compare models with different fixed effects (Bolker et al., 2009)

The best fitting dietary fiber component, i.e. the dietary fiber model that resulted in the lowest AIC statistics within a trait category, was obtained by ranking the AIC values of each trait within category. The overall fit of the eleven dietary fiber components within category was assessed as the average ranking of the assays. The assay showing the best fit within category was then compared to the goodness-of-fit when using Ingred for each trait.

Regression Equations of the Best Dietary Fiber Component and Loss of Predictability. The linear, quadratic, and cubic effects of dietary fiber concentration in Eq. 2 were tested for and kept in the model according to the significance of the highest order term. To assess the loss in predictability of the dietary fiber concentration models compared to the Ingred, the residuals obtained from Eq. 2 were further analyzed including only the fixed effect of Ingred in the model without the intercept. The variance explained by the dietary fiber concentration using the best fitting dietary fiber component in Eq. 2 was compared to the variance explained by Ingred using the marginal coefficient of determination (***R²***) for linear mixed-models (***R²LMM(m)***; Nakagawa and Schielzeth, 2013), as:

$$R^2_{LMM(m)} = \frac{\sigma_f^2}{\sigma_f^2+\sigma_p^2+\sigma_a^2+\sigma_e^2} \quad \text{(Eq. 3)}$$

Where σ_f^2 is the variance calculated from the fixed effect (concentration of the best fitting dietary fiber component) components (Snijders and Bosker, 1999), whereas σ_p^2, σ_a^2, and σ_e^2 are the period, experimental unit, and residual variances. For simplicity, $R^2_{LMM(m)}$ will hereafter be referred to as $\boldsymbol{R^2_{fiber}}$. Similarly, the variance due to Ingred ($\boldsymbol{\sigma_i^2}$) was calculated on the residuals of Eq. 2 and computed an R^2 using the same variance components as in Eq. 3 but σ_f^2, as:

$$R^2_{ingredient} = \frac{\sigma_i^2}{\sigma_p^2+\sigma_a^2+\sigma_e^2} \quad \text{(Eq. 4)}$$

The advantage of this sequential approach is that it measures the variance explained by Ingred on the portion of the variance not explained by the dietary fiber concentration, allowing the direct comparison of these two R^2. The loss in predictability of the dietary fiber concentration in place of the Ingred was computed as $R^2_{Ingred}/(R^2_{Ingred}+ R^2_{fiber})$. All statistical analyses were performed using SAS 9.3 (Statistical Analysis System Institute, Inc., Cary, NC).

RESULTS AND DISCUSSION

Nutrient composition of corn co-products

All pigs were successfully cannulated at the distal ileum and recovered from surgery without complications. Corn co-products came from the same source, but different batches, as in Anderson et al. (2012), and the analyzed composition was similar (Table 4.2). Extensive variation in nutrient composition was observed among ingredients, reflecting the diversity of the selected co-products and the manufacturing processes used.

The NDF and TDF concentration of DDGS was close to values reported in the literature (Stein et al., 2006; Anderson et al., 2012; NRC, 2012), and was similar to the NDF and TDF concentration in HP-DDG. The concentration of NDF and TDF in HP-DDG was expected to be less than in the 3 sources of DDGS, because the bran is separated from the corn kernel during HP-DDG production. However, the bran may have been added back to the HP-DDG after production, which is supported by the higher concentration of NSP glucose residue in HP-DDG than in the 3 sources of DDGS, because bran is rich in cellulose and therefore has a high concentration of NSP glucose. The NDF concentration in HP-DDDG was similar to values

reported in NRC (2012), but have been shown to range from 16 to 41% depending on the manufacturing process used (Widmer et al., 2007; Robinson et al., 2008; Kim et al., 2011). The dietary fiber concentration varied among similar co-products such as CB-S and CB. In CB-S, solubles remaining from the corn-ethanol distillation process were added to the corn bran, and the NDF and TDF concentration were half of previously reported values for corn bran without solubles (Sauvant et al., 2004; Anderson et al., 2012). The NDF concentration of CGmM (46.2%) and CGnM (12.1%) was similar to previously reported values (Almeida et al., 2011; Anderson et al., 2012; NRC, 2012). The NDF concentration in CGnM was, however, greater than values reported by Sauvant et al. (2004) and NRC (2012).

In theory, TDF should be higher than NDF because soluble dietary fiber components are lost in NDF due to solubilisation with the neutral detergents. The TDF to NDF ratio in CB, CB-S, and DDGS-CV was 1.05, 1.11, and 1.03 respectively, but in the remaining 6 ingredients ranged from 0.61 in DDC to 0.95 in CGmM. Urriola et al. (2010) reported lesser TDF than NDF values in 8 sources of corn-DDGS, with TDF to NDF ratios ranging from 0.79 to 0.91. In corn and co-products, however, most of the dietary fiber is insoluble and a reasonable relative agreement between NDF and TDF is expected as they are supposed to measure the same chemical entities. Although only 3 ingredients showed greater TDF than NDF concentrations, values of TDF and NDF were similar overall in the present study, with the exception of DDC. Comparable differences between TDF and NDF values have been previously documented. The TDF to NDF ratios reported by Anderson et al. (2011) for CB (0.94), CB-S (1.06), DDGS (0.79 to 1.07), HP-DDG (0.66 to 0.98), CGnM (0.75), and DDC (0.61), agree with the TDF and NDF values and variation reported in the present study. Likewise, Campbell et al. (1997) reported differences between TDF and NDF concentrations in feed ingredients with high concentration of

insoluble dietary fiber such as corn bran (0.90), rice bran (0.94), peanut hulls (0.97), and solka floc (1.07).

Total NSP values were lower but followed the same concentration pattern as NDF and TDF values, with the exception of CGmM. The NSP to TDF ratio ranged from 0.48 in DDC to 0.87 in CB, but was 1.01for CGmM. Total NSP values were expected to be lower than TDF values because lignin is included in the latter. However, similar variation in NSP to TDF ratios was observed in feed ingredients rich in insoluble dietary fiber content, with NSP to TDF ratios of 0.52, 0.55, 0.61, and 0.75 for solka floc, peanut hulls, corn bran, and rice bran respectively (Campbell et al., 1997).

The inconsistency between expected and observed NDF, TDF, and NSP ratios reported in the literature, and in the present study, may be caused by differences in the nature of the analytical procedures used (acid and neutral detergents, enzymatic-gravimetric, enzymatic-chemical etc.). For example, TDF values determined in feed ingredients rich in insoluble dietary fiber by Prosky-TDF (enzymatic-gravimetric; Prosky et al., 1985) or Uppsala-TDF (enzymatic-chemical; Theander et al., 1994), showed differences between the two TDF values in corn bran (53.5 vs. 42.8), rice bran (17.2 vs. 21.3), peanut hulls (76 vs. 73.4), or solka floc (96.2 vs. 43; Campbell et al., 1997). Discrepancies may be exacerbated by low dietary fiber concentration in the feed ingredient, as observed in DDC.

The analysis of monosaccharide residues of NSP indicated that glucose was the most prevalent residue, followed by xylose, arabinose, galactose, and mannose. Insoluble monosaccharide residues composed the majority of total NSP in all 9-corn co-products. In DDGS-RO, CGmM, and CGnM, however, about a third of total NSP were soluble. The total NSP, monosaccharide residues of NSP, and insoluble NSP observed for DDGS in the present

study agree with the concentrations reported by Widyaratne and Zijlstra (2007). The monosaccharide composition relates structurally to the polysaccharides forming the NSP of corn co-products, such as arabinoxylans, cellulose, and galactomannans (Bach Knudsen, 1997; Choct, 2002).

The CP (7.5 to 59.5%) and AA concentrations varied among corn co-products, with CGnM exhibiting the greatest values for CP and each AA, contrasting with CB-S, CB, and DDC (Table 4.3). As expected, the AA concentrations in HP-DDG were greater than in DDGS, and in agreement with data published for HP-DDG (Widmer et al., 2007; Kim et al., 2011; NRC, 2012). The range in AA composition noted for DDGS was also similar to data published in the literature (Spiehs et al., 2002; Almeida et al., 2011; NRC, 2012). In CGmM and CGnM, the CP (20.6 and 59.5%, respectively) and AA concentrations were close to expected values (Almeida et al., 2011; NRC, 2012).

Apparent Ileal Digestibility of Traits and Energy Concentrations

The AID and ATTD of GE and DM differed ($P < 0.05$) among ingredients (Table 4.4). Because most of the DM in DDC and in CGnM is starch and protein, respectively, the AID of GE and DM were the greatest ($P < 0.05$) among all ingredients. The AID of GE and DM were similar ($P > 0.05$) in the 4 sources of DDGS and both corn brans.

As expected, the ATTD of GE in both DDC (99.6%) and CGnM (91.6%) were the greatest ($P < 0.05$). In contrast, the ATTD of GE and DM in CB-S and CB were the lowest, but similar to the observed AID values, meaning that both ingredients were highly resistant to hindgut fermentation. The observed ATTD of GE and DM of DDGS, CGmM and CGnM are in agreement with values reported previously (Stein et al., 2006; Rojas and Stein, 2013). The ATTD of GE and DM of HP-DDG were, however, less than values obtained previously for HP-DDG

(Widmer et al., 2007; Kim et al., 2009), which may be explained by the greater dietary fiber concentration caused by the added bran in the HP-DDG used in this study.

The apparent digestibility of NDF, on the other hand, did not differ at the ileal level ($P = 0.11$), but differed ($P < 0.05$) at the total tract level among ingredients. The difference between AID and ATTD of NDF values observed for the 3 DDGS sources indicated that approximately 18% of the NDF was fermented in the hindgut, which is in agreement with data reported by Urriola et al. (2010). In CB-S and CB, however, values of ATTD of NDF were lower than AID values. Unreliable values of AID of TDF have been previously reported in wheat bran (Graham et al., 1986; Jorgensen et al., 1996) and in low and medium fiber diets (Wilfart et al., 2007), which was attributed to a combination of sampling or analytical errors and the relatively high variability of results. Partial separation of dietary fiber components and Cr_2O_3 as they flow through the digestive tract may also negatively affect the reliability of estimation of dietary fiber digestibility (Graham and Åman, 1986). Additionally, the ATTD of NDF in DDC (136.8%) largely surpassed 100%. It is very difficult to accurately estimate the AID and ATTD of a nutrient present in low concentrations in the tested ingredient, because the nutrient value is calculated by difference, and the analytical methods may not be precise enough to determine small nutrient concentrations.

The observed AID of all indispensable AA differed ($P < 0.05$) among ingredients. Values of AID of indispensable AA in DDGS determined in the present experiment were close to previously published data (Stein et al., 2006; Urriola et al., 2009; NRC, 2012). For CGmM and CGnM, the AID of indispensable AA concurs with previously published values (Almeida et al., 2011; NRC, 2012), but are slightly less than European values (Sauvant et al., 2004). Additionally, the AID of indispensable AA in HP-DDG are less than values reported by Widmer

et al. (2007) and Kim et al. (2009), which may be a consequence of the previously reported variability in nutrient composition of different sources of HP-DDG.

The observed DE and ME values differed ($P < 0.05$) among ingredients (Table 4.5). The DE and ME values were greatest ($P < 0.05$) for DDC and CGnM, because of their low dietary fiber and high concentrations of starch and CP, respectively. In contrast, the high dietary fiber concentration in CB, in addition to its low starch and EE, resulted in DE and ME to be less ($P < 0.05$) than the rest of corn co-products. The high EE concentration in CB-S, on the other hand, caused its DE and ME content to be greater ($P < 0.05$) than in CB, and similar to CGmM. The DE and ME of HP-DDG were similar to the values for DDGS-CV and DDGS-BPX. The lower EE in DDGS-RO resulted in DE and ME to be less ($P < 0.05$) than in DDGS-CV. Anderson et al. (2011) determined the DE and ME content on different batches of the same corn co-product sources, but values were greater for CB-S, CB, DDGS-RO, HP-DDG, and CGmM. The discrepancy in DE and ME may originate from the fact that values in Anderson et al. (2011) were obtained by total collection of urine and feces from finishing gilts, whereas values in the present study were obtained by grab sampling of feces from growing pigs fed diets formulated with Cr_2O_3 as an inert marker. Values of DE and ME observed in the present trial, however, agree with values available in the literature for CB (Sauvant et al., 2004), DDGS-CV (Stein et al., 2006; Pedersen et al., 2007), DDGS-BPX, DDC, and CGnM (Anderson et al., 2011), HP-DDG and CGmM (NRC, 2012).

Best Fitting Fiber Component by Trait Categories

A best fitting dietary fiber component that better explain variation due to dietary fiber concentration was determined for each trait. The goodness-of-fit of the 11-selected fiber components for each trait was assessed and ranked, showing that the variation in AID and ATTD

traits, DE, and ME of corn co-products was best explained by the concentration of monosaccharide residues in NSP, predominantly xylose and arabinose, and their polymer arabinoxylan (Table 4.6). This finding suggests that the monosaccharide composition of dietary fiber in corn co-products, which is ultimately defined by the polysaccharides they form, is a better predictor of the nutrient value of the ingredient than commonly used dietary fiber assays such as ADF, NDF, and TDF.

In corn and its co-products, polymers of glucose and xylose are the most abundant NSP, organized mainly in the form of cellulose and arabinoxylans, respectively (Bach Knudsen, 1997; Bach Knudsen, 2001). Cellulose is a glucose polymer, and is the most abundant polysaccharide in corn cell walls. In spite of its high concentration in NSP, glucose was the best model fit for ATTD of NDF only. The effect of glucose concentration on ATTD of NDF may be related to the highly organized structure of the cellulose polymer which is inaccessible to water. Thus, cellulose is usually less degraded than arabinoxylans in cereals, but with a wide variability of degradability between structural components of the corn kernel (e.g. cellulose present in the bran vs. endosperm). Xylose is the backbone residue in arabinoxylan, and to a varying degree substituted with arabinose. Xylose was a better fit than glucose or hemicellulose for most of the traits, implying that the xylose content in dietary fiber may relate to the nutrient value of corn co-products better than cellulose or hemicellulose. Cellulose and hemicellulose have been previously used to predict the ME of ingredients in pigs (Anderson et al., 2012) and chickens (Rochell et al., 2011). The microbial degradation of arabinoxylans varies substantially in different components of the corn kernel; from hardly anything in the pericarp and testa to almost 85-90% in the endosperm (Bach Knudsen, 1997), and may also encapsulate lipids and proteins in the aleurone layer of corn (Benamrouche et al., 2002), which may explain why NSP xylose and

arabinoxylan were the best fit for the digestibility and energy value traits in the tested ingredients. Galactose was the best fitting NSP monosaccharide for AID of Lys and the average of dispensable AA, but ranked below NSP xylose for the rest of the AA. Mannose, on the other hand, forms the backbone of mannans, but they are rarely present in cereal grains (Choct, 1997), hence its low concentration in corn co-products. The lesser ranking of NSP galactose and NSP mannose, compared to the other monosaccharides, may be related to the low concentration and functionality of the polysaccharides they form.

To simplify the estimation of the effect of dietary fiber concentration and its adequacy to predict the nutrient value of the ingredient, a single best fitting dietary fiber component was selected for each category (Table 4.7). The arabinoxylan concentration was the best fitting dietary fiber component for AID of GE, DM, and NDF. The NSP xylose residue was, on the other hand, the best fitting dietary fiber component for the remaining 3 categories, including ATTD of GE, DM, and NDF, AID of AA, and on DE and ME. Zijlstra et al. (1999) reported xylan to be a better predictor than NDF for differences among wheat samples (Zijlstra et al., 1999). The comparison of the goodness-of-fit between the dietary fiber concentration and Ingred models showed that Ingred was better than dietary fiber concentration for explaining variation in most traits. Dietary fiber concentration, however, showed a better fit when used in the model for AID of GE (550.3) and DM (562.2), when compared to the models using Ingred (555.4 and 570.1, respectively). The effect of Ingred in the model includes the combined effects of other analytical components such as CP, EE, starch, minerals, and dietary fiber concentrations, which together can describe the variation in traits better than dietary fiber concentration alone. In prediction equations of DE and ME values of feed ingredients fed to swine, Noblet and Perez (1993) reported that the DE and ME values increased with the concentration CP and EE, and

decreased with the concentrations of minerals, crude fiber, NDF or hemicellulose. Predictability usually increased as more chemical components were added to the model. Other prediction models of digestible nutrients and energy values have also been developed for feed ingredients based on their chemical composition (Anderson et al., 2012; Urriola et al., 2013).

Although the effect of dietary fiber concentration is not as good as the effect of Ingred to explain the variation, the dietary fiber concentration showed significant effect on most traits (Table 4.8). The arabinoxylan concentration, for example, showed a cubic effect on AID of GE ($P = 0.02$) and DM ($P = 0.04$). Similarly, the NSP xylose concentration showed a cubic effect ($P < 0.01$) on the ATTD of GE and DM, on the AID ($P < 0.05$) of Met, Met+Cys, Trp, and average of indispensable AA and on the ME value ($P < 0.01$). Additionally, the DE was linearly affected ($P = 0.02$) by the NSP xylose concentration. This finding agree with previous data were the ATTD of energy, DM, and CP of complete diets decreased linearly with dietary increase of insoluble dietary fiber (Huisman et al., 1985; Noblet and Perez, 1993; Le Goff and Noblet, 2001). The AID of Lys and Thr in the present trial, however, was not affected ($P > 0.05$) by the NSP xylose concentration. The NSP xylose concentration affected the AID and ATTD of NDF differently. The AID of NDF was not affected ($P > 0.05$), but a cubic effect ($P < 0.01$) was observed for ATTD of NDF with NSP xylose concentration.

Interestingly, the R^2_{fiber} showed a moderate to high predictability of GE and DM digestibility, and DE and ME values, from arabinoxylan or NSP xylose residue concentrations in the feed ingredient. The arabinoxylan concentration explained approximately 66% of the variance in AID of GE and DM, and the NSP xylose residue explained 80, 78, and 63% of the variance in ATTD of GE, DM, and NDF, respectively. The NSP xylose residue was able to explain 66 and 71% of the variability in DE and ME values, respectively. The increase in

insoluble and low-fermentable dietary fiber concentration in the ingredient, at the expense of a highly digestible source of carbohydrates, may explain why NSP and xylose concentration are good predictors of these traits. Predictability of AID of AA from the NSP xylose residue concentration was poorer, ranging from 0.11 in AID of Trp to 0.44 in AID of Met + Cys. These observations coincide with the lack of correlation ($r \approx 0.33$) between the NDF content and the SID of Lys, Met, Thr, or Trp in DDGS reported by Urriola et al. (2013). The lower predictability of AID of AA maybe caused by the high insoluble to soluble dietary fiber concentration ratio in ingredients, because insoluble dietary fiber may have a lesser impact on the availability of AA than the soluble dietary fiber concentration (Urriola et al., 2013). Another contributing factor may be that some of the ingredients have been processed, therefore reducing the encapsulation of AA in intact cell structures e.g. aleurone cells.

Assessment of Loss of Predictability

The R^2_{fiber} demonstrated that the dietary fiber concentration in corn co-products is an acceptable predictor for most traits. However, a portion (model residuals) of the total predictable variance could not be explained by dietary fiber concentration, but can be explained by the effect of Ingred. For the traits with significant effects of dietary fiber concentration (Table 4.8), the residuals of these models were tested for the effect of Ingred, and the portion of the variance explained by Ingred (R^2_{Ingred}) was determined (Table 4.9). The loss of predictability is the proportion of variance from the residuals of dietary fiber models that is explained by the effect of Ingred (R^2_{Ingred}) out of the total explainable variance ($R^2_{fiber} + R^2_{Ingred}$).

Ingredient did not affect ($P > 0.05$) the residuals of dietary fiber concentration models for AID of GE, DM, and Met + Cys, and thus low R^2_{Ingred} (0.01, 0.01, and 0.07, respectively) and minimum loss of predictability (0.02, 0.01, and 0.13, respectively) values were observed. The effect of Ingred on these 3 traits did not account for more variation, because the concentration of arabinoxylan and NSP xylose residue explained the overwhelming majority of the variation in AID of GE and DM, and AID of Met + Cys, respectively.

In the remaining traits, however, Ingred affected ($P < 0.05$) the residuals of dietary fiber concentration models. Therefore, an additional portion of the variance not explained by dietary fiber concentration was accounted by the effect of Ingred (R^2_{Ingred}). In the case of AID of Trp, for instance, the R^2_{Ingred} was greater than the R^2_{fiber}, and dietary fiber concentration showed the highest loss of predictability (0.59), indicating that dietary fiber concentration is not sufficient to explain the variation in this trait.

The loss of predictability, however, revealed that the share of the variance explained by Ingred after accounting for the effect of dietary fiber concentration was lower overall for the remaining traits, ranging from 0.14 in ATTD of GE to 0.27 in DE value. The fact that the loss of predictability was overall low, except for AID of Trp, indicates that the concentration of arabinoxylan or NSP xylose residue explained the majority of the predictable variance and can be used to predict the AID of GE, DM, Met, and indispensable AA, the ATTD of GE, DM, and NDF, and DE and ME values, without substantial loss of predictability.

In conclusion, extensive variation was observed in digestibility of energy, dietary fiber, and indispensable AA, and on DE and ME in a wide variety of corn co-products. Part of the variation is explained by differences in the dietary fiber concentration in these ingredients. The arabinoxylan and NSP xylose residue were the dietary fiber components that best explained

variation due to dietary fiber concentration, and can therefore be used to explain digestibility of energy, DM and NDF, and DE and ME values in corn co-products, without substantial loss of predictability. The AID of Lys and most AA was not predictable from the dietary fiber concentration in corn co-products.

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Table 4.1. Ingredient composition (%) of the basal and experimental diets (as-fed basis)[1]

Item	Basal	Experimental diets
Ingredient		
Corn	65.15	45.60
Soybean meal, 46.5%	29.00	20.30
Corn co-product	-	30.00
Soybean oil	2.00	1.40
Limestone	1.10	0.77
Monocalcium phosphate	1.20	0.84
Cr_2O_3	0.55	0.39
Vitamin premix[2]	0.20	0.14
Trace mineral premix[3]	0.20	0.14
Salt	0.60	0.42
Energy and nutrients[4]		
DM, %	90.36	87.94 – 92.87
GE, Mcal/kg	3.89	3.85 – 4.25
CP, %	18.32	13.76 – 30.29
NDF, %	6.97	5.93 – 18.67
Lys, %	0.86	0.66 – 1.04
Thr, %	0.61	0.51 – 1.03
Met, %	0.24	0.21 – 0.64
Met+Cys, %	0.47	0.42 – 1.16
Trp, %	0.23	0.16 – 0.25
Indispensable AA, %	7.13	5.96 – 13.69
Dispensable AA, %	8.37	7.25 – 16.68

[1]Experimental diets were obtained by mixing 70% of the basal diet and 30% of the corn co-product tested.

[2]Provided per kilogram of complete diet: 6,614 IU of vitamin A; 827 IU of vitamin D; 26 IU of vitamin E; 2.6 mg of vitamin K; 29.8 mg of niacin; 16.5 mg of pantothenic acid; 5.0 mg of riboflavin; 0.023 mg of vitamin B_{12}.

[3]Provided per kilogram of complete diet: Zn, 165 mg as $ZnSO_4$; Fe, 165 mg as $FeSO_4$; Mn, 39 mg as $MnSO_4$; Cu, 17 mg as $CuSO_4$; I, 0.3 mg as $Ca(IO_3)_2$; and Se, 0.3 mg as Na_2SeO_3.

[4]Analyzed values

Table 4.2. Analyzed nutrient composition of ingredients (as-fed basis)

	Ingredient[1]								
Item	CB-S	CB	DDGS-CV	DDGS-RO	DDGS-BPX	HP-DDG	DDC	CGmM	CGnM
DM, %	95.3	80.9	89.4	90.1	91.5	93.9	90.1	91.9	92.1
GE, Mcal/kg	4.58	3.68	4.77	4.72	4.74	4.88	3.86	4.33	5.06
Ether extract, %	7.9	1.2	9.9	8.8	8.3	3.2	1.1	3.1	1.5
Starch, %	19.0	21.1	2.8	2.9	5.2	8.2	68.5	16.4	12.0
ADF, %	5.1	10.5	9.2	14.3	7.9	11.8	0.4	11.5	7.0
NDF, %	22.7	40.6	34.5	38.7	30.8	31.1	3.8	46.2	12.1
Hemicellulose[2], %	17.6	30.1	25.3	24.4	22.9	19.3	3.4	34.7	5.1
TDF, %	25.3	42.5	32.6	32.9	29.1	28.9	2.3	44.1	8.8
I-NSP[3], %									
Arabinose	3.4	8	4.7	4.1	4.4	3.8	0.5	10.4	0.8
Xylose	5.9	14.4	5.9	6.1	6.3	4.9	0.4	9.9	0.7
Mannose	0.1	0.3	0.6	0.5	0.7	1.3	-	0.3	-
Glucose	5.3	11.7	6.9	6.6	7.3	8.6	0.2	10.8	1.4
Galactose	1.1	2.4	1.3	1	1.2	0.8	-	2	0.6
Total insoluble	15.7	36.8	19.2	18.2	19.9	19.3	1.1	33.5	3.5
S-NSP[4], %									
Arabinose	0.1	-0.1	0.2	2.2	0.5	0.3	-0.1	5.4	0.3
Xylose	0.1	-0.2	-	1.9	0.1	0.2	-	3.5	0.2
Mannose	0.6	0.1	0.3	0.4	0.5	0.6	-	-0.3	-
Glucose	0.4	0.5	0.5	1.7	0.8	1.1	0.1	1.5	0.4
Galactose	0.1	-	-	0.5	0.2	0.2	-	0.8	0.5
Total soluble	1.4	0.2	1.2	6.8	2.1	2.6	-	10.9	1.4

Table 4.2. (continued)

T-NSP[5], %									
Arabinose	3.5	7.9	4.9	6.3	4.9	4.1	0.4	15.8	1.1
Xylose	6	14.2	5.9	8	6.4	5.1	0.4	13.4	0.9
Mannose	0.7	0.4	0.9	0.9	1.2	1.9	0	0	0.1
Glucose	5.7	12.2	7.4	8.3	8.1	9.7	0.3	12.3	1.8
Galactose	1.2	2.4	1.3	1.5	1.4	1	0	2.8	1.1
Total NSP[6], %	17.1	37.0	20.4	25.0	22.0	21.9	1.1	44.4	4.9
Total arabinoxylan[7], %	9.5	22.1	10.8	14.3	11.3	9.2	0.8	29.2	2.0

[1]CB-S = corn bran with solubles; CB = corn bran; DDGS-CV = cooked DDGS; DDGS-RO = reduced oil DDGS; DDGS-BPX = uncooked DDGS; HP-DDG = high protein distillers dried grains; DDC = dehulled-degermed corn; CGmM = corn germ meal; CGnM = corn gluten meal.

[3]Hemicelluose = NDF - ADF

[3]Insolule monosaccharide residues in NSP, as % of the ingredient.

[4]Soluble monosaccharide residues in NSP, as % of the ingredient. S-NSP = T-NSP – I-NSP

[5]Total monosaccharide residues in NSP, as % of the ingredient.

[6]Total NSP = sum of T-NSP monosaccharide residues.

[7]Total arabinoxylan = $T\text{-}NSP_{arabinose} + T\text{-}NSP_{xylose}$.

Table 4.3. Analyzed AA concentration (%) of ingredients (as-fed basis)

	Ingredient[1]								
Item, %	CB-S	CB	DDGS-CV	DDGS-RO	DDGS-BPX	HP-DDG	DDC	CGmM	CGnM
CP	13.0	7.5	25.4	24. 5	25.5	36.5	7.6	20.6	59.5
Indispensable AA									
Arg	0.7	0.5	1.3	1.3	1.3	1.5	0.3	1.5	2.2
His	0.4	0.3	0.7	0.8	0.8	1.1	0.2	0.7	1.3
Ile	0.5	0.3	1.0	1.1	1.0	1.8	0.3	0.8	2.6
Leu	1.2	0.9	3.1	3.7	3.1	6.0	1.1	1.8	9.8
Lys	0.6	0.5	1.1	0.9	1.0	1.3	0.2	1.1	1.3
Met	0.2	0.2	0.5	0.6	0.5	0.9	0.1	0.4	1.3
Phe	0.5	0.4	1.4	1.4	1.2	2.2	0.4	0.9	3.8
Thr	0.6	0.4	1.0	1.1	1.0	1.5	0.2	0.8	2.0
Trp	0.1	0.1	0.2	0.2	0.2	0.1	0.1	0.2	0.2
Val	0.7	0.5	1.4	1.6	1.4	2.2	0.3	1.3	2.9
Dispensable AA[2]	6.9	4.8	13.6	15.8	13.9	22.8	4.3	10.0	35.0
All AA[3]	12.5	8.6	25.2	28.4	25.3	41.2	7.4	19.4	62.4

[1] CB-S = corn bran with solubles; CB = corn bran; DDGS-CV = cooked DDGS; DDGS-RO = reduced oil DDGS; DDGS-BPX = uncooked DDGS; HP-DDG = high protein distillers dried grains; DDC = dehulled-degermed corn; CGmM = corn germ meal; CGnM = corn gluten meal.

[2]Sum of all dispensable AA.

[3]Sum of all indispensable and dispensable AA.

Table 4.4. Apparent ileal and total tract digestibility traits of ingredients[1,2]

	Ingredient										
Item	CB-S	CB	DDGS-CV	DDGS-RO	DDGS-BPX	HP-DDG	DDC	CGmM	CGnM	Pooled SEM	*P*-value
AID, %											
GE	52.1^{b}	46.7^{bc}	55.1^{b}	48.5^{bc}	53.9^{b}	52.8^{b}	84.4^{a}	30.9^{c}	75.8^{a}	4.00	<0.01
DM	46.5^{b}	41.5^{b}	47.0^{b}	40.7^{b}	45.8^{b}	48.4^{b}	87.8^{a}	29.5^{c}	74.7^{a}	4.45	<0.01
NDF	19.8	19.5	32.4	42.0	28.8	38.7	20.4	28.0	61.0	11.12	0.11
ATTD, %											
GE	53.4^{d}	40.3^{e}	72.1^{b}	64.8^{bc}	67.6^{bc}	70.7^{bc}	99.6^{a}	63.2^{c}	91.6^{a}	1.99	<0.01
DM	52.3^{e}	39.9^{f}	68.6^{cd}	61.9^{d}	64.9^{cd}	71.9^{c}	101.7^{a}	67.0^{cd}	91.5^{b}	2.01	<0.01
NDF	8.5^{d}	6.0^{d}	58.2^{c}	50.7^{c}	49.4^{c}	67.7^{c}	136.8^{a}	73.0^{bc}	94.3^{b}	6.19	<0.01
AID of AA, %											
Arg	74.4^{ab}	65.6^{ab}	80.0^{ab}	82.4^{ab}	71.5^{ab}	59.6^{b}	67.2^{ab}	79.0^{ab}	86.5^{a}	5.98	0.03
His	61.3^{bc}	56.2^{c}	73.7^{ab}	71.8^{abc}	65.5^{abc}	63.9^{bc}	74.6^{ab}	62.1^{bc}	81.2^{a}	3.74	<0.01
Ile	56.7^{bc}	49.6^{c}	67.7^{bc}	73.2^{ab}	60.4^{bc}	62.9^{bc}	71.1^{ab}	60.9^{bc}	86.6^{a}	4.14	<0.01
Leu	66.7^{cde}	60.8^{e}	80.9^{ab}	79.2^{ab}	77.1^{bc}	75.9^{bcd}	84.6^{ab}	63.2^{de}	90.4^{a}	2.81	<0.01
Lys	35.9^{ab}	35.9^{ab}	51.7^{ab}	51.3^{ab}	40.0^{ab}	44.5^{ab}	20.2^{b}	54.4^{ab}	65.5^{a}	4.46	<0.01
Met	68.8^{cd}	61.7^{d}	78.3^{bc}	81.4^{ab}	75.2^{bc}	73.3^{bcd}	80.1^{bc}	70.5^{bcd}	92.4^{a}	2.55	<0.01
Phe	59.0^{d}	55.6^{d}	75.2^{abc}	76.2^{abc}	68.2^{cd}	70.3^{bcd}	84.0^{ab}	66.0^{cd}	88.5^{a}	3.49	<0.01
Thr	50.3^{bc}	33.3^{c}	66.0^{ab}	66.3^{ab}	54.4^{bc}	54.6^{bc}	62.0^{ab}	46.1^{bc}	79.3^{a}	5.42	<0.01
Trp	35.0^{bc}	16.9^{c}	55.1^{ab}	58.5^{ab}	51.8^{abc}	37.9^{bc}	46.0^{bc}	58.6^{ab}	76.2^{a}	5.67	<0.01
Val	52.1^{bc}	42.2^{c}	67.7^{ab}	70.3^{ab}	60.5^{bc}	60.4^{bc}	67.1^{ab}	61.8^{bc}	85.6^{a}	4.96	<0.01
Indispensable[3]	58.4^{cd}	50.6^{d}	72.4^{abc}	73.4^{abc}	65.3^{bcd}	65.9^{bcd}	74.7^{ab}	63.3^{bcd}	86.6^{a}	3.54	<0.01
Dispensable[4]	58.5^{bc}	44.4^{c}	69.0^{ab}	69.9^{ab}	68.1^{ab}	64.2^{abc}	53.9^{bc}	52.4^{bc}	82.0^{a}	6.08	<0.01
All AA[5]	57.8^{bc}	47.2^{c}	70.6^{ab}	71.6^{ab}	66.9^{b}	65.0^{b}	60.2^{bc}	57.6^{bc}	84.1^{a}	4.39	<0.01

[1]Least squares means of 8 pigs per ingredient.

[2]CB-S = corn bran with solubles; CB = corn bran; DDGS-CV = cooked DDGS; DDGS-RO = reduced oil DDGS; DDGS-BPX = uncooked DDGS; HP-DDG = high protein distillers dried grains; DDC = dehulled-degermed corn; CGmM = corn germ meal; CGnM = corn gluten meal.

[3]Average AID for all indispensable AA.

[4]Average AID for all dispensable AA.

[5]Average AID for all AA (indispensable and dispensable)

Table 4.5. Digestible and metabolizable energy value of ingredients[1,2]

	Ingredient									Pooled	
	CB-S	CB	DDGS-CV	DDGS-RO	DDGS-BPX	HP-DDG	DDC	CGmM	CGnM	SEM	*P*-value
As-fed basis, Mcal/kg											
DE	2.45^{e}	1.48^{f}	3.58^{bc}	3.19^{d}	3.34^{cd}	3.59^{bc}	3.84^{b}	2.74^{e}	4.64^{a}	0.09	<0.01
ME	2.39^{d}	1.46^{e}	3.40^{b}	3,03^{c}	3,17^{bc}	3.33^{bc}	3.79^{a}	2,63^{d}	4.07^{a}	0.08	<0.01

[1] Least squares means of 8 pigs per ingredient.

[2]CB-S = corn bran with solubles; CB = corn bran; DDGS-CV = cooked DDGS; DDGS-RO = reduced oil DDGS; DDGS-BPX = uncooked DDGS; HP-DDG = high protein distillers dried grains; DDC = dehulled-degermed corn; CGmM = corn germ meal; CGnM = corn gluten meal.

Table 4.6. Goodness-of-fit ranking of dietary fiber assays by trait

	Ranking of chemical analyses[1]										
Trait	Best fit	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	Worst fit
AID											
GE	AraXyl	Ara	Hemi	NSP	NDF	Xyl	TDF	Glc	Gal	ADF	Man
DM	AraXyl	Ara	Hemi	NSP	TDF	Xyl	NDF	Glc	Gal	ADF	Man
NDF	TDF	Gal	ADF	NDF	NSP	Xyl	Glc	Hemi	AraXyl	Man	Ara
ATTD											
GE	Xyl	AraXyl	Glc	NSP	Ara	TDF	Hemi	Gal	NDF	ADF	Man
DM	AraXyl	Xyl	Ara	NSP	Glc	TDF	Hemi	Gal	NDF	Man	ADF
NDF	Glc	Xyl	AraXyl	TDF	Ara	Gal	NDF	Hemi	NSP	Man	ADF
AID of AA											
Lys	Gal	ADF	NDF	TDF	NSP	AraXyl	Ara	Glc	Hemi	Xyl	Man
Thr	Xyl	Glc	NSP	AraXyl	TDF	Gal	Ara	Hemi	NDF	ADF	Man
Met	Xyl	NSP	Glc	AraXyl	TDF	Ara	Hemi	Gal	NDF	ADF	Man
Met+Cys	Xyl	Glc	NSP	AraXyl	TDF	Hemi	Ara	Gal	NDF	ADF	Man
Trp	NSP	Xyl	AraXyl	Ara	TDF	Man	NDF	Glc	Hemi	Gal	ADF
Indispensable AA	Xyl	AraXyl	NSP	Glc	TDF	Ara	Hemi	Gal	NDF	Man	ADF
Dispensable AA	Gal	TDF	NSP	Xyl	Glc	AraXyl	Ara	NDF	Hemi	ADF	Man
Energy concentration, as-fed basis											
DE	Xyl	AraXyl	NSP	Ara	Gal	TDF	Glc	Hemi	NDF	Man	ADF
ME	Xyl	AraXyl	NSP	Ara	Gal	Glc	TDF	Hemi	NDF	Man	ADF

[1]Monosaccharide residues in NSP: Ara = NSP arabinose; Gal = NSP galactose; Glc = NSP glucose; Man = NSP mannose; Xyl = NSP Xylose. AraXyl = arabinoxylan. Hemi = hemicellulose. NSP = total NSP.

Table 4.7. Goodness-of-fit for the best dietary fiber within category and feed ingredient models across traits

Trait	Chemical assay	AIC[1]	
		Dietary fiber	Ingredient
AID			
GE	AraXyl	546.9	555.4
DM	AraXyl	561.0	570.1
NDF	AraXyl	666.1	663.0
ATTD			
GE	Xylose	504.2	448.9
DM	Xylose	513.7	450.1
NDF	Xylose	649.8	593.2
AID of AA			
Lys	Xylose	569.5	556.1
Thr	Xylose	592.8	585.9
Met	Xylose	504.1	482.9
Met+Cys	Xylose	553.4	551.0
Trp	Xylose	578.7	561.1
Indispensable AA	Xylose	548.7	537.6
Dispensable AA	Xylose	574.7	564.4
Energy concentration, as-fed basis			
DE	Xylose	1093.4	987.5
ME	Xylose	1065.2	981.7

[1]Akaike information criterion. Smaller is better.

Table 4.8. Regression coefficients and model fit of the best fitting dietary fiber across traits

		Regression components					
Trait	DF[1]	Intercept	Linear	Quadratic	Cubic	R^2_{fiber}	*P*-value[2]
AID, %							
GE	AraXyl	88.618	-6.559	0.380	-0.008	0.65	<0.01
DM	AraXyl	92.280	-8.336	0.463	-0.009	0.67	<0.01
NDF	AraXyl	-	-	-	-	n/a	>0.05
ATTD, %							
GE	Xylose	106.455	-18.346	2.596	-0.113	0.80	<0.01
DM	Xylose	108.411	-19.661	2.721	-0.115	0.78	<0.01
NDF	Xylose	147.595	-52.227	7.844	-0.337	0.63	<0.01
AID of AA, %							
Lys	Xylose	-	-	-	-	n/a	>0.05
Thr	Xylose	-	-	-	-	n/a	>0.05
Met	Xylose	90.469	-9.020	1.514	-0.072	0.40	0.02
Met+Cys	Xylose	87.475	-10.333	1.610	-0.076	0.44	0.04
Trp	Xylose	71.795	-20.447	3.874	-0.185	0.11	0.04
Indispensable AA	Xylose	86.045	-11.075	1.831	-0.086	0.35	0.02
Dispensable AA	Xylose	-	-	-	-	n/a	>0.05
Energy concentration, Mcal/kg (as-fed basis)							
DE	Xylose	4.464	-0.457	-	-	0.66	0.02
ME	Xylose	4.215	-0.520	0.078	-0.004	0.71	0.01

[1]DF = Dietary fiber

[2]*P*-value of the highest order regression component.

Table 4.9. Comparison of model adequacy and effect of ingredient on the residuals from the dietary fiber models

Trait	Dietary fiber	R^2_{fiber}[1]	R^2_{Ingred}[2]	*P*-value[3]	Loss of predictability[4]
AID					
GE	AraXyl	0.65	0.01	>0.05	0.02
DM	AraXyl	0.67	0.01	>0.05	0.01
ATTD					
GE	Xylose	0.80	0.13	<0.01	0.14
DM	Xylose	0.78	0.15	<0.01	0.16
NDF	Xylose	0.63	0.23	<0.01	0.27
AID of AA					
Met	Xylose	0.40	0.12	<0.01	0.24
Met+Cys	Xylose	0.44	0.07	>0.05	0.13
Trp	Xylose	0.11	0.17	<0.01	0.59
Indispensable AA	Xylose	0.35	0.13	<0.01	0.27
Energy concentration, as-fed basis					
DE	Xylose	0.66	0.26	<0.01	0.28
ME	Xylose	0.71	0.21	<0.01	0.23

[1]R^2 of dietary fiber on the observed values (Eq. 3).

[2]R^2 of Ingred on the residuals of the dietary fiber model (Eq. 4).

[3]*P*-value of Ingred on the residuals of the dietary fiber model.

[4]Loss of predictability = $\frac{R^2_{Ingredient}}{R^2_{Ingredient} + R^2_{fiber}}$

CHAPTER 5: INTEGRATIVE SUMMARY

Typical corn and soybean meal diets offered to pigs in the US are changing because of cost and competition for corn. The high availability of co-products from the corn-ethanol distillation industry, such as DDGS, offers an alternative to successfully supply pigs with energy and AA. However, these feed ingredients are also high in plant derived carbohydrates and lignin that are undigested by mammalian enzymes, and are commonly known as dietary fiber (Gutierrez et al., 2014).

Because of its high fiber content, the dietary inclusion of DDGS and most corn co-products increases the concentration of dietary fiber (NRC, 2012). Therefore, substitution of highly digestible carbohydrates with dietary fiber suppose a reduction in the dietary energy supply, which can only be compensated with addition of external fat or using co-products with a high fat content (DDGS with >10% fat).

Dietary fiber is degraded to a variable degree in the gastrointestinal tract by anaerobic fermentation, and may contribute to the dietary supply of energy. In pigs, the efficiency of energy utilization from fibrous feed ingredients is affected by the digestibility of dietary fiber and the production of VFA (Bindelle et al., 2008). The digestibility of dietary fiber in the gastrointestinal tract depends on the degree of lignification, solubility, and structure of the polysaccharides of dietary fiber (Bach Knudsen, 2001). Additionally, corn co-products are also changing permanently due to technological advances at the production plant, and differences in AID and ATTD of dietary fiber of DDGS have been previously reported (Guo et al., 2004; Stein et al., 2009; Urriola et al., 2010). These differences contribute to variation in digestibility of energy in diets containing DDGS or other corn co-products, and increase the difficulty of predicting the energy value of the feed ingredient and the supply of dietary energy.

The use of co-products from the corn ethanol distillation industry may also decrease the AA, energy, and fiber digestibility of diets offered to pigs (Noblet and Le Goff, 2001; Urriola and Stein, 2010). Similarly, the high concentration of fiber in the feed ingredient may have a negative effect on the nutrient value of the feed ingredient.

Stein and Shurson (2009) reported that the greater concentration of fiber in DDGS compared with corn might be one of the primary reasons for the decreased digestibility of energy in DDGS. The reason dietary fiber reduces digestibility of energy and AA is that fiber has less digestibility, induces and increase in endogenous nutrient losses, and increases the rate of passage (Grieshop et al., 2001; Souffrant, 2001). Another possibility is that the plant cell wall may act as a physical barrier to the release of nutrients or may increase the viscosity of the liquid phase restricting nutrient absorption (Bach Knudsen, 2001). For example, soluble dietary fiber has been reported to influence the absorption of nutrients from the small intestine through its effect on luminal viscosity, which may reduce the rate of nutrient absorption (Bach Knudsen, 2001).

The effect of dietary fiber on the availability of dietary nutrients is variable and is mostly influenced by the physicochemical properties of dietary fiber. These properties of dietary fiber are associated with the type of polymers that make up the cell wall and their intermolecular association (Bach Knudsen, 2001). Therefore, knowledge of the polymers and the monosaccharide residues that constitute fiber may be helpful to better explain the effect of dietary fiber on the nutritional value of corn co-products. Modern analytical techniques enable quantification and characterization of the physical and chemical properties of dietary fiber in plant materials, but understanding of the nutritional significance of these measurements is far from complete. Specifically, analytical values concerning the degree of lignification and water

solubility provide important information about the degradability of dietary fiber over the entire intestinal tract, but the relationship between dietary fiber and processes of digestion and absorption in the small intestine is more difficult to establish from the chemical parameters currently measured.

A quantification of the effects of dietary fiber concentration on the nutrient value of corn co-products and diets formulated with them is unavailable. We therefore proposed a series of experiments, using the ileal-cannulated animal model, to determine the digestibility of energy, nutrients, and dietary fiber at the terminal ileum and over the entire intestinal tract, with the objective of:

1) Determine the site and extent of digestion of dietary fiber from corn and its co-products

2) Determine the impact of dietary fiber increase on the utilization of dietary nutrients

3) Identify dietary fiber components to more accurately predict the effect of dietary fiber concentration in corn co-products on their energy and nutrient value

It was observed that insoluble monosaccharide residues composed the majority of the dietary fiber in corn co-products. From the total NSP in corn co-products, glucose was the most prevalent monosaccharide residue followed by xylose, arabinose, galactose, and mannose. The monosaccharide composition, solubility, and concentration relate structurally to the polysaccharides forming the NSP of corn co-products, such as arabinoxylans, cellulose, and

galactomannans (Bach Knudsen, 1997; Choct, 2002). The implication of this chemical composition is that a portion of the dietary NDF originated from corn co-products is fermented by the terminal ileum (approximately 25% AID of NDF) and the fermentability was not affected by the level of NDF intake. However, increasing the amounts of dietary insoluble and low-fermentable fiber from corn may reduce the ability of the growing pig to ferment the dietary fiber in the hindgut, as the ATTD of NDF decreased (from 42.6 to 30.5%) with the dietary increase of corn fiber. This response, however, appear to be modulated by the dietary fat concentration, because in diets formulated with high concentrations of extracted fat from soybean oil a quadratic response of the AID of NDF and a reduction of the ATTD of NDF were observed with the addition of low fat DDGS. The high concentration of extracted fat in these diets may increase the transit time of digesta, resulting in the longer exposure of the dietary NDF to the intestinal microbiota. However, at low concentrations of dietary fat the apparent digestibility of NDF at the terminal ileum and over the entire tract was not affected by the dietary increase of DDGS. Results also showed that in spite of the reduction in digestibility of energy with insoluble and low fermentable fiber level from corn, growth performance was not affected when energy is correctly balanced in the diet.

It was concluded that the AID of AA was negatively associated with the inclusion of corn co-products from the corn ethanol distillation industry, but the decrease in AID of AA may be attributed to the effects of the manufacture processes rather than the effect of NDF concentration in DDGS. Insoluble fiber has minimal effect on the ileal digestion and absorption of nutrients and energy, which has been demonstrated in several experiments that used different sources of insoluble dietary fiber (Wang et al., 2002; Serena et al., 2008b). Similar results were obtained

when the AID of AA was measured in nine corn co-products and it was determined that the AID of Lys and most AA was not predictable from the dietary fiber concentration.

Extensive variation was observed in digestibility of energy, dietary fiber, and indispensible AA, and on DE and ME in a variety of 9 corn co-products. It was concluded that part of the variation is explained by the increase in insoluble and low-fermentable fiber concentration in the feed ingredient, at the expense of starch or fat. It was determined that the arabinoxylan and NSP xylose residues were the dietary fiber components that best explained variation due to dietary fiber concentration. The NSP xylose residue, for example, was able to explain 66 and 71% of the variation in DE and ME values, respectively. Xylose is the backbone residue in arabinoxylan and the fact that it was the best fit implies that relates better to the nutrient value of corn co-products than cellulose or hemicellulose.

In conclusion, the present work suggests that the current panorama of high fiber diets is not so dire since fiber from corn co-products can be fed to pigs without negative effects on the digestibility of AA, and performance can be maintained as long as energy is correctly balanced in the diet. However the challenge of a new generation of co-products with a lower fat content mean that digestibility of dietary fiber need to be improved to maximize the energy supply.

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