DIGESTIBILITY OF ENERGY AND TOTAL DIETARY FIBER BY GESTATING AND LACTATING SOWS BUT NOT REPRODUCTIVE PERFORMANCE ARE INFLUENCED BY EXOGENOUS XYLANASE

BY

JESSICA PAOLA ACOSTA MEDELLIN

THESIS

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Master's Committee:

Professor Yuan-Xiang Pan, Chair

Professor Hans Henrik Stein, Director of Research

Professor Maria Cattai de Godoy

ABSTRACT

Because pigs lack fiber-digesting enzymes, addition of exogenous carbohydrases (e.g., xylanase) in diets for pigs may enhance hydrolysis of glycosidic bonds between monosaccharides in undigestible carbohydrates, increasing fiber fermentation and utilization of energy. Sows have larger digestive tracts than growing pigs, which allows feed to reside in the hindgut for longer timer; therefore, it is possible that exogenous enzymes may positively impact fermentation of fiber in sows. However, limited research on the efficacy of exogenous enzymes in diets fed to sows has been published. The objective of the research reported in this thesis was to test the hypothesis that exogenous xylanase added to diets for gestating and lactating sows will increase the apparent total tract digestibility (**ATTD**) of gross energy (**GE**) and total dietary fiber (**TDF**), increase concentrations of digestible energy (**DE**) and metabolizable energy (**ME**), and improve reproductive performance. Two diets for gestating and two diets for lactating sows containing corn, soybean meal, distillers dried grains with solubles, wheat middlings, and soybean hulls were formulated without or with 16,000 units per kg of exogenous xylanase. Diets were fed to gestating and lactating sows in two reproductive cycles. A total of 106 gilts and sows were randomly allotted to the two gestation diets 7 d after breeding in a randomized complete block design with 4 blocks. From 98 sows confirmed pregnant on d 30, 48 sows (24 replicates per treatment, 12 sows per block) were placed in metabolism crates on d 35 (mid-gestation) for 10 d with feces and urine collected for 4 d. The same 48 sows were placed in metabolism crates again on d 95 (late-gestation). All sows were moved to the lactation unit on d 106 and lactation diet feeding was initiated. Fecal samples were collected for 5 d starting on d 10 post-farrowing via grab sampling. Body weight and feed intake of the sows at the beginning of the experiment, at the beginning and conclusion of each collection period, at farrowing and at weaning was

recorded. Pigs were weaned on d 20 and 63 sows were rebred. Of these sows, 46 sows were placed in metabolism crates on d 35 and 95 as in the first cycle, and treatments in the farrowing unit were also as in the first cycle. Sow and litter performance was recorded in each lactation period, and the ATTD of DM, GE, insoluble dietary fiber (**IDF**) and TDF were calculated for each gestation period and each lactation period. Concentrations of DE and ME in gestation and De in lactation were also calculated for each diet. Results indicated that the performance of sows and litters was not different between sows fed control diets or diets with xylanase during the two reproductive cycles. In the first cycle, the ATTD of DM, IDF, and TDF in late-gestation were greater ($P < 0.05$) in sows fed the xylanase-diet compared with sows fed the control diet. During the first lactation period, sows fed the xylanase-diet had greater ($P < 0.05$) ATTD of DM, GE, and TDF, and greater ($P < 0.05$) DE than sows fed the control diet. During the second gestation period, sows fed the xylanase-diet had greater ($P < 0.05$) DE in mid-gestation, and xylanase increased ($P < 0.05$) ATTD of DM and tended to increase ($P < 0.10$) DE in late-gestation. During the second lactation period, sows fed the xylanase-diet had greater ($P < 0.05$) ATTD of DM, GE, IDF, and TDF, and greater ($P < 0.05$) DE than sows fed the control diet. In conclusion, DE was greater in gestation and lactation diets containing xylanase than in control diets during two reproductive cycles, and sows fed lactation diets with xylanase had greater digestibility of fiber.

Keywords: dietary fiber, energy, sows, xylanase.

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CHAPTER 1: INTRODUCTION

Pig production is one of the most important industries to supply meat for human nutrition. It is forecasted that pork consumption will increase from 112,000 tons in 2021 to about 127,000 tons by 2030 worldwide (Statista, 2022a), and in the U.S., 24 kg of pork per capita will be needed by 2030 (Statista, 2022b). Pigs consume great quantities of feed to reach market weight, and feed represents 60 to 75 percent of the total cost of pork production. Therefore, strategies to increase efficiency of production and nutrition are needed to meet the growing demand for pork.

Swine diets are formulated to meet nutritional needs for amino acids, fatty acids, energy, vitamins, minerals, and water. Grains (e.g., corn, wheat) mainly contribute energy, whereas oilseed-coproducts, (e.g., soybean meal, canola meal, sunflower meal) provide amino acids in the diets (Stein et al., 2016). The corn-soybean meal diet has been the most broadly fed diet since 1950 in the U.S., whereas the wheat-soybean meal diet is widely used in Canada, Europe, and Australia (NRC, 2012).

Although the grain-soybean meal diet is commonly used to meet nutritional requirements, these ingredients may be replaced with co-products to provide similar nutrient profile and reduce feed cost. As an example, distillers dried grains with solubles (**DDGS**), the co-product from ethanol production, may be used as an alternative ingredient in diets fed to pigs (Stein and Shurson, 2009). Likewise, wheat middlings, the co-product of flour production for human consumption (NRC, 2012), and soybean hulls, a co-product from soybean oil production are also sometimes used in pig diets. These co-products have increased concentration of dietary fiber compared with cereal grains and oilseeds, which makes these ingredients less expensive (Anguita et al. 2006).

Plant-based feed ingredients are major sources of carbohydrates that supply energy to pigs. Carbohydrates are nutrients with different physicochemical properties that can be classified by the location in the plant as non-cell wall or cell-wall carbohydrates (NRC, 2012). The non-cell wall carbohydrates include starch, disaccharides, oligosaccharides, fructan polysaccharides, and resistant starch, whereas plant cell wall carbohydrates include cellulose, hemicellulose, β-glucans, pectins, and gums (Bach Knudsen, 2011; NRC, 2012). Carbohydrates can also be classified into digestible and non-digestible carbohydrates (Bach Knudsen et al., 2012). Digestible carbohydrates (i.e., starch and sugars) are those that pigs can digest after secretion of endogenous enzymes, whereas non-digestible carbohydrates are those that are not digested by enzymes secreted by pigs, and therefore, need to be fermented by microbial enzymes to make a contribution to the energy status of the pig (Englyst and Englyst, 2005).

Dietary fiber, which includes complex carbohydrates and lignin, is found in plant cells and include all non-digestible carbohydrates. The non-starch polysaccharides (**NSP**) in fiber consist of pectins, cellulose, hemicelluloses, β-glucans, arabinoxylans, fructans, oligosaccharides, and resistant starch (Navarro, et al., 2019). Lignin, the second component of fiber, is not a carbohydrate; however, this compound is made of alcohols and ring structures associated with carbohydrates in the plant cell wall (Bach Knudsen, 2001). Fiber is primarily fermented in the hindgut of pigs (Grieshop et al., 2001), which results in production of volatile fatty acids that can be used to synthesize energy (Bach Knudsen, 2001).

Dietary fiber has been associated with negative effects in pigs, which limits the use of co-products in pig diets. Pedersen et al. (2007) demonstrated that fiber increased the quantity of manure being excreted and reduced digestibility of nutrients and energy. However, dietary fiber may have beneficial effects in pigs due to its role in maintaining the physiological functions of

the gastrointestinal tract (e.g., good peristalsis, satiation, less constipation) depending on the amount and type of dietary fiber being fed (Bosse, 2017).

Because pigs lack fiber-digesting enzymes, including exogenous carbohydrases (e.g., xylanase) in pig diets may facilitate hydrolysis of carbohydrate bonds, which increases fiber degradation and metabolizable energy (Casas and Stein, 2016; Abelilla and Stein, 2019). The efficacy of exogenous fiber-degrading carbohydrases is inconsistent when determined in growing pigs, particularly when supplemented to swine diets containing corn and corn coproducts (Jones et al., 2010; Abelilla and Stein, 2019). However, because sows have larger digestive tracts than growing pigs, which allows feed to reside in the hindgut for longer time, it is possible that exogenous enzymes may have a greater effect in sows than in growing pigs, but there is very limited research with exogenous enzymes fed to sows. It is, therefore, the objective of this research to test the hypothesis than inclusion of exogenous enzymes such as xylanase in diets for gestation and lactation sows will positively impact energy digestibility and reproductive performance.

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CHAPTER 2: DIETARY FIBER AND POSSIBLE BENEFICIAL EFFECTS OF XYLANASE IN DIETS FOR PIGS: A REVIEW

INTRODUCTION

Carbohydrates serve as source of energy in diets for pigs and often account for approximately 60 to 70% of the total energy intake (Bach Knudsen et al., 2013). Carbohydrates consist of monosaccharides linked together via α- or β-glycosidic bonds that form compounds with different degree of polymerization, such as disaccharides, oligosaccharides, and complex organized polysaccharides that are present in plants cells (Cummings and Stephen, 2007; Navarro et al., 2019).

The small intestine can absorb only monosaccharide units; therefore, digestive enzymes break down glycosidic bonds of bigger structures to liberate monosaccharides (NRC, 2012). However, the carbohydrate-digesting enzymes only digest a limited number of α-glycosidic bonds; therefore, some compounds reach the large intestine where these compounds are fermented by microbes resulting in synthesis and absorption of short-chain fatty acids (**SCFA**; NRC, 2012).

More than 20 monosaccharides existing in nature are categorized based on the number of carbons they contain. Monosaccharides that contain of five carbons are called pentoses, whereas monosaccharides that have six carbons are called hexoses. Pentoses include arabinose, xylose, and apiose, whereas hexoses include glucose, fructose, mannose, and galactose (NRC, 2012). Glucose is the main monosaccharide in cereal grains included in diets for pigs (Navarro et al., 2019). Other monosaccharides such as D-fructose, D-galactose, L-arabinose, D-xylose, and D-mannose may also be present in pig diets (NRC, 2012).

Disaccharides consist of two monosaccharides linked together by a glycosidic bond. The three most common disaccharides are maltose, lactose, and sucrose (BeMiller, 2014). Lactose consists of glucose and galactose units from milk and milk products, whereas sucrose consists of glucose and fructose units. Maltose consists of two units of glucose linked by an α-(1-4) bond and is an intermediate in starch digestion (NRC, 2012). Disaccharides are hydrolyzed by maltase, lactase, and sucrose, which release monosaccharide units that can be rapidly absorbed in the small intestine (Navarro et al., 2019).

Oligosaccharides (e.g. mannan-, fructo-, or galacto-oligosaccharides) consist of a limited number of monosaccharides linked together by glycosidic bonds with a defined structure, and these bonds cannot be digested by digestive enzymes (NRC, 2012; Bach Knudsen et al., 2016). Mannan-oligosaccharides are chains of mannose mostly present in yeast cell walls (Spring et al. 2015). Fructo-oligosaccharides are fructose polymers with different degree of polymerization (i.e., inulins or levans) that are present in fruits and vegetables or produced by bacteria and fungi (Cromwell, 2013). Galacto-oligosaccharides (i.e., raffinose, stachyose, and verbascose) are present in legumes and made up of sucrose units linked to one, two, or three galactose units (Navarro et al., 2019).

Most of the carbohydrates in feed ingredients are polysaccharides that can be subdivided into starch and non-starch polysaccharides (**NSP**; Bach Knudsen et al., 2016). Starch is the storage form of energy in cereal grains and is made up of glucose molecules linked by glycosidic bonds forming granules of amylose and amylopectin polymers (BeMiller, 2019). Amylopectin is a highly branched polymer with both α-1,4 and α-1,6 glycosidic bonds, whereas amylose consists of non-branched helical chains of glucose residues connected by α-1,4 glycosidic bonds (Ring et al., 1988). Amylase and isomaltase, which are digestive enzymes produced by the pancreas and

brush border in the small intestine, hydrolyze the glycosidic bonds of starch to produce glucose for absorption. However, a fraction of starch may resist digestion in the small intestine and enter the large intestine where it is fermented by microbial enzymes. This undigested starch is called resistant starch (Tan et al., 2021) and five categories of resistant starch exist: 1) physically enclosed starch within intact cell wall structures; 2) raw starch granules; 3) retrograded amylose formed by recrystallization during cooling of gelatinized starch; 4) chemically modified starch, and 5) amylose-lipid or amylose-protein complexes (Englyst et al., 1992; Raigond et al., 2015).

Non-starch polysaccharides are the most diverse category of carbohydrates that consist of a variety of molecular structures mostly present in plant cell walls and plant gums (Burton and Fincher, 2014). The monosaccharides of NSP is not connected by α-1,4 glycosidic bonds or other bonds that may be hydrolyzed by digestive enzymes (Englyst et al., 2007). Therefore, NSP reach the large intestine where NSP may be hydrolyzed by microbial enzymes and consequently converted to SCFA through different metabolic pathways (Bach Knudsen, 2016).

Cell wall NSP consist of cellulose, hemicellulose, and pectin (Bach Knudsen et al., 2016). Cellulose consists of straight chains of β-1,4-linked glucose units that can pack tightly together in a 3-dimensional structure. Hemicelluloses, also known as non-cellulosic polysaccharides, includes a diverse class of heteropolymers (i.e., arabinoxylans, xyloglucans, arabinogalactans, galactans, and mixed β-glucans) composed of hexose and pentose sugars in highly-branched chains (Cummings and Stephen, 2007), whereas pectin is a β-1,4 galacturonic acid polymer (Lara-Espinoza et al., 2018). Non-carbohydrate components (i.e., lignin and suberin) are also associated with NSP in plants cell walls, making them very rigid and difficult to degrade and digest (Bach Knudsen, 2011).

Carbohydrates may also be categorized into digestible carbohydrates and dietary fiber. Endogenous enzymes secreted by pigs can digest digestible carbohydrates (e.g., monosaccharides, disaccharides, some oligosaccharides, starch), whereas dietary fiber cannot be digested by endogenous enzymes, and therefore, must be fermented to yield energy to the pig (Bach Knudsen et al., 2012). In pigs, most fermentation takes place in the hindgut. Non-digestible oligosaccharides, resistant starch, NSP, and lignin are the components included in dietary fiber (Bindelle et al., 2008).

Different types of dietary fiber have different functionality, physical properties, and fermentability. Depending on solubility in water and fermentability, dietary fiber may be classified into soluble dietary fiber and insoluble dietary fiber. Soluble dietary fiber (e.g., pectins, gums, fructans, beta-glucans, soluble hemicelluloses) are highly fermentable in the hindgut (Lattimer and Haub, 2010; Jaworski and Stein, 2017), whereas insoluble dietary fiber (e.g., cellulose, lignin, and insoluble hemicelluloses) are much less fermentable compared with the soluble fraction (Urriola et al., 2010). Some soluble dietary fiber may increase digesta viscosity, decreases stomach emptying, increases satiety and digesta retention time, and supports the proliferation of gut commensal bacteria (de Godoy et al., 2013); however, soluble dietary fiber rapidly hydrate and create thick gel that reduces nutrient absorption in the small intestine (Blaxter et al., 1990). Insoluble dietary fiber increases passage rate, fecal bulk, frequency of laxation, and results in softer feces (Wenk, 2001).

CHARACTERISTICS OF DIETARY FIBER IN FEED INGREDIENTS

Whole grain cereals

Although cereal grains are not required by pigs, cereal grains are present in all commercial diets and account for the majority of the energy in the diets due to their high

concentration of starch (50 to 75%; Stein et al, 2016). However, concentration of dietary fiber varies among cereal grains. For instance, the total dietary fiber is 1.2% in polished white rice, 8% in sorghum, 9% in corn and wheat, 11% in rye, 18.8% in barley, and 22.8% in oats (NRC, 2012; Stein et al, 2016; McGhee and Stein, 2020). The level, type, and composition of dietary fiber is significantly influenced by tissue type, tissue maturity, and numerous agronomic and environmental conditions (Izydorczyk and Biliaderis, 2007; Saulnier et al., 2007).

The cereal grain structure consists of tissues that contain cell walls with varying features, composition, and layers. Although components of cereal grains are different among species, they usually contain the embryo, endosperm, and outer tissues surrounding the endosperm and embryo (Fig. 1; Evers and Millar, 2002). The starch in cereal grains is located in their endosperm, whereas the outer parts contain proteins and NSP that form thick and hydrophobic tissues (Bautil and Courtin, 2019). The aleurone layer of the endosperm also contains NSP such as insoluble arabinoxylans and β-glucans, which protect and give shape to the grain (Brouns et al., 2012).

Dietary fiber in commonly used feed ingredients is composed of NSP (e.g., arabinoxylans, β-glucans, and cellulose) and lignin (Bach Knudsen, 2014); however, composition varies depending on grain type and tissue (Izydorczyk and Dexter, 2008). Some cereal grains also contain fructans, galactomannans, and phenolic acids (Bunzel et al., 2001; Saulnier et al., 2007)

Arabinoxylans are the main NSP in cereal grains such as corn, wheat, sorghum, rye, and triticale (Navarro et al., 2019). Arabinoxylans have a linear backbone of β-(1,4)-D-xylopyranosyl residues (i.e. D-xylose), which can be substituted with α-L-arabinofuranosyl residues (i.e. L-arabinose) at the C(O)-2 and/or C(O)-3 positions distributed along the xylan backbone creating

branches and open regions (Courtin and Delcour, 2002). In addition, ferulic or coumaric acids can link to the C(O)-5 position of L-arabinose, which facilitate reactions with other polysaccharides and lignin. D-glucuronic acid can substitute xylan in the backbone and xylose units may link to arabinose units in the sidechains, which may be further replaced with galactose (Bautil and Courtin, 2019). These variable intermolecular interactions impair enzymatic breakdown and may enclose nutrients within the cell wall because of the arabinoxylans cross-linking (Pedersen et al., 2014).

The degree to which the xylan backbone is substituted by arabinose residues is shown by the arabinose over xylose ratio (**A/X**), which reflects the structural features of the arabinoxylans (Bach Knudsen et al., 2014). A higher A/X indicates a highly branched structure, and this can be related as a factor that influences solubility in water, because when arabinoxylans lose arabinose side chains become less soluble (Courtin and Delcour, 2002). For example, sorghum has an A/X greater than 1.23, whereas the A/X of oats is less than 0.22, which indicates that sorghum can bind more water and is more soluble than oats (Navarro et al., 2019). Wheat arabinose residues are single side-chain mono-substitutions or di-sustitutions, with an A/X between 0.57 to 0.70 of mostly insoluble arabinoxylans (Laerke et al., 2015; Buksa et al., 2016) whereas corn arabinoxylans are more substituted and form complex three-dimensional structures that are intertwined with other components in the plant cell wall, although the A/X for corn is 0.81 (Jeremic et al., 2014; Petry and Patience, 2020). Corn has the lowest solubility of NSP among cereal grains because corn arabinoxylans are cross-linked with phenolic acid to a greater degree than in wheat, rye, rice, and oats (Sosulski et al., 1982).

Cellulose is the second most abundant NSP in cereals, accounting for 1.7% in corn, 1.5% in sorghum, and 1.3% in wheat (Jaworsky et al., 2015). Cellulose is composed of β-(1-4)-D-

glucosyl units, which consists of 500 to 15,000 D-glucose units linked together by β-(1-4) glycosidic bonds and hydrogen bonds forming a ribbon-like structure (Alberts et al., 2002).

Beta glucans are linear homopolysaccharides of β-D-glucopyranosyl residues (i.e. D-glucose), and three or four residues are linked to each other by 1,4 glycosidic linkages to form trisaccharide and tetrasaccharide units, respectively. The trisaccharide and tetrasaccharide units are linked via β-(1,3) linkages (Cui and Wand, 2009). Barley and oats have the highest concentration of β-glucans (5.0 and 2.8%, respectively; Bach Knudsen, 2014). Corn, wheat, sorghum, triticale and rice contain less than 1% β-glucans, and rye contains 1.7% β-glucans (Navarro et al., 2019).

Cereal coproducts

The dry and wet milling industries uses cereal grains to produce flour and bioethanol, which involves processing of grains to separate the starchy endosperm from the fiber-rich aleurone and pericarp/testa and hull structures (Barron et al., 2021). As a result, the key carbohydrate components differ significantly among whole cereal grains and their coproducts (Bach Knudsen, 2014). Concentration of starch is reduced from 62% in corn, 69% in sorghum, and 62% in wheat to between 0 and 20% in cereal coproducts (Jaworski et al., 2015). On the other hand, bran and hulls have reduced starch concentration and increased dietary fiber concentration compared with the whole grains (Bach Knudsen, 2014). As an example, the concentration of dietary fiber is 46% and 41% in corn and wheat bran, respectively (Jaworski et al., 2015), and there is 48 to 50% dietary fiber in barley and oat hulls (Bach Knudsen, 2014).

Dietary fiber in cereal co-products mainly consists of cellulose, β-glucans, and arabinoxylans (Navarro et al., 2019); however, each cereal co-product has specific types of fiber that may change its functionality. The mixture of co-products from flour milling that make up

wheat middlings includes wheat bran, wheat shorts, wheat germ, and wheat flour, and the amount of the different flour milling fractions varies across suppliers (AAFCO, 2011). The fiber in wheat middlings and wheat, which contain primarily arabinoxylans and cellulose, and 35% is insoluble dietary fiber and 2% is soluble dietary fiber (Jaworski and Stein, 2017).

Distillers dried grains with solubles (**DDGS**) is a cereal coproduct from dry mill ethanol plants, and the process to produce DDGS involves fermentation of starch from cereal grains (e.g., corn, wheat, and sorghum) to produce ethanol and carbon dioxide; therefore, protein, oil, and dietary fiber contents are increased in DDGS compared with corn (Widmer et al., 2007). Corn and sorghum DDGS contain approximately 35% insoluble dietary fiber and 1% soluble dietary fiber (Urriola et al., 2010). However, the nutrient composition of DDGS varies depending on the parent grain and ethanol plants used to produce the DDGS (Pedersen et al., 2014; Jha et al., 2015). Indeed, wheat DDGS contains more soluble dietary fiber than corn DDGS, whereas corn DDGS contains more insoluble dietary fiber than wheat DDGS (Pedersen et al., 2014).

Oilseeds and oilseed meals

The outer part of the seed in oilseeds is a layer of thick and hydrophobic tissue that protects the embryo and endosperm where the oil and protein complexes are located (Hu et al., 2013). The outer tissues are mostly composed of NSP such as cellulose, xyloglucans, pectin polysaccharides, and lignin (Navarro et al., 2019).

Oilseeds are fed to pigs in the form of defatted meals after removal of oil via solvent or mechanical extraction (NRC, 2012). Due to high concentrations of protein and amino acids in coproducts from soybean, rapeseed, linseed, cotton, coconut, palm, and sunflower, these feed ingredients are used as protein sources in animal feeding (Bach Knudsen, 1997). The

carbohydrate portion of these feedstuffs is also a source of energy despite having a composition very different from cereals (Bach Knudsen, 2014; Navarro et al., 2019).

Pectin polysaccharides are high-molecular-weight carbohydrate polymers of α-1,4-d-galacturonic acid units. Homogalacturonan, rhamnogalacturonans I and II, xylogalacturonan, apiogalacturonan, arabinan, galactan, and arabinogalactan I and II are some of the many pectin polysaccharides in cell walls of oilseeds (Gawkowska et al. 2018). Homogalacturonans are linear chains of galacturonic acid units, whereas rhamnogalacturonans are branched chains of galacturonic acid and rhamnose units (Kaczmarska et al., 2022). Arabinogalactans are branched polysaccharides made of polymerized galactose connected to an arabinose side chain (Schols and Voragen, 1994). The pectin concentrations are difficult to measure due to its complex structure; however, the pectin fraction consists mostly of rhamnogalacturonans in oilseeds and oilseed meals (Pettersson and Pontoppidan, 2013). In comparison with other oilseed meals, soybean meal has greater concentration of rhamnogalacturonan, whereas the greater side chains in rapeseed and sunflower meal are arabinogalactans (Lannuzel et al., 2022).

Xyloglucans are linear polysaccharides consisting of β-(1,4)-linked D-glucosyl units substituted with xylose, galactose, fucose, and arabinose (Smith and Melton, 2012). Xyloglucans and cellulose are also components of the plant cell walls (Navarro, et al. 2019), and both compounds are present at the highest concentrations in oilseed hulls (Bach Knudsen, 2014).

Concentration of lignin varies among oilseeds and oilseed meals. Lignin in sunflower and rapeseed is greater than in soybean due to high lignification of the hulls (Bach Knudsen, 2014). The lignin content of sunflower and soybean meal may fluctuate depending on the amount of hulls added back to the meal after oil extraction, but compared with sunflower meal, the concentration of lignin in soybean meal is low (Lannuzel et al., 2022).

There are also galacto-oligosaccharides in some oilseed meals. Raffinose is the predominant oligosaccharide in cottonseed meal and sunflower meal, whereas soybean meal and rapeseed meal primary contain stachyose (Bach Knudsen, 1997).

ANALYSIS OF DIETARY FIBER

Crude fiber analysis

Different methods are used to measure and characterize dietary fiber in ingredients. Crude fiber is the most commonly used and oldest method for animal nutrition. Crude fiber, which is used in the Weende analysis system, is a chemical-gravimetric method that uses hot 0.255*N* sulfuric acid hydrolysis to extract sugars and starch, and 0.313*N* sodium hydroxide is used for alkaline hydrolysis to digest protein, certain hemicelluloses, and lignin (Bach Knudsen, 2001). The residues after sample digestion in acid and alkali solutions are quantified into crude fiber and nitrogen free extract; however, this method underestimates the fiber content by 30 to 50% because digestion results mostly in cellulose, little hemicellulose and variable lignin concentrations (Fahey et al., 2019).

Detergent fiber analyses

Fiber may be analyzed using the Van Soest method, which measures acid detergent lignin (**ADL**), acid detergent fiber (**ADF**), and neutral detergent fiber (**NDF**; Van Soest et al., 1991). The ADF residues (i.e., cellulose and lignin) were created as a preliminary step for the detection of lignin, and it is obtained after boiling a test sample in sulfuric acid detergent solution, whereas the remaining insoluble residue after boiling a substance in neutral detergent solution is referred to as NDF (i.e., hemicellulose, cellulose, and lignin). Although measuring fiber using NDF and ADF is more representative than measuring crude fiber, the Van Soest technique ignores a

significant portion of fiber, in cereal grains and oilseeds and their co-products because soluble hemicelluloses are not included in the analyzed NDF portion (Bach Knudsen, 2001).

Total dietary fiber analysis

Prosky et al. (1992) developed an enzymatic-gravimetric method in which fiber can be measured as soluble, insoluble, and total dietary fiber. This approach is the most common fiber analysis procedure in human nutrition because it is robust and rapidly reproducible. The non-fiber components are removed via the extraction of low-molecular weight sugars and lipids, and protein and starch are degraded enzymatically. The residue of the process is precipitated in aqueous ethanol to obtain the soluble dietary fiber components, and the residue is then weighed and corrected for ash and protein concentrations (McCleary, 2003). However, this process only quantifies a portion of the resistant starch, and inulin and polydextrose are excluded (Bach Knudsen, 2001).

Non-starch polysaccharides analysis

Englyst et al. (2007) introduced the enzymatic-chemical approach, where dietary fiber is measured as total soluble and insoluble NSP, via direct extraction of low-molecular weight sugars, enzymatic removal of starch, acid hydrolysis of dietary fiber polysaccharides, and determination of monosaccharide residues through gas-liquid chromatography, high-performance liquid chromatography, or colorimetry (McCleary et al., 2019). The concentration of individual monosaccharides (i.e., rhamnose, fucose, arabinose, xylose, mannose, galactose, and glucose) and uronic acids (via a colorimetric method; Scott, 1979) is equal to the total NSP (Bach Knudsen, 1997). This method allows a more comprehensive analysis of fiber components, but it is time consuming and expensive. Each method previously described allows for analysis of

dietary fiber and classification of the fiber portions depending on the solubility and type of compound in the feed sample.

NUTRITIONAL VALUE OF DIETARY FIBER TO SOWS AND PIGS

Fermentation

Dietary lipids, proteins, and carbohydrates are nutrients that pigs may use for synthesis of metabolic energy, but not all dietary nutrients are digested and absorbed from the gastrointestinal tract. Undigested proteins and carbohydrates may undergo fermentation by microbes (Abelilla and Stein, 2019) and fermentation mostly takes place in the large intestine due to low oxygen level, low flow rate, and high moisture content (Bach Knudsen et al., 2013; Jha and Berrocoso, 2015). Proteolytic fermentation produces branched-chain fatty acids and potentially harmful metabolites (e.g., ammonia, indoles, and phenols), whereas saccharolytic fermentation produces SCFA and lactate (Tiwari et al., 2019).

Anaerobic microorganisms degrade polysaccharides into smaller polysaccharides or monosaccharides to use as an energy source (Jha and Berrocoso, 2015). Hexoses are broken down via glycolysis, whereas pentoses are degraded via the pentose phosphate pathway, which results in the production of pyruvate, which is then oxidized to lactate and SCFA. The most common SCFA are acetate (C2), propionate (C3), and butyrate (C4), which are characterized as the saturated aliphatic organic acids (Cook and Sellin, 1998). Gases such as hydrogen, carbon dioxide, and methane are also generated (Macfarlane and Macfarlane, 2003). Most of the SCFA generated by microorganisms are absorbed through the intestinal cells via passive and active transport and enter the bloodstream. However, some of the butyrate is metabolized by colonocytes to produce adenosine triphosphate (**ATP**). The absorbed SCFA are transported to the liver where butyrate and acetate may be used for ATP synthesis or as precursors for fatty acid

synthesis, whereas propionate is used to synthesize glucose via gluconeogenesis. A small part of the SCFA are not absorbed and instead are excreted in the feces (Jha and Berrocoso, 2015).

In addition, SCFA promotes development and activity of advantageous microbes in the gut, which indicates that fermentable carbohydrates can have a prebiotic-like effect on gut microbiota modulation (Jha and Berrocoso, 2015). As a result, pathogenic bacteria such as *E. coli* and other *Enterobacteriaceae* members cannot survive in an acidic environment are reduced (Tiwari et al., 2019). Indeed, fermentation of cereal grain fiber resulted in increased concentration of bacteria that resemble *Ruminococcus* and *Clostridium*, which break down insoluble fiber and produce SCFA (Bindelle et al., 2006, Ivarsson et al., 2014). Fermentation of wheat fiber also results in proliferation of *Bifidobacteria* and *Lactobacilli* species, which subsequently may improve intestinal morphology (Chen et al., 2014).

Barriers to fiber fermentation

Pigs lack endogenous enzymes to digest dietary fiber, and therefore, dietary fiber results in microbial fermentation (Anguita et al., 2006). Compared with other nutrients, contribution of dietary fiber to the energy requirement of pigs is low and variable (i.e., 5 to 28%; Kerr and Shurson, 2013) due to energy loss from gas production. Pigs are unable to absorb and metabolize gas, and approximately 25% of dietary energy is lost in gas and heat (Jørgensen et al., 2007; Bach Knudsen et al., 2013).

Differences in the structure and physicochemical properties of dietary fiber contribute to variation in nutrient and energy digestibility. For instance, the solubility of arabinoxylans and β-glucans affects synthesis of SCFA as insoluble arabinoxylans and β-glucan are less fermentable compared with soluble fibers (Tiwari et al., 2019). Among the fibrous feed ingredients, the proportion of insoluble fiber is greater relative to soluble fiber, and insoluble fiber fractions are

hydrophobic, crystalline, and resistant to microbial fermentation (Bach Knudsen, 2011; 2014). The viscosity of fiber may influence nutrient digestibility (Dikeman and Fahey, 2006; Wu et al., 2018) and soluble dietary fiber increases digesta viscosity, which may create a physical barrier in the intestinal surface and subsequently reduces nutrient digestion and absorption (Molist et al., 2014).

Hydrolysis of dietary fiber is variable and lower than that of other nutrients, ranging from 40 to 60% (Jha and Berrocoso, 2015). Increased concentration of dietary fiber in diets for pigs results in reduced of digestibility of energy and other nutrients. Gutierrez et al. (2016) demonstrated that when DDGS was included in diets, the apparent ileal digestibility and apparent total tract digestibility of energy and dry matter decreased. Inclusion of DDGS and wheat middlings in diets for pigs also decreased the apparent ileal digestibility of all indispensable amino acids due to reduced absorption of N and increased endogenous losses of amino acids in the intestine of pigs (Gutierrez et al., 2016; Casas and Stein, 2017).

Growth performance is also reduced when dietary fiber increases in diets for pigs. Average daily gain of weaned pigs was reduced and deposition of lean meat decreased in finishing pigs (De Jong et al., 2014; Wang et al., 2016). However, the ability of the pig to ferment fiber varies with age. Nursery pigs that are fed diets with greater concentration of DDGS had decreased growth performance (Avelar et al., 2010) compared with pigs fed a diet without DDGS; however, inclusion of DDGS did not affect growth performance in growing or finishing pigs (Kerr et al., 2015). Although dietary fiber may not reduce growth in growing pigs, young pigs have reduced ability to ferment fiber due to gut immaturity (Cho et al., 2021).

Dietary fiber is better fermented in adult sows than in growing pigs due to prolonged digesta retention period in the hindgut of sows and greater gut capacity (Jha and Berrocoso,

2014; Agyekum and Nyachoti, 2017). However, the type of dietary fiber influences fermentability. Increased intake of insoluble fiber decreased energy digestibility in gestating sows, whereas increased soluble fiber intake improved energy digestibility (Renteria-Flores et al., 2008). Nonetheless, dietary fiber may promote satiety in gestation sows that have fed a limited amount of feed (De Leeuw et al., 2008). Dietary fiber also relieves constipation before farrowing, which reduces stillborns and increases piglet weight gain during lactation (Oliviero et al., 2009; Feyera et al., 2017).

Possibilities for increasing fermentation using exogenous enzymes

Pigs are not able to digest fiber, but mechanical processing or inclusion of exogenous enzymes in the diets may improve fermentability (Kerr and Shurson, 2013; Agyekum and Nyachoti, 2017). There are many exogenous carbohydrases currently used in animal nutrition (i.e. xylanase, β-glucanase, mannanase, maltase, pectinase, galactosidase and cellulase), and are widely used to increased fermentation of high-fiber ingredients by monogastric animals and to ameliorate the adverse effects of high dietary fiber (Patience et al., 2022). Enzymes aid in the hydrolysis of some of the main fiber components (i.e., cellulose and arabinoxylans) into sugar monomers or oligosaccharides that may be fermented by the animals or microorganism present in the hindgut of the pigs. However, the efficiency of exogenous enzymes on nutrient digestibility are inconsistent and variable, depending on the enzymes used and the type of dietary fiber present in the diets. Zhang et al. (2014, 2020) demonstrated that xylanase, cellulose, βglucanase, α-amylase, and protease improved growth rate of pigs by increasing the digestibility of dry matter, crude protein, dietary fiber and energy. However, Lee et al. (2019) reported that nutrient digestibility and growth performance of pigs were not affected when cellulose or arabinoxylans degrading enzymes were fed to pigs. However, fiber-degrading enzymes increased

concentrations of SCFA in the intestines and feces of pigs (Jha et al., 2015; Zhao et al., 2020).

Exogenous xylanase

Exogenous xylanase hydrolyzes the β-1,4-glycosidic bonds between xylose units in the backbone of arabinoxylans, which is the major dietary fiber component in cereal grains and grain coproducts. The arabinoxylan backbone is hydrolyzed randomly and results in release of D-xylose, L-arabinose molecules, or xylo-oligosaccharides. Other nutrients, such as amino acids, Ca, and P, are also potentially released because these nutrients are associated with arabinoxylans located in the grain endosperm and aleurone layers (Paloheimo et al., 2011). Therefore, the method of action of xylanase added in diets for pigs is the hydrolysis of the xylose backbone in arabinoxylans into lower molecular weight fragments that may be absorbed or fermented (Petry and Patience, 2020). Indeed, xylanase and debranching enzymes increased the *in vitro* generation of SCFA from insoluble arabinoxylans (Lei et al., 2016), which is believed to increase nutrient and energy digestibility from the fermentation of dietary fiber in the diet.

Energy digestibility may increase if xylanase is added to wheat-based diets (Yin et al., 2000; Barrera et al., 2004, Nortey et al., 2007, 2008), and corn-based diets fed to growing pigs (Fang et al., 2007; Kairie et al., 2016). Overall, the digestibility of dry matter, crude protein and gross energy improves with xylanase (Torres-Pitarch et al., 2019). However, the beneficial effects of xylanase on digestibility have not always resulted in greater responses in growth performance. Inclusion of xylanase in pigs fed wheat or corn-based diets did not improved growth performance (Mavromichalis et al., 2000; Jang et al., 2016; Jones et al., 2010, 2015; Mejicanos et al., 2020), whereas added xylanase to a wheat or corn-based diet high in insoluble fiber increased average daily gain and energy availability (Vahjen et al., 2007; Lan et al., 2017; Petry et al., 2020). The different results are likely related to the carbohydrate composition of

dietary ingredients, enzyme or enzyme combinations, enzyme dose, age of pigs and experimental times among experiments (Patience and Petry, 2019). Addition of xylanase to diets for growing pigs has also reduced pig mortality and increased pig viability (Zier-Rush et al., 2016) and improved immune function and gut barrier integrity (Li et al., 2018; Tiwari et al., 2018; Duarte et al., 2019).

There is, however, limited information about effects of addition of xylanase to diets for gestating and lactating sows. Digestibility of nutrients and energy has not been measured in gestating sows, but in lactating sows, results indicated that the digestibility of DM and nutrients increased by xylanase supplementation (de Souza et al. 2007; Zhou et al., 2018). Xylanase improved lactating sow feed intake (Walsh et al., 2012), but no effects on reproductive performance of sows were reported. Results of a meta-analysis by Cozannet et al. (2018) indicated that sows fed xylanase-containing diets had reduced body weight loss in lactation and greater litter weigh gain resulting in greater body weight of pigs at weaning. Zhou et al., (2018) reported that xylanase reduced sow body weight loss in lactation, but litter performance and milk yield were not affected.

Therefore, additional work is needed to determine effects of xylanase in diets for gestation and lactating sows. Information about the length of time it will take for xylanase to improve energy and nutrient digestibility, about dose or concentration of enzyme, or enzyme optimal conditions to be activated and functional is also needed.

CONCLUSIONS

Dietary fiber varies in terms of its type and composition in cereals, cereal coproducts and oilseed co-products. The effects of fiber on feed digestion and nutrient absorption can be influenced by the physicochemical characteristics of fiber; therefore, a thorough chemical analysis of fibrous

feed ingredients is necessary. Although dietary fiber has been demonstrated to decrease energy availability, nutrient digestibility, and growth performance in pigs, recent results indicate that dietary fiber is beneficial for sows and may act as a prebiotic, promoting beneficial bacterial growth, increasing satiety and releasing constipation. Despite the presence of barriers to hydrolyze fiber, dietary fiber can be included in pig diets and exogenous enzyme supplementation may improve the utilization of fiber and nutrients in fiber-rich feed ingredients. Exogenous xylanase needs to be further developed and described to fully understand its effects when included in fibrous diets, and therefore, more information is needed in evaluating specific enzymes for each type of fiber. Furthermore, the type of fiber in each cereal and oilseed co-product must be evaluated to subsequently determine the enzyme needed to increase degradation of fiber.

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FIGURE

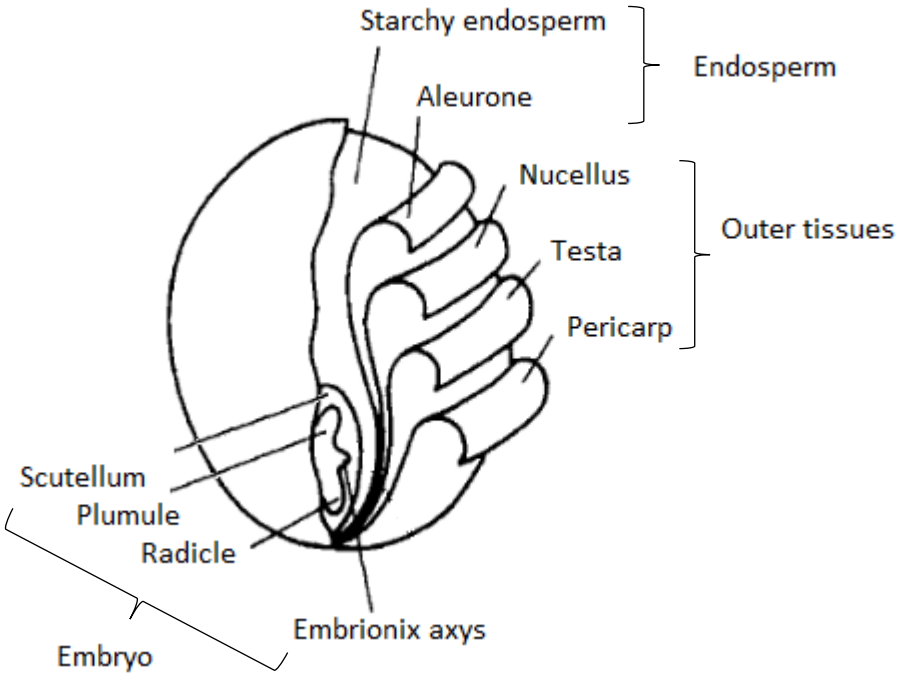

FIGURE 1. Generalized cereal structure. Adapted from Evers and Millar, 2002.

CHAPTER 3: EXOGENOUS XYLANASE INCREASES DIGESTIBILITY OF ENERGY AND FIBER IN DIETS FOR GESTATING AND LACTATING SOWS, BUT XYLANASE DOES NOT INFLUENCE REPRODUCTIVE PERFORMANCE OF SOWS

ABSTRACT

An experiment was conducted to test the hypothesis that exogenous xylanase added to diets for gestating and lactating sows would increase the apparent total tract digestibility (**ATTD**) of gross energy (**GE**) and total dietary fiber (**TDF**), increase concentrations of digestible energy (**DE**) and metabolizable energy (**ME**), and improve the reproductive performance of sows and growth performance of their litters during lactation. Two diets for gestating and two diets for lactating sows containing corn, soybean meal, distillers dried grains with solubles, wheat middlings, and soybean hulls were formulated without or with 16,000 units per kg of exogenous xylanase. Lactation diets contained 0.4% titanium oxide used as indigestible marker. Diets were fed to gestating and lactating sows in two reproductive cycles. In each cycle, 48 sows (24 sows per treatment, 12 sows per block) were placed in metabolism crates on d 35 (mid-gestation) for 10 d with feces and urine collected for 4 d. The same 48 sows were placed in metabolism crates again on d 95 (late-gestation). All sows were moved to the lactation unit on d 106 and lactation diet feeding was initiated. Fecal samples were collected (grab-sampling) for 5 d starting on d 10 post-farrowing. Number and weight of pigs born, mummified, stillborn, and weaned per sow was recorded, and survival rate, and litter average daily gain was calculated. Pigs were weaned on d 20 and sows were rebred. Forty-six sows were placed in metabolism crates on d 35 and 95 as in the first cycle, and treatments in the farrowing unit were also as in the first cycle. Results indicated that the performance of sows and litters was not different between sows fed control diets and sows fed diets with xylanase during the two reproductive cycles. In

the first cycle, the ATTD of DM, insoluble dietary fiber (**IDF**) and TDF in late-gestation was greater ($P < 0.05$) in sows fed the xylanase-diet compared with sows fed the control diet. During the first lactation period, sows fed the xylanase-diet had greater ($P < 0.05$) ATTD of DM, GE, and TDF, and greater ($P < 0.05$) DE than sows fed the control diet. During the second gestation period, sows fed the xylanase-diet had greater ($P < 0.05$) DE in mid-gestation, and xylanase increased ($P < 0.05$) ATTD of DM and tended to increase ($P < 0.10$) DE in late-gestation. During the second lactation period, sows fed the xylanase-diet had greater ($P < 0.05$) ATTD of DM, GE, IDF, and TDF, and greater ($P < 0.05$) DE than sows fed the control diet. In conclusion, DE was greater in gestation and lactation diets with xylanase than in control diets during the two reproductive cycles, and sows fed lactation diets with xylanase had greater digestibility of fiber than sows fed the control diet.

Keywords: digestibility, energy, fiber, reproductive performance, sows, xylanase.

INTRODUCTION

Diets for sows and finishing pigs commonly include co-products that are less expensive than corn and soybean meal, but coproducts usually contain more dietary fiber, which cannot be fully digested by pigs (Jaworski et al., 2015). However, several technologies have been developed to increase fermentation and energetic contribution of dietary fiber in co-products, which include the use of direct-fed microbials, fermentation of raw materials, and the use of exogenous enzymes (i.e., carbohydrases, phytase, lipase, and protease; Kerr and Shurson, 2013; Aranda-Aguirre et al., 2021). Carbohydrases may improve the fermentability of dietary fiber in swine diets by hydrolyzing non-starch polysaccharides into oligosaccharides and sugars. In particular, the enzyme xylanase hydrolyzes the β-(1-4) glycosidic bonds between the xylose units in the backbone of arabinoxylans that are present in cereal grains and grain coproducts (Navarro

et al., 2019). As a result, xylanase liberates a combination of xylose, arabinose, and xylooligosaccharides from arabinoxylans that can be absorbed or fermented by pigs (Dodd and Cann, 2009). Indeed, xylanase increased the degradation of dietary fiber in diets for growing pigs (Passos et al., 2015, Pedersen et al., 2015a; Abelilla and Stein, 2019), increased energy digestibility (Nortey et al., 2007a, Yang et al., 2016, Torres-Pitarch et al., 2019), and improved growth performance of pigs (Tsai et al., 2017; He et al., 2020; Petry et al., 2020a). Xylanase also reduced pig mortality (Zier-Rush et al., 2016) and improved the gut barrier integrity in nursery pigs (Tiwari et al., 2018; He et al., 2020). However, data demonstrating the efficacy of xylanase in gestating and lactating sows on reproductive performance and nutrient digestibility are limited. Inclusion of xylanase to a corn-soybean meal diet increased nutrient digestibility during lactation in sows; however, no effects were observed during gestation (de Souza et al., 2007). Inclusion of xylanase to a wheat-based lactation diet increased sow feed intake and nutrient digestibility, and reduced sow body weight loss; however, milk yield and piglet performance were not affected (Zhou et al., 2018). There are, however, no data for the impact of xylanase on energy and fiber digestibility in gestating and lactating sows and it is not known how feeding of xylanase during the entire reproductive cycle influences lactation performance. Therefore, an experiment was conducted to test the hypothesis that supplementation of xylanase to gestation and lactation diets would increase the apparent total tract digestibility (**ATTD**) of gross energy (**GE**) and total dietary fiber (**TDF**), concentrations of digestible energy (**DE**) and metabolizable energy (**ME**), and improve reproductive parameters of gestating and lactating sows fed diets containing corn, soybean meal, DDGS, wheat middlings and soybean hulls during two reproductive cycles.

MATERIALS AND METHODS

The protocol for the experiment was submitted to the Institutional Animal Care and Use Committee at the University of Illinois and was approved prior to initiation of the experiment. The experiment was conducted at the Swine Research Center at the University of Illinois at Urbana Champaign.

Experimental diets

Two gestation diets and two lactation diets were formulated to meet estimated requirements for gestating and lactating sows (NRC, 2012; Tables 1, 2, and 3). Within each stage of production, a control diet containing corn, soybean meal, DDGS, wheat middlings, and soybean hulls was formulated, and an additional diet was formulated by adding 16,000 BXU per kg of an exogenous xylanase (Econase XT; AB Vista, Marlborough, UK) to the control diet. One BXU is defined as the amount of enzyme that will release 0.06 micromoles of reducing sugars (xylose equivalents) from birch xylan per min at pH 5.3 and 50°C. All diets were in meal form. Diets were fed during two reproductive cycles; therefore, the experiment was conducted from April, 2021, to March, 2022. Ten batches of gestation diets and 5 batches of lactation diets were mixed, and diet samples were collected for each batch of feed produced. Each batch of each diet was analyzed for xylanase activity immediately after production and before feeding of the batch started. At the conclusion of the experiment, diet samples were pooled and subsampled for chemical analysis. Diets for lactating sows contained 0.40% titanium dioxide as an indigestible marker, but an indigestible marker was not included in gestating diets. Representative amounts of each ingredient (i.e., corn, soybean meal, soybean hulls, distillers dried grains with solubles, wheat middlings) were also collected at each mixing, pooled at the conclusion of the experiment, and subsampled for chemical analysis.

Animals, housing, and feeding

A total of 106 animals, 44 gilts and 62 Camborough sows (Pig Improvement Company, Hendersonville, TN, USA) were bred to terminal line boars (Line 800, Pig Improvement Company). In the first cycle, sows and gilts were allotted to 4 blocks of 23 to 30 gilts and sows per block, using a randomized complete block design. Animals were housed individually in gestation stalls and they were allotted to experimental diets 7 days after breeding. They were fed the same experimental diets until day 105 of gestation. During the gestation period, daily feed allotments were provided at 0600 h. Daily feed allowance was 1.5 times the maintenance energy requirement for gestating sows (i.e., 100 kcal ME/kg body weight$^{0.75}$; NRC, 2012), but feed allowance was adjusted every other week, if needed, to maintain or achieve ideal sow body condition by visual scoring (approximately 3.0 on a 1 to 5-point scale; Patience and Tacker, 1989). On d 30 post-breeding, all animals were pregnancy checked and 8 non-pregnant animals were removed. From the remaining 96 animals, 48 sows were placed in metabolism crates from d 35 to 45 (i.e., mid-gestation). Crates were equipped with a self-feeder, a nipple drinker, and a fully slatted tri-bar floor. The selected sows had an average parity of 2.18 ± 1.03, and an average initial body weight of 194.57 ± 18.29 kg. Because there were 4 blocks with 12 sows in each block (6 sows per treatment), there was a total of 24 replicated sows per treatment. A screen and a urine pan were installed under the tri-bar floor in the metabolism crates to allow for the total collection of feces and urine. The initial 3 d of each period in the metabolism crates were considered the adaptation period. The adaptation period was followed by 4 d of fecal and urine collection using the marker to marker procedure (Adeola, 2001). Fecal collection was initiated when the first marker (i.e. ferric oxide) appeared in the feces and ceased when the second marker (i.e. chromium oxide) appeared (Adeola, 2001). Urine was collected in buckets placed under

urine pans and 50 mL of 6*N* HCl were added to each bucket. Buckets were emptied daily, the weight of the collected urine was recorded, and 10% of the collected urine was stored at −20 °C until subsampling. From day d 95 to 105 (i.e., late-gestation), the same 48 sows were moved back into the metabolism crates, and feces and urine were collected for 4 days again, following the same procedures as in mid-gestation. At the conclusion of each collection period, urine samples were thawed and mixed within animal and diet, and a subsample was lyophilized before analysis. Fecal samples from each animal were thawed and mixed, and then dried in a 50 °C forced-air drying oven and ground using a grain mill (500G Swing Type Grain Mill, RRH, Zhejiang, China) prior to analysis.

On d 106 of gestation, sows and gilts were moved to the lactation unit and housed in farrowing crates (2.1 × 1.5 m) with plastic coated slatted floors. Each crate was equipped with a stainless steel feeder and 2 nipple waterers. Sows were fed experimental lactation diets starting the day sows were moved to the lactation unit and had *ad libitum* access to feed and water during the remaining gestation period and throughout the lactation period. From d 14 post-farrowing, litters were offered a standard creep feed diet according to normal farm practices and this diet did not contain xylanase. During lactation, fecal samples from the 48 sows that had been placed in metabolism crates in gestation were collected for 5 d via grab sampling starting on d 10 post-farrowing. These samples were used to determine nutrient and energy digestibility. Fresh fecal samples were also collected in both cycles on d 1, 10, and d 20 post-farrowing to assess fecal quality of sows via anal stimulation.

After weaning on d 20.72 ± 0.71 d, 63 sows (32 sows fed the control diets and 31 sows fed the diet with xylanase) were rebred when heat was observed (approximately 5 days after weaning) and housed individually in gestation stalls throughout gestation. Bred sows were fed

the same experimental gestation diets as in the first cycle from the day after weaning and until d 106 of the second gestation period. On d 30 post-breeding, sows were pregnancy checked and 8 non-pregnant animals (2 sows fed the control diets and 6 sows fed the diet with xylanase) were removed. From the remaining 55 animals, 47 sows were placed in metabolism crates from d 35 to 45 and again from d 95 to 105 as in the first cycle and feces and urine were collected as in the first cycle. On d 106, sows were moved to the lactation unit where treatments were as in the first cycle, and fecal samples were collected for 5 d starting on d 10 as in the first cycle. Fresh fecal samples were also collected on d 1, 10 and 20 as in the first cycle.

Data collection

In both cycles, individual body weights of sows were recorded on d 7 after breeding, when sows were moved into and out of metabolism crates, when they were moved to farrowing crates, within 24 h after farrowing, and on the day of weaning. Daily feed intake of gestating sows and weekly feed intake during lactation were recorded as well. The number and body weight of pigs born alive, the number of mummies, stillborn pigs, and total pigs born per litter were recorded within 24 h of farrowing. Pig body weight at birth and at cross-fostering, which was completed within 24 h of farrowing within treatment groups, were recorded as well. Pigs were processed within 24 h of birth, and according to normal farm practices, processing included clipping needle teeth, docking tails, castrating male pigs, administering iron dextran and ceftiofur antibiotic (Excede, Zoetis, Parsippany, NJ, USA), and ear notching for identification. Following normal farm practices, pigs weighing less than 0.8 kg at birth were considered low vitality and immediately euthanized. Pig body weight at weaning and the number of days between weaning and estrus were also recorded.

Sample analyses

Ingredients, diets, and fecal samples were analyzed for dry matter (**DM**) determined by oven drying at 135 °C for 2 h (Method 930.15; AOAC Int., 2019). Diet and ingredient samples, fecal samples, and urine samples were analyzed for GE on an isoperibol bomb calorimeter (Model 6400, Parr Instruments, Moline, IL) using benzoic acid as the internal standard. Diets and ingredients were analyzed for ash (Method 942.05; AOAC Int., 2019). Diets and ingredients were analyzed for N by the combustion procedure (Method 990.03; AOAC Int., 2019) using a LECO FP628 (LECO Corp., Saint Joseph, MI) and crude protein calculated as N × 6.25. Starch was analyzed in diets and ingredients by the glucoamylase procedure (method 979.10; AOAC Int., 2019). Diets and ingredients were analyzed for amino acids on a Hitachi Amino Acid Analyzer (Model No. l8800; Hitachi High Technologies America, Inc., Pleasanton, CA) using ninhydrin for postcolumn derivatization and norleucine as the internal standard [Method 982.30 E (a, b, c); AOAC Int., 2019]. Acid hydrolyzed ether extract was analyzed in diets and ingredients by acid hydrolysis using 3*N* HCl (Ankom^{HCl}, Ankom Technology, Macedon, NY) followed by crude fat extraction [Method Am 5-04; AOCS, 2013] using petroleum ether (Ankom^{XT15}, Ankom Technology, Macedon, NY). Diets, ingredients, and fecal samples were analyzed for insoluble dietary fiber (**IDF**) and soluble dietary fiber (**SDF**) according to method 991.43 (AOAC Int., 2019) using the AnkomTDF Dietary Fiber Analyzer (Ankom Technology, Macedon, NY). Total dietary fiber was calculated as the sum of IDF and SDF. Calcium, P, K, Mg, Na, Cu, Fe, Mn, and Zn in diets and ingredients were analyzed (Method 985.01 A, B and C; AOAC Int., 2019) using inductively coupled plasma-optimal emission spectrometry (**ICP-OES**; Avio 200, PerkinElmer, Waltham, MA). Sample preparation included dry ashing at 600 °C for 4 h (Method 942.05, AOAC Int., 2019) and wet digestion with nitric acid (Method 3050 B; U.S.

Environmental Protection Agency, 2000). The concentration of titanium in fecal samples and lactation diets was analyzed following the procedure of Myers et al. (2004). Fresh fecal samples collected on d 1, 10, and 20 of lactation of both reproductive cycles were analyzed for fecal DM by oven drying at 50 °C for at least 24 h (Method 2.2.1.1; National Forage Testing Association. 1993), followed by drying at 135 °C for 2 h (Method 930.15; AOAC Int., 2019).

Calculations and statistical analyses

At the conclusion of the experiment, data for estimated milk yield (calculated as 4 g milk per g of litter body weight gain; Close and Cole, 2000) and litter performance data were calculated for each sow as follows: number of total born, mummified, and still born pigs, number of pigs after cross-fostering, number of pigs weaned, and pig survival rate (i.e., calculated as the percentage of live born pigs after adjusting for cross fostering divided by the weaned pigs from birth to weaning × 100). Total litter birth weight, live litter birth weight after cross fostering, litter weight at weaning, and litter average daily gain (**ADG**) were calculated as well. Average pig weights and ADG for each pig were also calculated. Apparent total tract digestibility of DM, GE, IDF, SDF and TDF were calculated for each diet, and the concentration of DE and ME in each diet were also calculated (Adeola, 2001).

Data were analyzed using the MIXED Procedure (SAS Inst. Inc., Cary, NC, USA). Homogeneity of the variances among treatments was confirmed using the UNIVARIATE procedure, and this procedure was used to test for outliers. The sow was the experimental unit for all analyses. The fixed effect was diet, and block and replicate within block were random effects. The LS Means statement was used to calculate treatment means. Statistical significance and tendencies were considered at $P < 0.05$ and $0.05 \leq P < 0.10$, respectively.

RESULTS

Reproductive parameters

During the first reproductive cycle, differences in body weights of sows between treatment groups were not observed during gestation or lactation (Table 4). There was no difference in total feed intake of sows between treatment groups during gestation or lactation, and there were no differences in the days between weaning and estrus and the estimated total and daily milk yields. There were also no differences between sows fed the control diet and sows fed the xylanase diet for the number of pigs born per litter, number of pigs born alive per litter, number of pigs per litter after cross-fostering, number of still born pigs per litter, number of mummified pigs per litter, or number of pigs weaned per litter (Table 5). Total litter birth weight was not affected by diet, but total litter weight after cross-fostering was greater ($P < 0.05$) for sows fed the control diet compared with sows fed the diet with xylanase. Total litter weaning weight and litter ADG were not different between diets. No differences were observed for individual pig weights at birth or at weaning. The survival rate of pigs was not influenced by dietary treatment.

For the second reproductive cycle, there were no differences in body weight of sows between treatment groups during gestation or lactation (Table 6). There was no difference in feed intake of sows between treatment groups during gestation, but sows fed the xylanase diet had less ($P < 0.05$) feed intake in week 3 of lactation. However, no difference was observed for the combined feed intake of sows during the entire lactation period. No differences between treatment groups were observed for days between weaning and estrus and the estimated total and daily milk yields were not different between treatment groups. There were no differences between the control and xylanase treatments for the number of pigs born per litter, number of

pigs born alive per litter, number of pigs per litter after cross-fostering, number of still born pigs per litter, number of mummified pigs per litter, or number or pigs weaned per litter (Table 7). Total litter birth weight, total litter weight after cross-fostering, total litter weaning weight, and litter ADG were not different between diets. No differences were observed for individual pig weights at birth or at weaning, and survival rate of pigs during lactation was not influenced by dietary treatment.

Energy and nutrient digestibility

During the first reproductive cycle, DM intake, fecal output, and ATTD of DM in mid-gestation (i.e. d 30 to 40) did not differ between diets (Table 8). There were no differences in GE intake, GE fecal and urine output, ATTD of GE, and concentrations of DE and ME between diets in mid-gestation. Although there were no differences in DM intake during late-gestation (i.e. d 95 to 105), sows fed the diet with xylanase in late-gestation had less ($P < 0.05$) DM fecal output and greater ($P < 0.05$) ATTD of DM compared with sows fed the control diet. No differences were observed in GE intake and GE urine output; but GE fecal output in late-gestation tended to be less ($P < 0.10$) in sows fed the diet with xylanase. However, the ATTD of GE was not different between diets, and no differences were observed in concentrations of DE and ME in late gestation. Sows fed the xylanase diet had greater ($P < 0.05$) ATTD of DM, and GE, and greater ($P < 0.05$) DE than sows fed the control diet during the first lactation period. Intake, fecal output, and ATTD of IDF, SDF, and TDF in mid-gestation were not different between diets (Table 9). There was no difference in IDF intake; but sows fed the control diets had greater ($P < 0.05$) IDF fecal output, therefore, the ATTD of IDF in late-gestation was greater ($P < 0.05$) in sows fed the diet with xylanase. There were no differences in SDF intake, SDF output, ATTD of SDF, and TDF intake; however, the TDF fecal output was reduced ($P < 0.05$) in sows fed the

diet with xylanase, resulting in a greater ($P < 0.05$) ATTD of TDF in late-gestation. Sows fed the xylanase diet had greater ($P < 0.05$) ATTD of IDF and TDF, and greater ($P < 0.05$) DE than sows fed the control diet during the first lactation period.

During the second reproductive cycle, DM intake and fecal output in mid-gestation did not differ between diets (Table 10); however, there was a tendency for greater ($P < 0.10$) ATTD of DM in mid-gestation in sows fed the diet with xylanase compared with sows fed the control diet. There were no differences in GE intake or fecal and urine output between dietary treatments, but the ATTD of GE and concentrations of DE in mid-gestation were greater ($P < 0.05$) in sows fed the diet with xylanase than sows fed the control diet. The DM intake and DM fecal output in late-gestation were not significantly different between diets; however, sows fed the diet with xylanase had greater ($P < 0.05$) ATTD of DM compared with sows fed the control diet. No differences were observed for GE intake and fecal and urine output between diets, and the ATTD of GE was not different between diets. However, concentration of DE tended to be greater ($P < 0.10$) in late-gestation for sows fed the diet with xylanase than for sows fed the control diet. Sows fed the diet with xylanase had greater ($P < 0.05$) ATTD of DM, and GE than sows fed the control diet, and DE was also greater ($P < 0.05$) for sows fed the diet with xylanase compared with sows fed the control diet during the second lactation period. Intake, fecal output, and ATTD of IDF, SDF, and TDF in mid-gestation were not different between diets (Table 11). There were no differences in IDF intake, IDF output, ATTD of IDF or SDF intake; but sows fed the diet with xylanase tended to have less ($P < 0.10$) SDF output, although the ATTD of SDF in late-gestation was not different between diets. No differences were observed for TDF intake, TDF output or ATTD of TDF in late-gestation. Sows fed the diet with xylanase had greater ($P < 0.05$) ATTD of IDF and TDF than sows fed the control diet during the second lactation period.

Fecal dry matter

Fecal DM percentage was assessed on d 1, 10, and 20 in each lactation period, and fecal IDF, SDF and TDF percentages on a DM basis were analyzed in feces collected on d 10 (Table 12). Fecal DM was not different between sows fed the control diet and the diet with xylanase on d 1 in the first reproductive cycle; however, on d 10 and d 20, sows fed the control diet had greater ($P < 0.05$) fecal DM than sows fed the diet with xylanase. The fecal SFD percentage was greater ($P < 0.05$) in sows fed the diet with xylanase than sows fed the control diet. During the second reproductive cycle, there was no difference on d 1 between sows fed experimental diets; but on d 10, sows fed the diet with xylanase had reduced ($P < 0.05$) fecal DM compared with sows fed the control diet. No difference was observed between sows fed experimental diets on d 20 and fecal concentrations of IDF, SDF, and TDF were not different between treatments on d 10.

DISCUSSION

Ingredients and diets composition

Sows derive more energy from fibrous feedstuffs than growing pigs due to prolonged digesta retention in the hindgut and a greater capacity to ferment fiber (Jørgensen et al., 2007), which results in beneficial effects for gestating sows (i.e., increased satiety, decreased stress, and reduced constipation; Meunier-Salaün et al., 2001). However, high inclusion of dietary fiber may reduce energy and nutrient utilization and decrease reproductive performance (Holt et al., 2006; Feyera et al., 2021); therefore, it is hypothesized that addition of xylanase in diets for sows may increase fiber fermentation and consequently will increase efficiency of energy utilization in ingredients. In this experiment, corn, soybean meal, DDGS, wheat middlings, and soybean hulls provided 30 and 21% of TDF in gestation and lactation diets, respectively, which are greater than

reported values for gestation (17 to 19%) and lactation diets (15 to 17%; Zhou et al., 2018). The majority of fiber in corn, DDGS, and wheat middlings consists of arabinoxylans (Navarro et al., 2019), and approximately 50% of dietary fiber from soybean hulls consists of hemicelluloses containing xylan polymers (Middelbos and Fahey, 2008). Xylanase hydrolyzes the backbone of xylans; therefore, feed ingredients used in this experiment provided the substrate for the xylanase enzyme.

Concentrations of DM, crude protein, amino acids, GE, starch, TDF, ash, and acid-hydrolyzed ether extract of ingredients were in agreement with reported values (NRC, 2012). The nutrient composition of diets were also in agreement with calculated values, which indicates that diet composition throughout the experiment was constant and differences among batches mixed likely was minimal. The average xylanase activity for the control diets did not exceed the detection limit (2,000 BXU/kg) and the average xylanase activity for the diets with added xylanase were 16,830 for the gestation diets and 18,640 for the lactation diets, which was in agreement with the expected values (16,000 ± 3,200 BXU/kg).

Digestibility values

Sows have greater digestibility of dietary fiber compared with growing pigs (Goff et al., 2002; Jørgensen et al., 2007; Shipman et al., 2022), but there are limited data on effects of carbohydrases in diets for gestating sows. The lack of effect of xylanase on nutrient digestibility during mid-gestation of the first cycle likely indicates that a long adaptation time is needed to demonstrate effects of xylanase as has been reported for growing pigs (Lan et al. 2017; Petry et al., 2020b).

However, the increased ATTD of DM, IDF and TDF in late gestation is in agreement with data indicating that a carbohydrase mixture in high-fibrous diets fed to gestating sows

increased ATTD of nutrients and NSP (Shipman et al., 2022). However, the observation that there was no effect of xylanase supplementation on the ATTD of GE, and concentrations of DE and ME is in contrast with reports where supplementation of xylanase improved energy concentrations in growing pigs (Abelilla and Stein., 2019; Petry et al., 2020a).

The greater ATTD of DM, GE, IDF, and TDF, and greater DE in lactation that was observed for sows fed the xylanase diets is in agreement with data indicating that addition of xylanase in lactation diets increased digestibility of DM, CP, energy, and NSP (de Souza et al., 2007; Cozannet et al., 2018; Zhou et al., 2018). Xylanase may enhance the fermentation of fiber by hydrolyzing the arabinoxylan backbone to release monosaccharides and oligosaccharides (e.g., xylooligosaccharides; Pedersen et al., 2015b). The smaller fiber fractions produced by xylanase are more fermentable and soluble; therefore, the fermentation of insoluble dietary fiber fragments is also enhanced (Adeola and Cowieson, 2011). Xylanase may degrade the physical fiber matrix, which releases trapped nutrients, and therefore, increasing the access of endogenous digestive enzymes to these nutrients (De Lange et al., 2010). Xylanase may also mitigate the negative physiochemical properties of fiber (e.g., decrease digesta viscosity; Raza et al., 2019), which can increase nutrient and energy digestibility (De Vries et al., 2012; Gonzalez-Ortiz et al., 2016). Likewise, xylanase may act as a "stimbiotic", which stimulates a fiber-degrading microbiome resulting in an increase in fiber fermentability even though the additive itself contributes little to short chain fatty acid production (González-Ortiz et al., 2019). Xylooligosaccharides that may be the result of xylanase action on arabinoxylans may act as prebiotics that change the composition of the substrate that hindgut microbiota can access, and this causes a shift in the population that causes pathogenic bacteria to starve (Bedford and Cowieson, 2012; Tiwari et al., 2020); therefore, xylanase promotes proliferation of microbiota

that degrade arabino-xylooligosaccharides, and subsequently increases production of SCFA (Bautil et al., 2020; Cho et al., 2020). Improvements in digestibility of DM, energy, and concentrations of DE observed in this experiment are likely due to hydrolysis of insoluble fiber, and possibly because of the combination of the mechanisms of action working simultaneously to hydrolyze dietary fiber directly or indirectly.

The reason the digestibility of IDF and TDF did not increase in sows fed diets with xylanase during the second gestation period although differences in digestibility of GE and DM were observed likely is that xylanase may have release non-fiber nutrients that may have been trapped in the fiber matrix. Those nutrients subsequently increased DE of the diet.

Sow performance

Gestating sows were fed limited amount of feed according to the visual assessment of body condition of sows to prevent excessive body weight gain (de Leeuw et al., 2008). The observation that sows body weight and feed intake during gestation in both reproductive cycles did not differ when xylanase was added to the diet indicates that xylanase did not release sufficient energy to impact these parameters.

Lactating sows generally mobilize body reserves to sustain milk production because of insufficient intake of energy and nutrients (Lawlor and Lynch, 2007). The observation that feed intake, body weight loss, and estimated milk yield was not different between treatments in the first lactation is in agreement with results from other experiments with lactating sows fed a carbohydrase (Walsh et al., 2012; Zhe et al., 2022). However, results of this experiment were in contrast with results reported by Cozannet et al. (2018), Zhou et al. (2018), and Lee et al. (2019) who reported that xylanase reduced body weight loss of sows during lactation.

Heat stress may increase sow body weight loss (Spencer et al., 2003), which was likely the reason for the observed body weight loss in the first cycle of 18 kg in sows fed the control diet and 15 kg in sows fed the diet with xylanase. In contrast, the observed body weight loss in the second cycle was 3 to 4 kg, indicating that sows were not heat stressed.

The observation that sows fed the xylanase diet had decreased feed intake in week 3 of lactation during the second cycle is in contrast with data indicating that added xylanase increased feed intake during lactation (Walsh et al., 2012; Zhou et al., 2018). This observation is likely due to sows being adapted to consuming increased amounts of dietary fiber, and xylanase was able to increase fermentation of fiber with subsequent increase in ATP production resulting in less feed needed for sows to fulfill their energy requirement, which is supported to the greater DE concentration observed in sows fed the diet with added xylanase. Addition of NSP-hydrolyzing enzymes to sow diets has increased nutrient digestibility during lactation in a previous experiment (de Souza et al., 2007), which was also observed in both cycles of this experiment.

Excess weight loss during lactation also has been associated with longer weaning to service intervals (Trottier and Johnson, 2001). The observation that days between weaning and estrus in the first cycle were not different is likely due to the lack of differences in body weight loss in lactation and is in agreement with previous data (Walsh et al., 2012).

Litter performance

Inclusion of different fiber ingredients during gestation and lactation in sows has been associated with reduced stillbirth, increased piglet weights at birth, and increased weaning weights (Feyera et al., 2017; Jarrett and Ashworth, 2018). Indeed, Lee et al. (2019) reported that pigs from sows fed diets with carbohydrases during lactation had greater average weight gain and body weight at weaning compared with pigs from sows fed no exogenous enzymes. The

observed tendency for greater average daily gain in litters from sows fed the diet with xylanase during the first reproductive cycle is possibly due to the observed increment of DE in sows fed the diet with xylanase which resulted in extra energy available in the milk, although this effect is only observed if sows are heat stressed. However, the lack of the effect of xylanase on litter performance is in agreement with Walsh et al., (2012) and Zhou et al., (2018) indicating that supplementation of xylanase to sow diets does not impact total born and live born pigs at parturition. However, the decrease in feed intake of sows fed the diet with xylanase in the second lactation did not influence litter gain, which indicates that the decreased feed intake was caused by increased energy availability in the diet with xylanase, and the extra energy is being used to maintain body condition of the sow.

Fecal dry matter

A possible explanation for the lower DM percentage in the feces of sows fed the xylanase diet on d 10 and 20 of lactation in the first cycle is the greater concentration of SDF in the feces, because SDF has the capacity to bind water (McRorie and McKeown, 2017). Xylanase may have solubilized some of the insoluble fiber, and therefore, there were more soluble fiber fractions in the feces of sows fed xylanase.

CONCLUSIONS

Addition of xylanase to diets for gestating and lactating sows in late gestation of the first cycle increased the digestibility of DM, IDF, and TDF, and in the second cycle, xylanase increased the digestibility of DM, GE, and concentrations of DE. However, addition of xylanase increased the digestibility of DM, GE, IDF, and TDF, and concentrations of DE in lactation in both cycles, which indicates there is an opportunity to include more fibrous ingredients in diets for lactating sows with the addition of xylanase, which may decreased the diet cost for

producers. However, addition of xylanase had no effects on sow body weight changes, estimated milk yield, number of pigs per litter, or birth and weaning weights of pigs during two reproductive cycles, indicating that the energy released by the enzyme was not sufficient to impact these parameters.

Greater DE during lactation in sows fed high fiber-diet with added xylanase increased litter weight gain likely due to greater energy in the milk during summertime, when sows reduced their feed intake due to heat stress; whereas during winter time, the greater DE sows during lactation in sows fed the diet with added xylanase reduced sows feed intake indicating sows meet their requirements with less feed, resulting also in an opportunity to decreased the diet cost during lactation for producers.

More research is needed to understand the action of xylanase in diets for gestating and lactating sows, with different types of dietary fiber to enhance the action of xylanase. The performance of the reproductive sows fed a low-fiber commercial diet need to be compare with sows fed high fiber diets with added xylanase to validate the results observed in this experiment. Research to determine the mechanism of action of xylanase in sow performance in lactation is also warranted.

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FIGURE

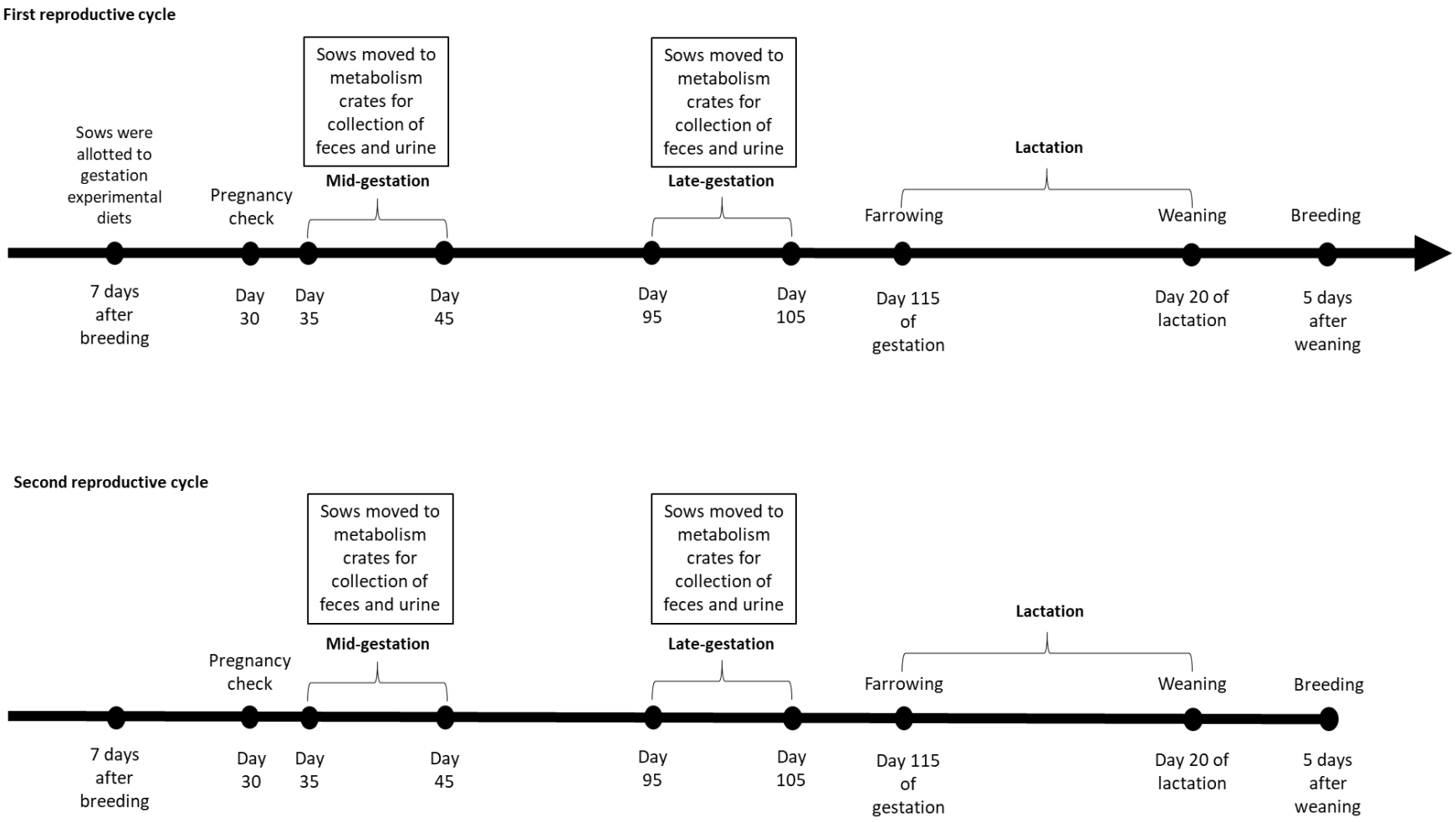

FIGURE 2. Experiment Timeline.

TABLES

Table 1. Analyzed nutrient composition of ingredients (as-fed basis)

Item	Corn	Soybean meal	Soybean hulls	Distillers dried grains with solubles	Wheat middlings
Gross energy, kcal/kg	3,868	4,191	3,928	4,475	3,976
Dry matter, %	87.62	89.58	90.74	87.31	88.65
Ash, %	1.59	6.34	4.68	6.24	4.72
Acid hydrolyzed ether extract, %	3.96	2.78	4.51	9.17	4.64
Crude protein, %	6.98	46.80	12.37	28.68	14.56
Starch, %	62.10	2.10	0.96	3.70	25.80
Insoluble dietary fiber, %	9.70	14.00	61.30	33.80	31.20
Soluble dietary fiber, %	N.D.[1]	3.40	5.70	2.40	2.60
Total dietary fiber, %	9.70	17.40	67.00	36.20	33.80
Indispensable amino acids, %					
Arg	0.42	3.24	0.59	1.29	0.96
His	0.24	1.17	0.29	0.79	0.39
Ile	0.33	2.09	0.44	1.14	0.45
Leu	0.94	3.58	0.80	3.21	0.92
Lys	0.39	2.95	0.83	0.97	0.65

Table 1. (cont.)

Met	0.19	0.62	0.14	0.54	0.23
Phe	0.42	2.37	0.48	1.22	0.58
Thr	0.33	1.78	0.43	1.13	0.49
Trp	0.07	0.62	0.07	0.17	0.13
Val	0.40	2.13	0.50	1.40	0.65
Dispensable amino acids, %					
Ala	0.59	1.98	0.50	1.89	0.70
Asp	0.70	5.18	1.13	1.73	1.06
Cys	0.18	0.65	0.22	0.55	0.33
Glu	1.66	8.57	1.48	3.55	2.70
Gly	0.35	1.95	0.91	1.10	0.78
Pro	0.66	2.17	0.57	2.01	0.81
Ser	0.41	1.97	0.62	1.25	0.55
Tyr	0.23	1.76	0.51	0.93	0.38
Minerals					
Ca, %	0.13	0.28	0.61	0.41	0.22
P, %	0.36	0.73	0.17	1.16	1.18
K, %	0.35	2.01	1.27	1.24	0.99
Mg, %	0.09	0.26	0.23	0.32	0.32
Na, %	0.04	0.01	0.03	0.34	0.01
Cu, mg/kg	3.16	10.15	8.69	31.09	5.56

Table 1. (cont.)

Zn, mg/kg	57.06	161.43	359.93	86.40	137.59
Fe, mg/kg	11.12	25.15	14.81	35.94	120.66
Mn, mg/kg	97.05	46.86	40.31	117.82	82.63

[1]N.D. = Not detected.

Table 2. Ingredient composition of experimental diets, as-fed basis

Ingredient, %	Gestation		Lactation	
	Control	Xylanase[1]	Control	Xylanase
Corn	35.18	30.18	54.76	49.76
Soybean meal	6.00	6.00	20.00	20.00
Soybean hulls	15.00	15.00	10.00	10.00
Distillers dried grains with solubles	20.00	20.00	-	-
Wheat middlings	20.00	20.00	10.00	10.00
Soybean oil	1.00	1.00	1.50	1.50
Econase XL premix[2]	-	5.00	-	5.00
Calcium carbonate	1.40	1.40	0.80	0.80
Dicalcium phosphate	0.35	0.35	1.40	1.40
L-Lysine HCl	0.17	0.17	0.19	0.19
L-Threonine	-	-	0.05	0.05
Titanium dioxide	-	-	0.40	0.40
Sodium chloride	0.40	0.40	0.40	0.40
Vitamin-mineral premix[3]	0.50	0.50	0.50	0.50

[1]Xylanase = Econase XL; AB Vista, Marlborough, UK.

[2]The Econase-XL premix contained 320,000 BXU/kg of exogenous xylanase (0.1 kg containing 160 million BXU/kg was mixed with 49.9 kg of ground corn). At 5% inclusion, the final diets were expected to contain 16,000 BXU/kg of xylanase. BXU is the amount of enzyme that will

Table 2. (cont.)

release 0.06 micromoles of reducing sugars (xylose equivalents) from birch xylan per min at pH 5.3 and 50°C.

[3]The vitamin-mineral premix provided the following quantities of vitamins and micro-minerals per kilogram of complete diet: Vitamin A as retinyl acetate, 11,136 IU; vitamin D3 as cholecalciferol, 2,208 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride,0.24 mg; vitamin B12, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 126 mg as ferrous sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese hydroxychloride; Se, 0.3 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc hydroxychloride.

Table 3. Analyzed composition of experimental diets, as-fed basis

Item	Gestation		Lactation	
	Control	Xylanase[1]	Control	Xylanase
Gross energy, kcal/kg	3,939	3,975	3,846	3,840
Dry matter, %	88.01	88.24	88.01	87.90
Ash, %	5.59	5.67	5.34	5.64
Acid hydrolyzed ether extract, %	5.55	5.65	4.22	3.87
Crude protein, %	16.11	16.19	15.71	15.88
Starch, %	29.90	28.20	36.90	38.60
Insoluble dietary fiber, %	26.90	27.10	20.60	18.50
Soluble dietary fiber, %	3.20	2.80	1.40	1.60
Total dietary fiber, %	30.10	29.90	22.00	20.10
Indispensable amino acids, %				
Arg	0.84	0.86	0.91	0.93
His	0.41	0.43	0.39	0.40
Ile	0.56	0.60	0.65	0.68
Leu	1.38	1.49	1.26	1.33
Lys	0.83	0.88	0.94	0.98
Met	0.26	0.26	0.22	0.23
Phe	0.68	0.73	0.74	0.77
Thr	0.57	0.60	0.61	0.60

Table 3. (cont.)

Trp	0.14	0.12	0.15	0.15
Val	0.70	0.74	0.72	0.73
Dispensable amino acids, %				
Ala	0.89	0.95	0.75	0.78
Asp	1.23	1.29	1.44	1.47
Cys	0.30	0.31	0.24	0.25
Glu	2.61	2.76	2.63	2.77
Gly	0.74	0.77	0.68	0.67
Pro	1.00	1.07	0.87	0.90
Ser	0.66	0.69	0.65	0.67
Tyr	0.50	0.54	0.50	0.52
Minerals				
Ca, %	0.84	0.85	0.66	0.67
P, %	0.77	0.73	0.69	0.74
K, %	0.87	0.86	0.84	0.80
Mg, %	0.23	0.22	0.17	0.17
Na, %	0.26	0.23	0.18	0.15
Cu, mg/kg	51.95	36.22	22.04	23.41
Zn, mg/kg	267.23	253.73	204.90	200.33
Fe, mg/kg	97.12	95.96	63.52	69.71

Table 3. (cont.)

Mn, mg/kg	197.46	202.02	138.39	132.35
Xylanase activity, BXU[2]/kg	<2,000	16,830	<2,000	18,640

[1]Xylanase = Econase XL; AB Vista, Marlborough, UK.

[2]BXU is the amount of enzyme that will release 0.06 micromoles of reducing sugars (xylose equivalents) from birch xylan per min at pH 5.3 and 50°C. All batches of all diets (10 for gestation and 5 for lactation) were analyzed. None of the control batches exceeded the detection limit (2,000 BXU/kg). Values for the xylanase diets are averages of all analyzed batches of each diet.

Table 4. Performance of sows fed experimental diets during the first reproductive cycle[1]

Item	Diet		SEM	*P*-value
	Control	Xylanase[2]		
Parity	2.29	2.08	0.34	0.660
Body weight, kg				
Day 7 after breeding	194.3	195.8	5.38	0.839
Day 35 gestation	209.0	211.4	5.32	0.705
Day 45 gestation	220.2	218.6	5.87	0.832
Day 95 gestation	233.6	236.6	5.48	0.600
Day 105 gestation	249.2	246.5	5.36	0.653
At farrowing	223.7	225.7	4.36	0.740
At weaning	205.8	211.2	4.82	0.438
Feed intake, kg				
Day 1 to day 34, gestation	66.50	66.74	1.00	0.865
Day 35 to day 44, gestation	28.46	28.46	1.15	0.994
Day 45 to day 95, gestation	92.69	92.68	0.47	0.325
Day 96 to 105, gestation	30.77	30.61	1.30	0.806
Day 106 to 115, gestation	21.70	22.13	1.98	0.226
Total, gestation	240.12	240.37	3.05	0.838
Week 1, lactation	24.44	25.03	1.22	0.155
Week 2, lactation	40.43	40.61	0.58	0.681

Table 4 (cont.)

Week 3, lactation	43.16	42.77	1.97	0.718
Total, lactation	108.03	108.41	1.38	0.794
Body weight loss during lactation	17.85	14.54	2.43	0.265
Days between weaning and estrus	5.95	5.90	0.17	0.832
Estimated total milk yield[3], kg	176.85	190.35	14.64	0.307
Estimated daily milk yield, kg	8.57	9.17	0.78	0.323

[1]Data are means of 24 observations.

[2]Xylanase = Econase XL; AB Vista, Marlborough, UK.

[3]Estimated milk yield was calculated as 4 g milk per 1 g of litter body weight gain (Close and Cole, 2000).

Table 5. Performance of litters from sows fed experimental diets during the first reproductive cycle[1]

Item	Diet		SEM	*P*-value
	Control	Xylanase[2]		
Pigs per litter, n				
Total born	15.83	15.08	1.02	0.477
Born alive	14.75	14.08	0.83	0.515
After cross-fostering	13.13	12.50	0.56	0.082
Still born	0.88	0.83	0.28	0.908
Mummified	0.21	0.21	0.12	1.000
Weaned	11.79	11.50	0.63	0.558
Litter weight, kg				
Total at birth	21.32	19.35	1.18	0.079
After cross-fostering	19.64	17.63	1.08	0.031
At weaning	63.85	65.22	4.29	0.713
Litter average daily gain[3], kg	2.08	2.36	0.18	0.062
Individual pig weight, kg				
Live at birth	1.72	1.54	0.09	0.094
At weaning	5.45	5.66	0.16	0.247
Survival[4], %	90.35	91.92	3.47	0.685

[1]Data are means of 24 observations.

[2]Xylanase = Econase XL; AB Vista, Marlborough, UK.

Table 5. (cont.)

[3]Litter weight after cross-fostering was included as a covariate.

[4]Survival was calculated as the percentage of weaned pigs divided by the live born pigs after adjusting for cross fostering × 100.

Table 6. Performance of sows fed experimental diets during the second reproductive cycle[1]

Item	Diet		SEM	*P*-value
	Control	Xylanase[2]		
Parity	2.58	2.73	0.28	0.721
Body weight, kg				
Day 7 after breeding	186.98	189.85	4.07	0.594
Day 35 gestation	191.30	193.94	4.69	0.647
Day 45 gestation	192.89	193.91	4.73	0.855
Day 95 gestation	211.13	213.41	3.90	0.688
Day 105 gestation	219.84	220.00	4.75	0.980
At farrowing	206.06	208.75	3.83	0.631
At weaning	202.46	204.11	3.83	0.767
Feed intake, kg				
Days from weaning to day 1	21.11	21.15	0.03	0.381
Day 1 to d 34, gestation	62.38	62.24	1.05	0.911
Day 35 to day 44, gestation	23.05	23.12	0.50	0.917
Day 45 to day 95, gestation	111.77	110.96	6.11	0.899
Day 96 to 105, gestation	33.66	35.28	1.63	0.208
Day 106 to 115, gestation	27.00	28.02	1.24	0.103
Total, gestation	278.86	280.99	6.81	0.794
Week 1, lactation	30.35	30.57	2.18	0.622

Table 6 (cont.)

Week 2, lactation	49.13	48.10	2.10	0.237
Week 3, lactation	51.08	48.11	3.66	0.021
Total, lactation	130.57	126.75	5.12	0.078
Body weight loss during lactation	3.56	4.67	1.76	0.649
Days between weaning and estrus	5.48	5.95	0.17	0.052
Estimated total milk yield[3] , kg	203.68	200.31	7.19	0.703
Estimated daily milk yield, kg	9.84	9.73	0.35	0.777

[1]Data are means of 24 observations for the control treatment and 22 observations for the xylanase treatment.

[2]Xylanase = Econase XL; AB Vista, Marlborough, UK.

[3]Estimated milk yield was calculated as 4 g milk per 1 g of litter body weight gain (Close and Cole, 2000).

Table 7. Performance of litters from sows fed experimental diets during the second reproductive cycle[1]

Item	Diet		SEM	*P*-value
	Control	Xylanase[2]		
Pigs per litter, n				
Total born	14.32	15.14	0.89	0.472
Born alive	13.78	14.39	0.75	0.553
After cross-fostering	11.94	12.28	0.49	0.260
Still born	0.45	0.52	0.18	0.775
Mummified	0.07	0.24	0.10	0.247
Weaned	11.30	11.54	0.51	0.528
Litter weight, kg				
Total at birth	17.48	17.72	0.88	0.841
After cross-fostering	15.22	15.35	0.80	0.878
At weaning	66.07	65.54	2.43	0.842
Litter average daily gain, kg	2.46	2.43	0.09	0.777
Individual pig weight, kg				
Live at birth	1.27	1.25	0.05	0.730
At weaning	5.85	5.71	0.18	0.412
Survival[3], %	94.68	93.99	1.78	0.777

[1]Data are means of 24 observations for the control treatment and 22 observations for the xylanase treatment.

Table 7. (cont.)

[2]Xylanase = Econase XL; AB Vista, Marlborough, UK.

[3]Survival was calculated as the percentage of weaned pigs divided by the live born pigs after adjusting for cross fostering × 100.

Table 8. Apparent total tract digestibility (ATTD) of dry matter (DM) and gross energy (GE), and concentrations of digestible energy (DE) and metabolizable energy (ME) in experimental diets fed to sows during the first reproductive cycle[1]

Item	Diet		SEM	*P*-value
	Control	Xylanase[2]		
Mid-gestation (i.e., d 35 to 45)				
DM intake, kg/d	2.36	2.40	0.04	0.427
DM fecal output, kg/d	0.37	0.38	0.02	0.639
ATTD of DM, %	84.11	84.10	0.58	0.977
GE intake, kcal/d	10,585	10,775	189.91	0.427
GE fecal output, kcal/d	1,609	1,638	77.52	0.653
GE urine output, kcal/d	293	276	36.26	0.518
ATTD of GE, %	84.79	84.81	0.56	0.961
DE, kcal/kg	3,355	3,356	22.44	0.961
ME, kcal/kg	3,246	3,255	31.34	0.616
Late-gestation (i.e., d 95 to 105)				
DM intake, kg/d	2.57	2.58	0.05	0.844
DM in fecal output, kg/d	0.44	0.40	0.02	0.016
ATTD of DM, %	82.88	84.36	0.68	0.028
GE intake, kcal/d	11,518	11,572	240.15	0.844
GE fecal output, kcal/d	1,895	1,795	66.05	0.083

Table 8 (cont.)

GE urine output, kcal/d	307	334	20.27	0.292
ATTD of GE, %	83.54	84.37	0.65	0.142
DE, kcal/kg	3,306	3,338	25.82	0.142
ME, kcal/kg	3,199	3,224	30.88	0.300
Lactation				
ATTD of DM, %	81.41	83.25	0.50	<0.001
ATTD of GE, %	80.74	82.82	0.63	<0.001
DE, kcal/kg	3,103	3,183	24.26	<0.001

[1]Data are means of 24 observations.

[2]Xylanase = Econase XL; AB Vista, Marlborough, UK.

Table 9. Apparent total tract digestibility (ATTD) of insoluble dietary fiber (IDF), soluble dietary fiber (SDF) and total dietary fiber (TDF) in experimental diets fed to sows during the first reproductive cycle[1]

Item	Diet		SEM	*P*-value
	Control	Xylanase[2]		
Mid-gestation (i.e., d 35 to 45)				
IDF intake, kg/d	0.72	0.74	0.01	0.427
IDF fecal output, kg/d	0.18	0.19	0.01	0.153
ATTD of IDF, %	75.09	73.73	1.10	0.176
SDF intake, kg/d	0.08	0.08	0.01	0.427
SDF fecal output, kg/d	0.01	0.02	0.01	0.381
ATTD of SDF, %	82.23	81.31	1.75	0.493
TDF intake, kg/d	0.80	0.82	0.01	0.427
TDF fecal output, kg/d	0.19	0.21	0.01	0.151
ATTD of TDF, %	75.81	74.49	1.06	0.172
Late-gestation (i.e., d 95 to 105)				
IDF intake, kg/d	0.79	0.80	0.01	0.844
IDF fecal output, kg/d	0.22	0.17	0.01	< 0.001

Table 9. (cont.)

ATTD of IDF, %	71.86	78.11	1.70	< 0.001
SDF intake, kg/d	0.09	0.09	0.01	0.844
SDF fecal output, kg/d	0.01	0.01	0.01	0.968
ATTD of SDF, %	83.46	83.53	0.88	0.954
TDF intake, kg/d	0.87	0.88	0.01	0.844
TDF fecal output, kg/d	0.23	0.19	0.01	< 0.001
ATTD of TDF, %	73.01	78.65	1.53	< 0.001
Lactation				
ATTD of IDF, %	62.99	67.74	0.89	< 0.001
ATTD of SDF, %	68.52	63.29	5.85	0.136
ATTD of TDF, %	63.38	67.43	1.05	0.001

[1]Data are means of 24 observations.

[2]Xylanase = Econase XL; AB Vista, Marlborough, UK.

Table 10. Apparent total tract digestibility (ATTD) of dry matter (DM) and gross energy (GE), and concentrations of digestible energy (DE) and metabolizable energy (ME) in experimental diets fed to sows during the second reproductive cycle[1]

Item	Diet		SEM	*P*-value
	Control	Xylanase[2]		
Mid-gestation (i.e., d 35 to 45)				
DM intake, kg/d	2.26	2.27	0.04	0.810
DM fecal output, kg/d	0.39	0.38	0.01	0.219
ATTD of DM, %	82.49	83.36	0.36	0.090
GE intake, kcal/d	10,142	10,207	215.83	0.810
GE fecal output, kcal/d	1,709	1,630	45.77	0.145
GE urine output, kcal/d	481	503	35.98	0.459
ATTD of GE, %	83.11	84.03	0.33	0.048
DE, kcal/kg	3,289	3,325	13.17	0.048
ME, kcal/kg	3,099	3,133	18.19	0.124
Late-gestation (i.e., d 95 to 105)				
DM intake, kg/d	2.43	2.52	0.08	0.331
DM in fecal output, kg/d	0.43	0.42	0.01	0.543
ATTD of DM, %	82.16	83.29	0.31	0.014
GE intake, kcal/d	10,907	11,326	341.62	0.330
GE fecal output, kcal/d	1,919	1,911	61.13	0.926

Table 10 (cont.)

GE urine output, kcal/d	463	469	25.03	0.855
ATTD of GE, %	82.40	83.12	0.31	0.103
DE, kcal/kg	3260	3289	12.33	0.096
ME, kcal/kg	3093	3125	15.53	0.108
Lactation				
ATTD of DM, %	81.96	83.48	0.35	0.004
ATTD of GE, %	81.48	82.74	0.41	0.031
DE, kcal/kg	3,131	3,180	15.91	0.031

[1]Data are means of 24 observations for the control treatment and 22 observations for the xylanase treatment.

[2]Xylanase = Econase XL; AB Vista, Marlborough, UK.

Table 11. Apparent total tract digestibility (ATTD) of insoluble dietary fiber (IDF), soluble dietary fiber (SDF), and total dietary fiber (TDF) in experimental diets fed to sows during the second reproductive cycle[1]

Item	Diet		SEM	*P*-value
	Control	Xylanase[2]		
Mid-gestation (i.e., d 35 to 45)				
IDF intake, kg/d	0.69	0.70	0.01	0.810
IDF fecal output, kg/d	0.19	0.18	0.01	0.206
ATTD of IDF, %	72.64	74.04	0.73	0.177
SDF intake, kg/d	0.08	0.08	0.01	0.810
SDF fecal output, kg/d	0.01	0.01	0.01	0.858
ATTD of SDF, %	84.00	83.69	1.78	0.835
TDF intake, kg/d	0.77	0.77	0.01	0.810
TDF fecal output, kg/d	0.20	0.19	0.01	0.252
ATTD of TDF, %	73.71	75.11	0.72	0.170
Late-gestation (i.e., d 95 to 105)				
IDF intake, kg/d	0.74	0.77	0.02	0.332
IDF fecal output, kg/d	0.21	0.23	0.01	0.204

Table 11. (cont.)

ATTD of IDF, %	71.45	70.48	0.97	0.306
SDF intake, kg/d	0.08	0.09	0.01	0.332
SDF fecal output, kg/d	0.01	0.01	0.01	0.107
ATTD of SDF, %	84.42	87.28	1.19	0.091
TDF intake, kg/d	0.83	0.86	0.02	0.332
TDF fecal output, kg/d	0.23	0.24	0.01	0.281
ATTD of TDF, %	72.74	72.18	0.86	0.534
Lactation				
ATTD of IDF, %	66.82	69.62	0.98	0.048
ATTD of SDF, %	58.83	63.06	3.70	0.156
ATTD of TDF, %	66.28	69.15	1.07	0.035

[1]Data are means of 24 observations for the control treatment and 22 observations for the xylanase treatment.

[2]Xylanase = Econase XL; AB Vista, Marlborough, UK.

Table 12. Fecal dry matter (**DM**), insoluble dietary fiber (**IDF**), soluble dietary fiber (**SDF**), and total dietary fiber (**TDF**) content assessment in sows fed lactation experimental diets

Item	Diet		SEM	*P*-value
	Control	Xylanase[1]		
First cycle[2]				
DM, d 1, %	61.53	60.79	1.02	0.467
DM, d 10, %	68.53	67.30	0.67	0.014
DM, d 20, %	69.16	67.87	0.42	< 0.001
IDF, %	39.04	37.73	0.92	0.141
SFD, %	2.53	3.27	0.41	0.013
TDF, %	41.57	41.00	0.64	0.487
Second cycle[3]				
DM, d 1, %	63.21	61.55	0.80	0.150
DM, d 10, %	68.47	66.44	0.86	0.017
DM, d 20, %	68.46	67.64	0.92	0.187
IDF, %	36.95	36.28	0.88	0.494
SFD, %	3.51	3.42	0.32	0.727
TDF, %	40.49	39.64	1.13	0.397

Table 12. (cont.)

[1]Xylanase = Econase XL; AB Vista, Marlborough, UK.

[2]Data are means of 24 observations.

[3]Data are means of 24 observations for the control treatment and 22 observations for the xylanase treatment.