COMPARATIVE DIGESTIBILITY OF ENERGY AND NUTRIENTS IN DIETS FED TO SOWS AND GROWING PIGS

BY

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THESIS

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ABSTRACT

It is well documented from European experiments that DE, ME, and apparent total tract digestibility (**ATTD**) of nutrients is greater in gestating sows fed close to the maintenance requirement than in growing pigs allowed ad libitum access to diets. Therefore, there is a need in North America to generate separate digestibility values for gestating sows and growing pigs as only 1 energy value is used to feed all categories of pigs. The objective of this research was to determine DE and ME values and ATTD of energy and nutrients in 11 diets fed to both growing pigs and gestating sows. Three diets were based on corn, wheat, or sorghum, and 8 diets were based on a combination of corn and soybean meal, canola meal, distillers dried grains with solubles (**DDGS**), and low-fat DDGS, corn germ meal, corn bran, wheat middlings, and soybean hulls. A total of 88 gestating sows (parity 2 to 6) and 88 growing barrows (40.1 ± 4.69 kg BW) were used and randomly allotted to the 11 diets with 8 replicate pigs per diet. Fecal and urine samples were collected for 4 d following a 19 d adaptation period. The DE, ME, and ATTD of GE, ADF, NDF, and CP in all diets were calculated. Gestating sows had greater ($P < 0.05$) ATTD of GE and CP, and DE values (as-fed and DM basis) for all diets compared with growing pigs. Gestating sows also had greater ($P < 0.05$) ME values (as-fed and DM basis) for the 3 grain diets and the diets containing soybean meal, canola meal, and DDGS than growing pigs. No differences were observed in ATTD of ADF and NDF between gestating sows and growing pigs for any of the diets. The ATTD of GE and CP, and DE values in gestating sows may be predicted from the values obtained in growing pigs. Results of this research indicate that apparent digestibility values of CP and GE obtained in gestating sows are greater than values obtained in growing pigs, but apparent digestibility of fiber obtained in growing pigs is not different from digestibilities in gestating sows.

Keywords: energy, digestibility, gestation, growing pigs, fiber, pigs

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CHAPTER 1: INTRODUCTION

Sows have greater apparent total tract digestibility (**ATTD**) of several nutrients compared with growing pigs (Fernandez et al., 1986). Digestible energy and ME values of diets and feed ingredients are dependent on the physiological stage/BW of the animal and/or feeding level, but increased ATTD also results in greater DE and ME of diets (Shi and Noblet, 1993; Shi and Noblet, 1994). Total tract digestibility of all nutrients, except starch, is improved with increased BW and this variation is most important for fiber-rich diets (Noblet and Shi, 1994). Sows are able to better ferment fiber in fiber rich ingredients because they have a larger digestive tract than growing pigs (Fernandez et al., 1986; Shi and Noblet, 1993; Le Goff and Noblet, 2001). Greater digestibility of energy and OM in sows is largely explained by the greater ability of sows to ferment fiber compared with growing pigs (Shi and Noblet, 1993).

Although it is well documented from European experiments that DE, ME, and ATTD of GE and nutrients is greater in gestating sows fed close to their maintenance requirement than in growing pigs allowed ad libitum access to their diets, no data from North America for the comparative ATTD of energy and nutrients, have been reported. As use of high-fiber ingredients increases in the United States, such values are needed to accurately formulate diets for growing pigs and sows. Therefore, the objective of this research was to test the hypothesis that values for the ATTD of energy and nutrients and the DE and ME of diets are greater in gestating sows than in growing pigs.

LITERATURE CITED

Fernandez, J. A., H. Jorgensen, and A. Just. 1986. Comparative digestibility experiments with growing pigs and adult sows. Anim. Prod. 43:127-132.

Le Goff, G., and J. Noblet. 2001. Comparative total tract digestibility of dietary energy and nutrients in growing pigs and adult sows. J. Anim. Sci. 79:2418-2427.

Noblet, J., and Shi, X. S. 1994. Effect of body weight on digestive utilization of energy and nutrients of ingredients and diets in pigs. Livest. Prod. Sci. 37: 323-338.

Shi, X. S., and J. Noblet. 1993. Digestible and metabolizable energy values of ten feed ingredients in growing pigs fed ad libitum and sows fed at maintenance level; comparative contribution of the hindgut. Anim. Feed Sci. Technol. 42: 223-236.

Shi, X. S., and J. Noblet. 1994. Effect of body weight and feed composition on the contribution of hindgut digestion of energy and nutrients in pigs. Livest. Prod. Sci. 38:225-235.

CHAPTER 2: COMPARATIVE DIGESTIBILITY OF ENERGY AND NUTRIENTS IN GROWING PIGS AND GESTATING SOWS: A LITERATURE REVIEW

INTRODUCTION

The apparent total tract digestibility (**ATTD**) of CP is greater in gestating sows than in growing pigs (Noblet and Shi, 1993) and values for standardized ileal digestibility (**SID**) of CP and most AA are also greater in gestating sows than in growing pigs (Stein et. al., 2001). Gestating sows also have greater ATTD of ether extract (**EE**) than growing pigs (Fernandez et. al., 1986; Noblet and Shi, 1993; Shi and Noblet, 1993; Shi and Noblet, 1994; Le Goff and Noblet, 2001).

Digestion of starch is efficient in both gestating sows and growing pigs and starch in most feed ingredients is almost completely digested before the end of the small intestine (Stein and Bohlke, 2007; Serena et. al., 2008; NRC, 2012). There is, therefore, no difference between gestating sows and growing pigs in the digestion of starch. However, the ATTD of NDF and ADF is greater in gestating sows than in growing pigs (Noblet and Shi, 1993) and the ATTD of NDF is greater than the ATTD of ADF for both sows and growing pigs (Le Goff and Noblet, 2001).

There are several reasons for the increased ATTD of CP, AA, EE, and fiber in gestating sows compared with growing pigs, but increased ATTD also results in greater DE and ME of diets (Shi and Noblet, 1993; Shi and Noblet, 1994). Therefore, European energy systems use greater values for the energy concentration in feed ingredients and diets for gestating sows than for growing pigs (Sauvant et. al., 2004). However, in North

America, only 1 energy value is used for ingredients and diets fed to all categories of pigs, although it is acknowledged that diets would be more accurately formulated if separate values for gestating sows and growing pigs were used (NRC, 2012). There is, therefore, a need for generating separate digestibility values for gestating sows and growing pigs.

FACTORS INFLUENCING DIGESTIBILITY AND FERMENTABILITY

Body Weight

Organ growth in swine follows a sigmoidal curve with respect to time because there is a close relationship between time and BW (Bridges et al., 1988; Brunsgaard, 1997). Organ growth is a continuous process from conception to maturity and increases with overall growth of the pig (Bridges et al., 1988). Research by Landgraf et al. (2006) evaluated 6 different BW of growing pigs (20 kg, 30 kg, 60 kg, 90 kg, 120 kg, and 140 kg) for development of carcass, organs, and body tissues during growth. As BW increased from 20 to 140 kg, weight of the intestinal tract increased from 1.37 to 6.28 kg indicating that as BW increases, overall weight of the digestive tract also increases. There is also a correlation between increased tissue weight of the small intestine (**SI**) and increased BW (Brunsgaard, 1997). As a consequence, the intestinal tract of an adult sow is larger and more developed than that of a growing pig (Bridges et al., 1986). However, as BW increased from 20 to 140 kg, the relative weight of the intestinal tract decreased from 6.85% of BW to 4.5% of BW indicating that BW and weight of the intestinal tract do not increase at the same rate (Doornenbal and Tong, 1981; Landgraf et al., 2006).

Hindgut Development

The length of the SI increases rapidly during early life of a pig and reaches its mature length, 16 to 21 m, by 5½ months (McCance, 1974). The SI develops earlier than the large intestine (**LI**) because pigs need a mature system of nutrient absorption at an early age (Moughan et al., 1990).

The length of the LI increases less rapidly than the length of the SI and continues to increase for several years (McCance, 1974; Brunsgaard, 1997). There is also a correlation between BW and tissue weight of the LI (Brunsgaard, 1997). As a consequence, tissue weights of the cecum, proximal colon, and distal colon increase with BW, which indicates that the LI is more developed in adult pigs than in growing pigs (Brunsgaard, 1997). Due to the increased size of the LI, adult pigs also have greater intestinal volume (Dierick et al., 1989).

Microbial Mass

Due to greater intestinal volume, residence time of ingesta is assumed to be longer in adult sows than in growing pigs (Varel, 1987; Low, 1993). Transition time of digesta is much slower through the LI than through the SI (Varel, 1987; Low, 1993). A result of the slow passage rate of digesta through the large intestine is that it supports extensive fermentation of fiber and encourages bacterial growth (Varel, 1987; Mosenthin, 1998). Fermentation in the large intestine is carried out by a diverse population of obligate anaerobic bacteria and some aerobic and facultative microorganisms (Mosenthin, 1998). The most dominant bacteria are: *Prevotella ruminicola, Selenomonas ruminantium, Butyrivibrio fibrisolvens, Lactobacillus acidophilus, Peptostreptococcus productus, and*

Eubacterium aerofaciens (Mosenthin, 1998). These bacteria and microorganisms ferment undigested feed components and endogenous secretions in the LI (Mosenthin, 1998). High concentrations of fiber increase the number of cellulolytic bacteria in the LI and this increase is similar for adult sows and growing pigs (Varel, 1987). However, age of the pig affects the population of microorganisms in the LI (Varel, 1987) and the number of cellulolytic bacteria in the hindgut of adult sows is 6.7 times greater than in growing pigs, indicating a correlation between increased microbial mass and increased intestinal volume (Varel, 1987). This difference may contribute to the increased fermentation of cellulosic material in adult sows compared with growing pigs (Varel, 1987).

Final microbial fermentation products are VFA, which include acetate, propionate, and butyrate (Varel, 1987; Mosenthin, 1998). Volatile fatty acids may provide from 5 to 30% of the maintenance energy requirements of pigs and even more for adult sows (Varel, 1987; Mosenthin, 1998). These fatty acids also provide energy for the LI and are important for maintaining the morphological and functional integrity of the colonic epithelium (Mosenthin, 1998).

Feeding Frequency

A major difference between growing pigs and adult gestation sows is the method of feeding. Growing pigs are usually allowed ad libitum intake of feed, whereas gestating sows are fed a restricted amount of diet (McGlone and Pond, 2003). A reduction in feeding level in growing animals or in sows is associated with increased digestibility of energy, CP, fiber, and EE (Cunningham et al., 1962; Everts et al., 1986; Shi and Noblet, 1993). These results indicate that digestibility is related to the level of feeding. Feeding levels do not greatly affect digestibility of AA in the SI of growing pigs (Haydon et al., 1984; Motor and Stein, 2004) although endogenous losses of AA per kg DMI are increased if feed intake is reduced (Stein et al., 1999; Moter and Stein, 2004). If sows and growing pigs are fed at similar levels, there are no significant differences in digestibility of AA (Everts et al., 1986; Stein et al., 2001). If growing pigs and lactating sows are allowed ad libitum access to feed, no differences between growing pigs and lactating sows are observed and values for SID of AA obtained in growing pigs are also representative for lactating sows (Stein et al., 2001). However, growing pigs given free access to feed have reduced ATTD for DM and GE compared with growing pigs fed restricted (Chastanet et al., 2007). In contrast, the ileal digestibility is not affected by level of feed intake if feed intake is greater than 3 times the maintenance requirement for ME (Chastanet et al., 2007). A reduction in feeding level is usually associated with an increased retention time of nutrients in the digestive tract, which is the reason for the increased digestibility of DM and GE (Everts et al., 1986).

Rate of Passage

The mean retention time of feed increases along the gastrointestinal tract averaging 1 h from mouth to proximal duodenum, 4 h from the proximal duodenum to the distal ileum, and 35 h from the distal ileum to fecal excretion (Wilfart et al., 2007). The length of time that feed remains in the digestive tract of pigs, and therefore is exposed to enzymatic and bacterial action, is greater when feed intake is reduced and increases with age (Cunningham et al., 1962; Fernandez et.al., 1986). The residence time of ingesta in adult pigs is presumed to be longer because of the large size of the intestinal tract, which may result in more extensive fermentation (Varel, 1987). Adult animals have reduced feed intake per unit of BW, a slower digestive transit, and, because of their size, greater intestinal volume (Dierick et al., 1989). Hindgut fermentation may supply 15 to 20% of DE for growing pigs, and this proportion may be enhanced when low feeding levels are applied (Shi and Noblet, 1993). This indicates that not only is fermentation affected by the stage of growth, but it is also affected by the level of feeding, as more feed causes the rate of passage to increase, which in turn results in less time for microbial action, and therefore, less complete fermentation and reduced production of VFA.

Digestive Capacity

Apparent total tract N digestibility in growing pigs increases with age and total tract N digestibility coefficients in sows appear to be greater than in growing pigs (Roth and Kirchgessner, 1984; Fernandez et al., 1986; Noblet and Shi, 1993; Shi and Noblet, 1993b; Etienne et al., 1997). When fed diets containing different levels of protein and AA, sows also had greater ($P < 0.05$) ATTD of protein compared with growing pigs (Stein et al., 1999).

Digestibility of fat increased with time in growing pigs (Azain, 2001), which may imply that sows have greater digestibility of fat compared with growing pigs. This theory was supported in a study where digestibility of fat by gestating sows was increased by 25% compared with growing pigs (Noblet and Shi, 1993). This increase is due to a difference in feeding level between the sows and growing pigs because sows were fed restricted and growing pigs were allowed ad libitum access to feed (Noblet and Shi, 1993).

Carbohydrate components such as sugars, oligosaccharides, starch, and nonstarch polysaccharides (**NSP**) are digested and absorbed at different sites and rates in the gastrointestinal tract (Bach Knudsen, 2005; Bach Knudsen et al., 2006). Most of the disaccharides and starch are hydrolyzed in the SI and the resulting monosaccharides are absorbed. However, disaccharides and NSP are not digested by endogenous enzymes in the SI and will pass to the LI (Bach Knudsen and Jorgensen, 2001). Nonstarch polysaccharides and lignin make up the fiber fraction of feed and limit-fed gestating sows derive more energy from fibrous feedstuffs than growing pigs allowed ad libitum access to feed (Grieshop et al., 2001).

High feed intake can diminish the efficiency of digestion as it increases rate of passage (Fernandez et al., 1986). The length of time that feed remains in the digestive tract of pigs where it is exposed to enzymatic and bacterial action is greater and digestibility of energy, CP, and DM is significantly increased in growing pigs when feed intake is reduced to the maintenance level (Cunningham et al., 1962).

Absorptive Capacity

In pigs, most available nutrients (AA, sugars, fats, minerals, and vitamins) are absorbed in the SI, whereas in the LI, undigested feed components (dietary fiber and insoluble proteins) and endogenous secretions are fermented by micro-organisms (Wenk, 2001). With an increase in dietary fiber, there is a significant increase in flow of nutrients or rate of passage through the intestinal tract (Wenk, 2001; Serena et al., 2008). The longer feed remains in the digestive tract of pigs, the more nutrients they are able to absorb in both the small and large intestine (Cunningham et al., 1962; Fernandez et al., 1986). As feed intake is increased, rate of passage increases, and absorption of nutrients is decreased (Cunningham et al., 1962). This indicates that it is possible to overwhelm or decrease the absorptive capacity of pigs by increasing feed intake.

Fermentative Capacity

Sows have greater ability to ferment high fiber ingredients than growing pigs (Cunningham et al., 1962; Fernandez et al., 1986) and as age of the pig increases, there is a larger contribution of the hindgut to total tract digestibility (Shi and Noblet, 1993). The largest differences in digestibility between sows and growing pigs are encountered in feed ingredients with low digestibility like cereal by-products and roughages, which indicate that the largest part of the differences is a result of greater hindgut activity or fermentation of sows than in growing pigs (Fernandez et al., 1986). Sows and growing pigs differ significantly in their ability to digest or ferment fiber at the hindgut level with hindgut digestibility of fiber roughly 25% greater in sows than growing pigs (Shi and Noblet, 1993). However, even when pigs are able to digest fiber, the available energy from this process is low compared with the energy that can be obtained from starch, fat, and CP (Shi and Noblet, 1993).

Both sows and pigs fed a higher fiber diet have greater cellulolytic activity than animals fed a low fiber diet indicating that high fiber diets can modify the microflora in the large intestine as well as bacterial metabolism in the LI (Varel, 1987). It is, therefore likely that microbes are not overwhelmed as the amount of fiber in the diet is increased, although the effectiveness of microbial fermentation may be reduced if feed intake is increased (Cunningham et al., 1962; Fernandez et al., 1986).

Adaptation to Diets

Results of some studies indicate that pigs adapt to longer periods of feeding fibrous material through an increase in fermentation, but in other studies, no effect of feeding period was observed (Cunningham et al., 1962; Gargallo and Zimmerman, 1981; Wenk, 2001). As an example, pigs fed diets containing purified cellulose for 15 weeks did not ferment the cellulose better than pigs receiving the diet for 1 week (Cunningham et al., 1962). However, Gargallo and Zimmerman (1981) concluded from several experiments that growing pigs fed varying levels of purified cellulose had an increase in digestibility partly due to progressive adaptation to the cellulose. Measurements of length and weight of digestive tract organs are often increased with increased levels of fiber in the diet (Nielson, 1962; Kass et al., 1980; Jorgensen et al., 1985; Stanogias and Pearce, 1985) because the microbial population adapts to substrates entering the caecum and colon and the population is increased after prolonged feeding of high-fiber diets (Varel et al., 1984; Mosenthin, 1998). This effect appears to be dependent of fiber source (Mosenthin, 1998) however; adult sows still have a greater number of microbes than growing pigs regardless of microbial adaptation (Varel et al., 1987).

Range of adaptation to diets varies among studies but does not appear to have an effect on differences in digestibility between sows and growing pigs. Sows still had greater total digestibility of nutrients than growing pigs whether adapted for 5 days (Fernandez et al., 1986), 10 days (Le Goff and Noblet, 2001), 12 days (Shi and Noblet, 1993 a&b; Noblet and Shi, 1993), or 17 days (Noblet and Shi, 1993).

Negative Effects of Fiber

Increasing the level of feeding through an increase in dietary fiber can have a negative effect on digestibility of other nutrients and many increase endogenous losses of nutrients (Cunningham et al., 1962; Fernandez et al., 1986; Roth and Kirchgessner, 1984). Reduction in energy digestibility as fiber is added to the diet may be a consequence of several things: Substitution of digestible CP and carbohydrates with CP and carbohydrates bound to less-digestible cell wall components in the fiber; influence of physiochemical characteristics of the fiber on digestion and absorption; and the physiological effects of fiber on the gastrointestinal tract (Le Gall et al., 2009). There is a negative correlation between dietary fiber and digestibility of protein, DM, and energy and the reduced digestibility in a high fiber diet compared with a low fiber diet is mostly attributed to the negative effects of dietary fiber on the digestibility of other nutrients (Eggum et al., 1982, 1984; Jorgensen et al., 1995). The level of dietary fiber also influences lipid digestibility, because decreasing fat digestibility was observed as the level of dietary fiber was increased (Urriola et al., 2013).

High dietary fiber also has a negative effect on hindgut fermentation (Fernandez et al., 1986). Hindgut fermentation is sensitive to the period of time the digesta are subjected to fermentation and as the level of dietary fiber increases, so does the rate of passage, which results in a decrease in fermentation (Cunningham et al., 1962; Everts et al., 1986; Fernandez et al., 1986; Roth and Kirchgessner, 1984). Higher degradation of fibre in sows is associated with higher losses of energy as methane, which reduces the ME/DE ratio in sows compared with growing pigs (Muller and Kirchgessner, 1986; Noblet and Shi, 1993).

An increase in dietary fiber increases endogenous losses, which contributes to the observed reduction in apparent digestibility of nutrients (Noblet and Shi, 1993). Endogenous losses include mucoproteins, sloughed cells, serum albumin, digestive enzymes, amides, and ingested hair and are divided into 2 main components: basal and specific losses (Nyachoti et al., 1997a; Stein et al., 2007). Specific endogenous losses are influenced by diet ingredient composition and if feed ingredients containing fibers are fed, specific losses may contribute more than 50% of the total ileal endogenous losses (Stein et al., 2007). Endogenous CP and AA recovered from the ileal digesta are mostly from pancreatic enzymes, epithelial cells, bacterial cells, and mucin, whereas endogenous components analyzed as carbohydrates are mostly from mucin (Lien et al., 1997; Miner-Williams et al., 2009). Feeding high fiber diets results in increased salivary, gastric, biliary, pancreatic, and intestinal secretions (Taverner et al., 1981; Partridge et al., 1982; Zebrowska et al., 1983; Zebrowska and Low, 1987; Dierick et al., 1989; Low, 1989), which contribute to endogenous losses. Higher fiber content also affects intestinal epithelial cell proliferation through an increase in programmed cell death (Jin et al., 1994; Howard et al., 1995). Based on this information, there will be an increase in endogenous loss through an increase in sloughed cells due to cell death.

Levels and types of antinutritional factors induce specific endogenous losses and decrease apparent digestibility (Stein et al, 2007). Examples of major naturally occurring antinutritional factors include trypsin inhibitors and haemagglutinins in legumes, tannins in legumes and cereals, phytates in cereals and oilseeds, glucosinolates in mustard and canola protein products, and gossypol in cottonseed protein products (Sarwar et al., 2011).

Although an increase in dietary fiber negatively affects digestion and fermentation of nutrients through increased rate of passage, increased endogenous losses, and antinutritional factors, there is no effect on differences in digestibility between sows and growing pigs (Cunningham et al., 1962; Everts et al., 1986; Fernandez et al., 1986; Roth and Kirchgessner, 1984; Noblet and Shi, 1993). There are no studies that have determined effects of antinutritional factors on digestibility of sows compared with growing pigs. However, because anitinutritional factors are present in cereals, oilseeds, and certain protein products, one could assume that there are antinutritional factors present in some of the ingredients used in previous studies and the results of these studies indicate that sows have greater digestibility of nutrients than growing pigs (Cunningham et al., 1962; Everts et al., 1986; Fernandez et al., 1986; Roth and Kirchgessner, 1984; Noblet and Shi, 1993).

CONCLUSIONS

Gestating sows have a greater ATTD of CP, AA, EE, and fiber in compared to growing pigs. A more developed intestinal tract, greater intestinal volume, greater microbial mass, method of feeding, decreased rate of passage, and greater digestive and fermentative capacity all contribute to the greater ATTD of nutrients in gestating sows. Therefore, it would be more accurate to use separate values to formulate diets for gestating sows and growing pigs. However, in North America, the same energy value is used for diets and ingredients fed to all pigs. Based on the differences in digestibility between gestating sows and growing pigs, there is a need to generate separate digestibility values for both categories of pigs.

LITURATURE CITED

Azain, M. 2001. Fat in Swine Nutrition. In: Swine Nutrition. 2nd ed. A.J. Lewis and L.L. Southern, editor. CRC Press, New York, NY. p. 95-105.

Bach Knudsen, K. E. 2005. Effect of dietary non-digestible carbohydrates on the rate of SCFA delivery to peripheral tissues. Food Ingred. J. Jpn. 211:1008-1017.

Bach Knudsen, K. E., H. N. Laerke, S. Steenfeldt, M. S. Hedemann, and H. Jorgensen. 2006. In vivo methods to study the digestion of starch in pigs and poultry. Anim. Feed Sci. Technol. 130:114-135.

Bach Knudsen, K. E., and H. Jorgensen. 2001. Intestinal degradation of dietary carbohydrates-from birth to maturity. Digestive Physiology in Pigs. J. E. Lindberg and B. Ogle, editor. Proceedings of the 8th Symposium, Appsala, Sweden. CABI Publishing, Wallingford, UK. p. 109-120.

Bridges, T. C., L. W. Turner, E. M. Smith, T. S. Stahly, and O. J. Loewer. 1986. A mathematical procedure for estimating animal growth and body composition. Amer. Soc. Agric. Eng. 29:1342-1347.

Bridges, T. C., L. W. Turner, T. S. Stahly, and E. M. Smith. 1988. Visceral organ growth of swine as a function of physiological age. Amer. Soc. Agric. Eng. 31:1192-1196.

Brunsgaard, G. 1997. Morphological characteristics, epithelial cell proliferation, and crypt fission in cecum and colon of growing pigs. Dig. Dis. Sci. 42:2384-2393.

Chastanet, F., A. A. Pahm, C. Pedersen, H. H. Stein. 2007. Effect of feeding schedule on apparent energy and amino acid digestibility by growing pigs. Anim. Feed. Sci. Technol. 132:94-102.

Cunningham, H. M., D. W. Friend, and J. W. G. Nicholson. 1962. The effect of age, body weight, feed intake, and adaptability of pigs on the digestibility and nutritive value of cellulose. Can. J. Anim. Sci. 42:167-175.

Dierick, N. A., I. J. Vervaeke, D. I. Demeyer, and J. A. Decuypere. 1989. Approach to the energetic importance of fibre digestion in pigs. I. Importance of fermentation in the overall energy supply. Anim. Feed. Sci. Technol. 23:141-167.

Doornenbal, H., and A. K. Tong. 1981. Growth, development, and chemical composition of the pig. IV. Relative growth of visceral organs. Growth. 45:279-285.

Eggum, B. O., R. M. Bearmes, J. Wolstrup, and K. E. Bach Knudsen. 1984. The effect of protein quality and fibre level in the diet and microbial activity in the digestive tract on protein utilization and energy digestibility in rats. Br. J. Nutr. 51:305-314.

Eggum, B. O., G. Thorbeck, R. M. Bearmes, A. Chwalibog, and S. Henckel. 1982. Influence of diet and microbial activity in the digestive tract on digestibility, and nitrogen and energy metabolism in rats and pigs. Br. J. Nutr. 48:161-175.

Etienne, M., J. Noblet, J. Y. Dourmad, and J. Castaing. 1997. Digestive utilization of feeds in lactating sows. Comparison with growing pigs. J. P. Laplace, C. Fevrier, and A Barbeau, editors. Digestive Physiology in Pigs. EAAP Publ, St. Malo, France. No. 88 p. 583-586.

Everts, H., B. Smits, and A. W. Jongbloed. 1986. Effect of crude fibre, feeding level, and body weight on apparent digestibility of compound feeds by swine. Neth. J. Agric. Sci. 34:501-503.

Fernandez, J. A., H. Jorgensen, and A. Just. 1986. Comparative digestibility experiments with growing pigs and adult sows. Anim. Prod. 43:127-132.

Gargallo, J. and D. R. Zimmerman. 1981. Effects of dietary cellulose levels on intact and cecectomized pigs. J. Anim. Sci. 53:395-402.

Grieshop, C. M., D. E. Reese, and G. C. Fahey. 2001. Nonstarch polysaccharides and oligosaccharides in swine nutrition. In: Swine Nutrition. 2nd ed. A. J. Lewis and L. L. Southern, editor. CRC Press, New York, NY. p. 107-130.

Haydon, K. D., D. A. Knabe, and T. D. Tanksley, Jr. 1984. Effects of level of feed intake on nitrogen, amino acid, and energy digestibilities measured at the end of the small intestine and over the total digestive tract of growing pigs. J. Anim. Sci. 59:717-724.

Howard, M. D., D. T. Gordon, L. W. Pace, K. A. Garleb, and M. S. Kerley. 1995. Effect of dietary supplementation with fructooligosaccharide on colonic microbiota populations and epithelial cell proliferation in neonatal pigs. J. Pediatr. Gastroenterol. Nutr. 21:297-303.

Jin, L., L. P. Reynolds, D. A. Redmer, J. S. Caton, and J. D. Crenshaw. 1994. Effect of dietary fiber on intestinal growth, cell proliferation, and morphology in growing pigs. J. Anim. Sci. 72:2270.

Jogensen, H., A. Just, and J. A. Fernandez. 1985. Influence of diet composition on the amount of gut fill, energy disappearing in the caecum-colon, and utilization of ME in growing pigs. 10th Symposium on Energy Metabolism. Airlie, VA, USA. E.A.A.P. Publications.

Jorgensen, H., X. Zhao, and B. O. Eggum. 1995. The influence of dietary fibre and environmental temperature on the development of the gastrointestinal tract, digestibility, degree of fermentation in the hind-gut and energy metabolism in pigs. Br. J. Nutr. 75:365-378.

Kass, M. L., P. J. Van Soest, W. G. Pond, B. Lewis, and R. E. McDowell. 1980. Utilization of dietary fiber from alfalfa by growing swine. 1. Apparent digestibility of diet components in specific segments of the gastrointestinal tract. J. Anim. Sci. 50:175-191.

Landgraf, S., A. Susenbeth, P. W. Knap, H. Looft, G. S. Plastow, E. Kalm, and R. Roehe. 2006. Developments of carcass cuts, organs, body tissues, and chemical body composition during growth of pigs. Anim. Sci. 82:889-899.

Le Gall, M., M. Warpechowski, Y. Jaguelin-Peyraud, and J. Noblet. 2009. Influence of dietary fibre level and pelleting on the digestibility of energy and nutrients in growing pigs and adult sows. Animal. 3:352-359.

Le Goff, G., and J. Noblet. 2001. Comparative total tract digestibility of dietary energy and nutrients in growing pigs and adult sows. J. Anim. Sci. 79:2418-2427.

Lien, K. A., W. C. Sauer, and M. Fenton. 1997. Mucin output in ileal digesta of pigs fed a protein-free diet. Z. Ernahrungswissenschaft. 36:182-190.

Low, A. G. 1989. Secretory response of the pig gut to non-starch polysaccharides. Anim. Feed Sci. Technol. 23:55-66.

Low, A. G. 1993. Role of dietary fiber in pig diets. Recent Developments in Pig Nutrition 2. D. J. A. Cole, W. Haresign, and P. C. Garnsworthy editors. Nottingham Univ. Press, Loughborough, UK. p. 137-162.

McCance, R. A. 1974. The effect of age on weights and lengths of pigs' intestines. J. Anat. 117:475-479.

McGlone, J., and W. Pond. 2003. Nutrients, Nutrition, and Life-Cycle Feeding. Pig Production: Biological Principles and Applications. J. McGlone and W. Pond, editors. Thompson Delmar Learning, Clifton Park, N.Y. p. 143-145.

Miner-Williams, W., P. J. Moughan, and M. F. Fuller. 2009. Endogenous components of digesta protein from the terminal ileum of pigs fed a casein-based diet. J. Agric. Food Chem. 57:2072-2078.

Mosenthin, R. 1998. Physiology of small and large intestine of swine -review-. Asian-Australasian J. Anim. Sci. 11:608-619.

Moter, V., and H. H. Stein. 2004. Effect of feed intake on endogenous losses and amino acid and energy digestibility by growing pigs. J. Anim. Sci. 82:3518-3525.

Moughan, P. J., W. C. Smith, and E. V. J. Stevens. 1990. Allometric growth of chemical body components and several organs in the pig (20-90 kg liveweight). New Zealand J. Agric. Res. 33:77-84.

Muller, H. L. and M. Kirchgessner. 1986. Some aspects of energy utilization in pigs. Pig News Info. 7:419-423.

Nielson, H. E. 1962. Avlens og fodringens indflydelse pa tarmkanalens udvikling hos svinet. Ugeskr. Landmaend. 107:235-240.

Noblet, J., and X. S. Shi. 1993. Comparative digestibility of energy and nutrients in growing pigs fed ad libitum and adult sows fed at maintenance. Livest. Prod. Sci. 34:137-152.

NRC. 2012. Nutrient Requirements of Swine. 11th rev. ed. Natl. Acd. Press, Washington, DC.

Nyachoti, C. M., C. F. M. de Lange, B. W. McBride, and H. Schulze. 1997. Significance of endogenous gut nitrogen losses in the nutrition of growing pigs: A review. Can. J. Anim. Sci. 77:149–163.

Partridge, I. G., A. G. Low, I. E. Sambrook, and T. Corring. 1982. The influence of diet on the exocrine pancreatic secretion of growing pigs. Br. J. Nutr. 48:137.

Roth, F. X., and M. Kirchgessner. 1984. Digestibility of energy and crude nutrients in pigs in relation to feeding plane and liveweight. Z. Tierphysiol. Tierenaehrg. Futtermittekld. 51:79-87.

Sarwar, G. G., C. W. Xiao, and K. A. Cockell. 2011. Impact of Antinutritional factors in food proteins on the digestibility of protein and the bioavailability of amino acids and on protein quality. Br. J. Nutr. 108:315-332.

Sauer, W. C., R. Mosenthin, F. Ahrens, and L. A. den Hartog. 1991. The effect of source of fiber on ileal and fecal amino acid digestibility and bacterial nitrogen excretion in growing pigs. J. Anim. Sci. 69:4070-4077.

Sauvant, D., J. –M. Perez, and G. Tran. 2004. Tables of composition and nutritional value of feed materials, 2nd Ed. D. Sauvant, J. –M. Perez, and G. Tran, ed. Wageningen, The Netherlands: Wageningen Academic Publishers.

Serena, A., H. Jorgensen, and K. E. Bach Knudsen. 2008. Digestion of carbohydrates and utilization of energy in sows fed diets with contrasting levels and physicochemical properties of dietary fiber. J. Anim. Sci. 86:2208-2216.

Shi, X. S., and J. Noblet. 1993. Digestible and metabolizable energy values of ten feed ingredients in growing pigs fed ad libitum and sows fed at maintenance level; comparative contribution of the hindgut. Anim. Feed Sci. Technol. 42:223-236.

Shi, X. S., and J. Noblet. 1994. Contribution of the hindgut to digestion of diets in growing pigs and adult sows: effect of diet composition. Livest. Prod. Sci. 34:237-252.

Stanogias, G., and G. R. Pearce. 1985. The digestion of fibre by pigs. 1. The effects of amount and type of fibre on apparent digestibility, nitrogen balance, and rate of passage. Br. J. Nutr. 53:513-530.

Stein, H. H., B. Seve, M. F. Fuller, P. J. Moughan, and C. F. M. de Lange. 2007. Invited review: Amino acid bioavailability and digestibility in pig feed ingredients: Terminology and application. J. Anim. Sci. 85:172-180.

Stein, H. H., and R. A. Bohlke. 2007. The effects of thermal treatment of field peas (Pisum sativum L.) on nutrient and energy digestibility by growing pigs. J. Anim. Sci. 85:1424-1431.

Stein, H. H., S. Aref, and R. A. Easter. 1999. Comparative protein and amino acid digestibilities in growing pigs and sows. J. Anim. Sci. 77:1169-1179.

Stein, H. H., S. W. Kim, T. T. Nielsen, and R. A. Easter. 2001. Standardized ileal protein and amino acid digestibility by growing pigs and sows. J. Anim. Sci. 79:2113-2122.

Taverner, M. R., I. D. Hume, and D. J. Farrell. 1981. Availability to pigs of amino acids in cereal grains. 1. Endogenous levels of amino acids in ileal digesta and faeces of pigs given cereal diets. Br. J. Nutr. 46:149-158.

Urriola, P. E., S. K. Cervantes-Pahm, and H. H. Stein. 2013. Fiber in Swine Nutrition. Sustainable Swine Nutrition. L. I. Chiba, editor. Wiley-Blackwell, Ames, IA. p. 255-276.

Varel, V. H., W. G. Pond, and J. T. Yen. 1984. Influence of dietary fiber on the performance and cellulose activity of growing finishing swine. J. Anim. Sci. 59:388-393.

Varel, V. H. 1987. Activity of fiber-degrading microorganisms in the pig large intestine. J. Anim. Sci. 65:488-496.

Wenk, C. 2001. The role of dietary fiber in the digestive physiology of the pig. Anim. Feed Sci. Technol. 90:21-33.

Wilfart, A., L. Montagne, P. H. Simmins, J. van Milgen, and J. Noblet. 2007. Sites of nutrient digestion in growing pigs: Effect of dietary fiber. J. Anim. Sci. 85:976-983.

Zebrowska, T., and A. G. Low. 1987. The influence of diets based on whole wheat, wheat flour, and wheat bran on exocrine pancreatic secretion in pigs. J. Nutr. 117:1212-1216.

Zebrowska, T., A. G. Low, and H. Zebrowska. 1983. Studies on gastric digestion of protein and carbohydrate, gastric secretion and exocrine pancreatic secretion in the growing pig. Br. J. Nutr. 49:401-410.

CHAPTER 3: COMPARATIVE DIGESTIBILITY OF ENERGY AND NUTRIENTS IN FEED INGREDIENTS FED TO SOWS AND GROWING PIGS

ABSTRACT

The objective of this research was to compare DE and ME values and ATTD of energy and nutrients in 11 diets fed to both growing pigs and gestating sows. Three diets were based on corn, wheat, or sorghum, and 8 diets were based on a combination of corn and soybean meal, canola meal, distillers dried grains with solubles (**DDGS**), and low-fat DDGS, corn germ meal, corn bran, wheat middlings, and soybean hulls. A total of 88 gestating sows (parity 2 to 6) and 88 growing barrows (40.1 ± 4.69 kg BW) were used and randomly allotted to the 11 diets with 8 replicate pigs per diet. Fecal and urine samples were collected for 4 d following a 19 d adaptation period. The DE, ME, and ATTD of GE, ADF, NDF, and CP in corn, wheat, and sorghum were calculated. Gestating sows had greater ($P < 0.05$) ATTD of GE and CP, and DE values (as-fed and DM basis) for all diets compared with growing pigs. Gestating sows also had greater ($P < 0.05$) ME values (as-fed and DM basis) for the 3 grain diets and the diets containing soybean meal, canola meal, or DDGS than growing pigs. No differences were observed in ATTD of ADF and NDF between gestating sows and growing pigs for any of the diets. The ATTD of GE and CP, and DE values in gestating sows may be predicted from the values obtained in growing pigs. For both gestating sows and growing pigs, prediction equations can be used to estimate ATTD of GE and CP, and DE and ME values in the diets from the concentrations of nutrients and GE. Results of this research indicate that apparent digestibility values of CP and GE obtained in gestating sows are greater than values obtained in growing pigs, but apparent digestibility of fiber obtained in growing pigs is not different from digestibilities in gestating sows.

Keywords: energy, digestibility, gestation, growing pigs, fiber, pigs

INTRODUCTION

Sows have a larger digestive tract than growing pigs; therefore, sows are able to ferment fiber in fiber rich ingredients better than growing pigs (Fernandez et al., 1986; Shi and Noblet, 1993; Le Goff and Noblet, 2001). Sows also have greater apparent total tract digestibility (**ATTD**) of several nutrients compared with growing pigs (Fernandez et al., 1986). The reduced feeding level in gestating sows compared with growing pigs also contributes to an increase in ATTD of dietary nutrients and energy. Digestible energy and ME values of diets and feed ingredients are dependent on physiological stage/BW of the animal and/or feeding level (Shi and Noblet, 1993). Total tract digestibility of all nutrients, except starch, is improved with increase in body size. This variation is most important for fiber-rich feeds (Noblet and Shi, 1994) and differences in DE are positively related to dietary fiber level (Le Goff and Noblet, 2001). Greater digestibility of energy and OM in sows is largely explained by the greater ability of sows to ferment fiber compared with growing pigs (Shi and Noblet, 1993).

Although it is well documented from European experiments that DE, ME, and ATTD of nutrients is greater in gestating sows fed close to their maintenance requirement than in growing pigs allowed ad libitum access to their diets, no data from North America for the comparative ATTD of energy and nutrients, have been reported. As use of high-fiber ingredients increases in the United States, such values are needed to accurately formulate diets for growing pigs and sows. The objective of this research was to test the hypothesis that values for the ATTD of energy and nutrients and the DE and ME of diets are greater in gestating sows than in growing pigs.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocol for this experiment.

Eleven feed ingredients were used (Table 1). Three of the ingredients were cereal grains (corn, sorghum, and wheat), 4 ingredients were commonly used protein sources [soybean meal (**SBM**), canola meal, conventional distillers dried grains with solubles (**DDGS-CV**), and low-fat DDGS (**LF-DDGS**)], and the remaining 4 ingredients were commonly used high-fiber ingredients [corn germ meal (**CGM**), corn bran, wheat middlings (**WM**), and soybean hulls (**SBH**)].

A total of 88 gestating sows (parity 2 to 6) and 88 growing barrows (40.1 ± 4.69 kg BW) were used in the experiment. Sows were Fertilis-25 females and barrows were the offspring of G-performer males mated to Fertilis-25 females (Genetiporc, Alexandria, MN). Pigs and sows were placed in metabolism crates that are equipped with a feeder and a nipple drinker, slatted floors, a screen floor, and urine trays. The crates allow for the total, but separate, collection of urine and feces from each individual animal. Metabolism crates for pigs are 0.9 × 1.8 m whereas metabolism crates for sows are 0.9 × 2.1 m.

Eleven diets were formulated (Tables 2 and 3). Three diets were based on corn, sorghum, or wheat, and 8 diets were based on a combination of corn and each of the remaining 8 ingredients. Vitamins and minerals were included in all diets to meet current requirements (NRC, 2012). The same diets were fed to sows and to growing pigs. A randomized complete block design was used within each group of animals and the 88 animals within each group were randomly allotted to the 11 diets with 8 blocks of 11 sows for a total of 8 replicate sows per diet and 4 blocks of 22 growing pigs, which also resulted in a total of 8 replicates per diet.

Feed was provided daily in an amount of 1.5 and 3.4 times the estimated energy requirement for maintenance in gestating sows and growing pigs, respectively. Daily feed rations were divided into 2 equal meals that were provided at 0700 and 1600 h, respectively. Pigs and sows were allowed ad libitum access to water throughout the experiment. Diets were fed to the animals for a total of 24 d. The initial 14 d were considered an adaptation period to the diet and during this period, pigs and sows were adapted to their respective diet in individual crates. On d 15, pigs and sows were moved into metabolism crates and d 15 to 19 was an adaptation period to the metabolism crates. A color marker was included in the meal provided in the morning of d 20 and again in the morning meal on d 24. Fecal samples were collected quantitatively according to the marker to marker procedure (Adeola, 2001) with collections starting when the marker first appeared in the feces after d 20, and collections ceased when the marker first appeared after d 24. Fecal samples were stored at -20°C as soon as collected. Urine collection was initiated on d 20 in the morning and ceased on d 24 in the morning. Urine was collected in urine buckets over a preservative of 50 mL of 3*N*HCL. Buckets were emptied once daily, the weights of the collected urine were recorded, and 20% of the urine was stored at -20^{o}C. Fecal samples were collected twice daily and stored at -20^{o}C. At the conclusion of the experiment, urine samples were thawed and mixed. Fecal samples were thawed and mixed and subsamples were collected for chemical analyses.

Fecal subsamples were oven dried and finely ground prior to analyses. Samples of all ingredients, all diets, and feces were analyzed for DM by oven drying at 135°C for 2 h (Method 930.15; AOAC Int., 2007) and dry ash (Method 942.05; AOAC Int., 2007). Concentrations of CP were analyzed in samples of ingredients, diets, and feces using a combustion procedure (Method 990.03; AOAC Int., 2007) on an Elementar Rapid N-cube protein/nitrogen apparatus (Elementar Americas Inc., Mt. Laurel, NJ). Aspartic acid was used as a calibration standard and CP was calculated as N × 6.25. The concentration of acid hydrolyzed ether extract in ingredients and diets was analyzed (Method 2003.06; AOAC Int., 2007) on a Soxtec 2050 automated analyzer (FOSS North America, Eden Prairie, MN). Gross energy was determined in all samples using bomb calorimetry (Model 6300, Parr Instruments, Moline, IL). Benzoic acid was used as the standard for calibration. Urine samples were prepared for GE analysis as previously outlined (Kim et al., 2009). Concentrations of ADF and NDF were determined in ingredients, diets, and fecal samples using Method 973.18 (AOAC Int., 2007) and Holst (1973), respectively. Both the SBM diet and soy hulls diet were analyzed for raffinose, stachyose, glucose, verbascose, maltose, sucrose, and fructose (Cervantes-Pahm and Stein, 2010). All ingredients were also analyzed for monosaccharides, sucrose, and oligosaccharides (Cervantes-Pahm and Stein, 2010), for AA (Method 982.30 E [a, b, c]; AOAC Int., 2007), Ca, P, Cu, Fe, Mg, Mn, K, Se, Na, S, Zn, and Cl (Method 975.03; AOAC Int., 2007), and total starch and lignin (Method 76-13; AACC Int., 2000; Method 973.18 (A-D); AOAC Int., 2006). The bulk density (Cromwell et al., 2000), particle size (ANSI/ASAE, 2008), and water holding capacity (Urriola et al., 2010) of each ingredient was determined as well. For particle size, the feedstuff material in each of the test sieves was recorded and weighed for calculations of particle size distribution and mean particle size. After determination of the mean particle size as described by ANSI/ASAE, (2008), the surface area was calculated using mean particle size of the grain as a reference (ANSI/ASAE, 2008).

The ATTD of energy, CP, ADF, and NDF and the concentrations of DE and ME in each diet were calculated (Adeola, 2001). Data were analyzed using the MIXED procedure of SAS (SAS Institute Inc., Cary, NC). Outliers were tested using the UNIVARIATE procedure. Data were analyzed separately for the 3 grain diets based on corn, wheat, or sorghum, the 4 protein diets based on corn and SBM, canola meal, DDGS-CV, or LF-DDGS, and the 4 high fiber diets based on corn and CGM, corn bran, WM, or SBH. The model used to analyze each group of diets included diet, physiological stage, and the interaction between diet and stage as the fixed effect and period as the random effect. Animal was used as the experimental unit for all analyses. Least squares means were calculated using the LSMeans procedure in SAS. The PDIFF option was used to separate means. An alpha level of 0.05 was used to assess significance among means and *P*-values between 0.05 and 0.10 were considered a trend.

Correlation coefficients between chemical components and ATTD of GE, CP, ADF, and NDF, and between chemical components and DE and ME in the 11 diets were determined using PROC CORR (SAS Inst. Inc., Cary, NC). Prediction equations were developed by PROC REG as previously described (Sulabo and Stein, 2013). The best regression models were determined using multiple criteria analyses where the Conceptual predictive [C(p)] criterion, the coefficient of determination (R2), the Akaike information criterion (AIC), root mean square error (RMSE), and the P-value of the model were considered. The prediction equation with C(p) closest to p, where p is the number of variables in the candidate model + 1, the least AIC, which is a measure of fit, and the least RMSE, which is a measure of precision, was considered the optimal model.

RESULTS

The ATTD of GE and CP and the DE (as-fed) in the wheat diet were greater ($P < 0.05$) than in the corn diet and the sorghum diet, and the DE and ME (DM-basis) in the wheat diet where also greater than in the corn diet (Table 4). There was no difference in ATTD of GE, DE, and ME between the corn diet and the sorghum diet, but the corn diet had greater ($P < 0.05$) ATTD of CP than the sorghum diet.

Gestating sows had greater ($P < 0.05$) ATTD of GE and CP, and greater DE and ME in all grain diets than growing pigs. The ATTD of ADF was greater ($P < 0.05$) in pigs than in gestating sows when they were fed the wheat diet, but not different between pigs and sows when they were fed corn or sorghum diets (interaction, $P < 0.05$). The ATTD of NDF was greater ($P < 0.05$) in sows than in pigs when they were fed the corn diet, less ($P < 0.05$) in sows than in pigs when they were fed the wheat diet, but not different between pigs and sows when they were fed the sorghum diet (interaction, $P <$

0.05). No diet effect was observed for the ME:DE ratio but there was a tendency ($P < 0.07$) for a greater ME:DE ratio in sows than in growing pigs.

Gestating sows had greater ($P < 0.05$) ATTD of GE and CP and greater DE than growing pigs when they were fed the 4 protein diets (Table 5). The ATTD of ADF was greater ($P < 0.05$) in growing pigs than in gestating sows when they were fed the SBM diet, but this was not the case when they were fed the canola meal diet, the DDGS-CV diet, or the LF-DDGS diet (interaction, $P < 0.05$). The ATTD of NDF was greater ($P < 0.05$) in growing pigs than in gestating sows if they were fed the canola meal diet, less ($P < 0.05$) in growing pigs than in gestating sows if they were fed the DDGS-CV diet, but not different between pigs and sows when they were fed the SBM diet or the LF-DDGS diet (interaction, $P < 0.05$). The DE for the 4 diets was greater ($P < 0.05$) for sows than for growing pigs, but there was no difference between sows and pigs when observed for ME. No diet effect and stage effect were observed for the ME:DE ratio.

The ATTD of CP and the ME:DE ratio were greater ($P < 0.05$) in sows than in pigs when fed the high fiber diets (Table 6). The ATTD of GE was greater ($P < 0.05$) in sows than in pigs when they were fed the WM diet or the SBH diet, but not different between sows and pigs when they were fed the CGM diet or the corn bran diet (interaction, $P < 0.05$). The ATTD of ADF was greater ($P < 0.05$) in pigs than in sows when they were fed the CGM diet and the ATTD of ADF and NDF was less ($P < 0.05$) in pigs than in sows when they were fed the SBH diet, but no difference between pigs and sows was observed for the corn bran and the WM diets (interaction, $P < 0.05$). On both as-fed and DM basis, the DE and ME values for the WM diet and the SBH diet were greater ($P < 0.05$) in sows than in pigs, but the DE and ME values of the CGM diet and the corn bran diet were not different between sows and pigs (interaction, $P < 0.05$).

The ATTD of GE and CP, and the DE values for gestating sows could be directly predicted from the values obtained in growing pigs, and the R^2 for these equations were 0.78, 0.72, and 0.78 respectively (Table 7). However, the R^2 of prediction equations for ATTD of ADF and NDF and the ME values for gestating sows were 0.55, 0.36, and 0.54 respectively.

The concentration of ADF and NDF in the diets were negatively correlated ($P < 0.05$) with the ATTD of GE and CP and DE and ME values both in gestating sows and growing pigs (Table 8). The concentration of CP in the diets was positively correlated ($P < 0.05$) with the ATTD of CP in growing pigs, but the concentration of AEE in the diets was negatively correlated ($P < 0.05$) with the ATTD of GE and NDF in growing pigs.

The optimal models to predict ATTD of GE and CP, and DE and ME in sows were (Table 9):

$$\text{ATTD of GE, \%} = 97.53 - 0.0248*\text{CP} - 0.0192*\text{AEE} - 0.0264*\text{ADF} - 0.0282*\text{NDF} \quad (1);$$

$$\text{ATTD of CP, \%} = 286.00 - 0.0503*\text{GE} + 0.1051*\text{CP} + 0.3434*\text{AEE} - 0.2018*\text{NDF} \quad (2);$$

$$\text{DE, kcal/kg DM} = 2{,}750 + 0.3294*\text{GE} - 0.4031*\text{CP} + 2.9577*\text{AEE} - 2.7199*\text{ash} - 1.1788*\text{ADF} - 1.7808*\text{NDF} \quad (3);$$

$$\text{ME, kcal/kg DM} = 3{,}361 + 0.1884*\text{GE} - 1.1757*\text{CP} + 3.2946*\text{AEE} - 3.3369*\text{ash} - 1.1621*\text{ADF} - 1.9782*\text{NDF} \qquad (4).$$

The optimal models to predict ATTD of GE and CP, and DE and ME in growing pigs were:

$$\text{ATTD of GE, \%} = 101.34 + 0.0353*\text{CP} - 0.0563*\text{AEE} - 0.2833*\text{ash} - 0.0364*\text{ADF} \qquad (5);$$

$$\text{ATTD of CP, \%} = 230.99 - 0.0209*\text{GE} + 0.1886*\text{CP} + 0.2043*\text{AEE} - 0.4122*\text{ash} - 0.0211*\text{ADF} - 0.0775*\text{NDF} \qquad (6);$$

$$\text{DE, kcal/kg DM} = -860 + 1.2275*\text{GE} + 0.8246*\text{CP} - 5.3211*\text{AEE} - 10.8080*\text{ash} - 1.4293*\text{ADF} + 0.1322*\text{NDF} \qquad (7);$$

$$\text{ME, kcal/kg DM} = -1{,}740 + 1.3693*\text{GE} + 0.8217*\text{CP} - 7.3042*\text{AEE} - 8.9457*\text{ash} - 1.1202*\text{ADF} + 0.4537*\text{NDF} \qquad (8).$$

All models had $R^2 > 0.85$.

DISCUSSION

Concentrations of energy, DM, CP, fat, and ash of all 11 ingredients were close to expected values (Sauvant et al., 2004; Baker and Stein, 2009; Kim et al., 2009; Urriola et al., 2010; NRC, 2012; Rojas et al., 2013; Stewart et al., 2013). Corn, wheat, and sorghum contained more starch than the 4 protein concentrates and the 4 high fiber ingredients. The percent of starch in corn, wheat, and sorghum was in agreement with published values (NRC, 2012; Rosenfelder et al., 2013). Soybean meal, canola meal, DDGS-CV, and LF-DDGS contained more CP than the 3 cereal grains and the 4 high fiber ingredients and these values are in agreement with previously reported data (Stein et al., 1999; Stein et al., 2006; Pahm et al., 2008; Stein et al., 2009; Goebel and Stein, 2011; Gonzalez and Stein, 2012; Kim et al., 2012; NRC, 2012; Rodriguez et al., 2013; Rojas et al., 2013). Both sources of DDGS contained more fat than the other 9 ingredients, which is in agreement with published data (Sauvant et al., 2004; NRC, 2012). The 2 sources of DDGS contained 12.20 and 7.99% AEE, respectively. A concentration of AEE of 12.20% is in agreement with expected values for DDGS-CV, the concentration of 7.99% is within the range of values observed in low-fat corn DDGS that has had fat skimmed off the solubles (Anderson et al., 2012; NRC, 2012; Kerr et al., 2013). Corn germ meal, corn bran, WM, and SBH contained more ADF and NDF than the other 7 ingredients.

The observation that the ATTD of GE and CP, as well as DE and ME of diets is greater in gestating sows fed at approximately1.5 times the maintenance requirement for energy than growing pigs fed close to the ad libitum intake is in agreement with results of several previous studies (Fernandez et al., 1986; Shi and Noblet, 1993; Le Goff and Noblet, 2001; Cozannet et al., 2010). Combined, the data indicate that gestating sows utilize energy and nutrients to a greater extent than growing pigs.

Previous research indicates that sows are able to utilize energy and nutrients to a greater extent than growing pigs because of age, BW, and feeding frequency (Cunningham et al., 1962; Everts et al., 1986; Bridges et al., 1988; Stein et al., 2001). Adult animals have greater BW, which correlates to a larger, more developed intestinal tract and thus, greater intestinal volume (Bridges et al., 1986; Dierick et al., 1989; Brunsgaard, 1997). An increased intestinal volume influences digestibility through a decreased rate of passage allowing for more exposure of feed to enzymes and bacteria and more absorption of nutrients in the small and large intestine (Cunningham et al., 1962; Fernandez et al., 1986; Varel, 1987; Dierick et al., 1989; Low, 1993). Some of the largest differences in digestibility result from greater hindgut activity of sows, which contributes to total digestibility of nutrients (Fernandez et al., 1986; Shi and Noblet., 1993a). Previous research also supports that a reduction of feeding frequency to maintenance level increases digestibility of energy and nutrients in sows (Cunningham et al., 1962; Everts et al., 1986; Shi and Noblet, 1993a).

We were not able to confirm a difference in digestibility of fiber between gestating sows and growing pigs. One possible reason for this observation is that the length of time we allowed the animals to adapt to their diets was longer in this experiment compared with previous experiments. We allowed both gestating sows and growing pigs to adapt to their respective diets for approximately 20 days before fecal collections were initiated. It is possible, with a longer adaptation, that growing pigs were able to adapt to the fiber, and therefore, ferment the fiber as well as the sows. Previous research indicates that pigs adapt to longer periods of feeding fibrous material through an increase in fermentation (Gargallo and Zimmerman, 1981; Wenk, 2001). This increase in fermentation may be due to an increase in hindgut size in the growing pigs. A longer adaptation time allows for increased BW and further development of the digestive tract (Bridges et al., 1986). As BW increases, overall weight of the digestive tract increases resulting in decreased rate of passage and increased digestibility of nutrients (Bridges et al, 1986; Varel, 1987). An increase in hindgut microbial mass may also explain the increase in fermentation in growing pigs. High concentrations of fiber increase the numbers of bacteria in the LI of both gestating sows and growing pigs (Varel,1987).

Gestating sows were fed approximately 1.5 times their maintenance requirement while growing pigs were fed 3.4 times their maintenance requirement. These levels are similar to previous studies (Fernandez et al., 1986; Noblet and Shi, 1993; Shi and Noblet, 1993a; Shi and Noblet, 1993b), and also close to feeding levels used in commercial production.

The observation that the presence of fiber in the diets negatively affects the digestibility of energy and CP was expected and is consistent with previous reports (Nyachoti et al., 1997; Yin et al., 2000; Wilfart et al., 2007). The main reason fiber negatively affects digestibility of energy and CP in both gestating sows and growing pigs is an increase in endogenous losses in the form of losses of mucin. As observed in previous research, endogenous losses are influenced by diet composition and increase with an increase in dietary fiber (Stein et al., 2007). Two other explanations for this negative effect are increased rate of passage and increased concentration of antinutritional factors. High dietary fiber may diminish the efficiency of digestion as it increases the flow of nutrients or rate of passage (Fernandez et al., 1986; Wenk, 2001; Serena et al., 2008). Levels and types of antinutritional factors induce specific endogenous losses, decreasing digestibility of energy and nutrients (Stein et al., 2007).

Although we observed differences in digestibility of energy and CP between gestating sows and growing pigs, values for the ATTD of GE and CP, and DE for sows can be directly predicted from the values obtained in growing pigs. However, more accurate prediction equations can be used to estimate digestibility of energy and CP, DE and ME in the diets from the concentration of nutrients and GE in the feed ingredients.

CONCLUSIONS

It is concluded from this experiment that apparent digestibility values of energy and CP, and DE and ME obtained in gestating sows are greater than values obtained in growing pigs, but apparent digestibility of fiber obtained in gestating sows is not different from values obtained in growing pigs. The present study provides equations for predicting the values for the ATTD of GE and CP, and DE for sows from the values obtained in growing pigs. When formulating diets, nutritional content should be considered as there may be differences in digestibility between gestating sows and growing pigs.

LITERATURE CITED

AACC International. 2000. Approved Methods of the American Association of Cereal Chemists. 10th ed. AACC Int., St, Paul, MN.

ANSI/ASAE. 2008. Method of determining and expressing fineness of feed materials by sieving. ANSI/ASAE Standard ANSI/ASAE S319.4.

AOAC Int. 2006. Official Methods of Analysis of AOAC Int. 18th ed. Rev. 1. W. Hortwitz and G. W. Latimer, Jr., ed. AOAC Int., Gaithersburg, MD.

AOAC Int. 2007. Official Methods of Analysis of AOAC Int. 18th ed. Rev. 2. W. Hortwitz and G. W. Latimer, Jr., ed. AOAC Int., Gaithersburg, MD.

Adeola, L. 2001. Digestion and balance techniques in pigs. Swine Nutrition. A. J. Lewis and L. L. Southern, editor. CRC Press, Washington, DC. p. 903-916.

Almeida, F. N., G. I. Petersen, and H. H. Stein. 2011. Digestibility of amino acids in corn, corn coproducts, and bakery meal fed to growing pigs. J. Anim. Sci. 89:4109-4115.

Anderson, P. V., B. J. Kerr, T. E. Weber, C. J. Ziemer, and G. C. Shurson. 2012. Determination and prediction of digestible and metabolizable energy from chemical analysis of corn coproducts fed to finishing pigs. J. Anim. Sci. 90:1242-1254.

Baker, K. M., and H. H. Stein. 2009. Amino acid digestibility and concentration of digestible and metabolizable energy in soybean meal produced from conventional, high-protein, or low-oligosaccharide varieties of soybeans fed to growing pigs. J. Anim. Sci. 87:2282-2290.

Cervantes-Pahm, S. K., and H. H. Stein. 2010. Ileal digestibility of amino acids in conventional, fermented, and enzyme-treated soybean meal and in soy protein isolate, fish meal, and casein fed to weanling pigs. J. Anim. Sci. 88:2674-2683.

Cozannet, P., Y. Primot, C. Gady, J. P. Metayer, M. Lessire, F. Skiba, and J. Noblet. 2010. Energy value of wheat distillers grains with solubles for growing pigs and adult sows. J. Anim. Sci. 88:2382-2392.

Cromwell, G. L., T. R. Cline, J. D. Crenshaw, T. D. Crenshaw, R. A. Easter, R. C. Ewan, C. R. Hamilton, G. M. Hill, A. J. Lewis, D. C. Mahan, J. L. Nelssen, J. E. Pettigrew, T. L. Veum, and J. T. Yen. 2000. Variability among sources and laboratories in analyses of wheat middlings. J. Anim. Sci. 78:2652-2658.

Ellis, R., E. R. Morris, and C. Philpot. 1977. Quantitative determination of phytate in the presence of high inorganic phosphate. Anal. Biochem. 77:536-539.

Fernandez, J. A., H. Jorgensen, and A. Just. 1986. Comparative digestibility experiments with growing pigs and adult sows. Anim. Prod. 43:127-132.

Goebel, K. P., and H. H. Stein. 2011. Phosphorus digestibility and energy concentration of enzyme-treated and conventional soybean meal fed to weanling pigs. J. Anim. Sci. 89:764-772.

González-Vega, J. C., and H. H. Stein. 2012. Amino acid digestibility in canola, cottonseed, and sunflower products fed to finishing pigs. J. Anim. Sci. 90:4391-4400.

Holst, D. O. 1973. Holst filtration apparatus for Van Soest detergent fiber analysis. J. AOAC. 56:1352–1356.

Kerr, B. J., W. A. Doizer III, and G. C. Shurson. 2013. Effects of reduced-oil corn distillers dried grains with solubles composition on digestible and metabolizable energy value and prediction in growing pigs. J. Anim. Sci. 91:3231-3243.

Kim, B. G., D. Y. Kil, Y. Zhang, and H. H. Stein. Concentrations of analyzed or reactive lysine, but not crude protein, may predict the concentration of digestible lysine in distillers dried grains with solubles fed to pigs. 2012. J. Anim. Sci. 90:3798-3808.

Kim, B. G., G. I. Petersen, R. B. Hinson, G. L. Allee, and H. H. Stein. 2009. Amino acid digestibility and energy concentration in a novel source of high-protein distillers dried grains and their effects on growth performance of pigs. J. Anim. Sci. 87:4013-4021.

Le Goff, G., and J. Noblet. 2001. Comparative total tract digestibility of dietary energy and nutrients in growing pigs and adult sows. J. Anim. Sci. 79:2418-2427.

Martin, S. K., and C. A. Hibberd. 1990. Intake and digestibility of low-quality native grass hay by beef cows supplemented with graded levels of soybean hulls. J. Anim. Sci. 68:4319-4325.

Noblet, J., and Shi, X. S. 1994. Effect of body weight on digestive utilization of energy and nutrients of ingredients and diets in pigs. Livest. Prod. Sci. 37: 323-338.

NRC. 2012. Nutrient Requirements of Swine. 11th rev. ed. Natl. Acad. Press, Washington, DC.

Pahm, A. A., C. Pedersen, and H. H. Stein. 2008. Application of the reactive lysine procedure to estimate lysine digestibility in distillers dried grains with solubles fed to growing pigs. J. Agric. Food Chem. 56:9441-9446.

Rodríguez, D. A., R. C. Sulabo, J. C. González-Vega, and H. H. Stein. 2013. Energy concentration and phosphorus digestibility in canola, cottonseed, and sunflower products fed to growing pigs. Can. J. Anim. Sci. 93:493-503.

Rojas, O. J., Y. Liu, and H. H. Stein. 2013. Phosphorus digestibility and concentration of digestible and metabolizable energy in corn, corn coproducts, and bakery meal fed to growing pigs. J. Anim. Sci. 91:5326-5335.

Rosenfelder, P., M. Eklund, and R. Mosenthin. 2013. Nutritive value of wheat and wheat by-products in pig nutrition: A review. Anim. Feed Sci. Technol. 185:107-125.

Salyer, J. A., J. M. DeRouchey, M. D. Tokach, S. S. Dritz, R. D. Goodband, J. L. Nelssen, and D. B. Petry. 2012. Effects of dietary wheat middlings, distillers dried grains with solubles, and choice white grease on growth performance, carcass characteristics, and carcass fat quality of finishing pigs. J. Anim. Sci. 90:2620-2630.

Sauvant, D., J. M. Perez, and G. Tran, eds. 2004. Tables of composition and nutritional value of feed materials: pig, poultry, cattle, sheep, goats, rabbits, horses, and fish. 2nd ed. Paris: INRA, and Wageningen, The Netherlands: Wageningen Academic Publishers.

Shi, X. S., and J. Noblet. 1993a. Digestible and metabolizable energy values of ten feed ingredients in growing pigs fed ad libitum and sows fed at maintenance level; comparative contribution of the hindgut. Anim. Feed Sci. Technol. 42:223-236.

Shi, X. S., and J. Noblet. 1993b. Contribution of the hindgut to digestion of diets in growing pigs and adult sows: effect of diet composition. Livest. Prod. Sci. 34:237-252.

Stein, H. H., M. L. Gibson, C. Pedersen, and M. G. Boersma. 2006. Amino acid digestibility in ten samples of distillers dried grain with solubles fed to growing pigs. J. Anim. Sci. 84:853-860.

Stein, H. H., S. P. Connot, and C. Pedersen. 2009. Energy and nutrient digestibility in four sources of distillers dried grains with solubles produced from corn grown within a narrow geographical area and fed to growing pigs. Asian-Austr. J. Anim. Sci. 22:1016-1025.

Stein, H. H., S. Aref, and R. A. Easter. 1999. Comparative protein and amino acid digestibilities in growing pigs and sows. J. Anim. Sci. 77:1169-1179.

Stewart, L. L., D. Y. Kil, F. Ji, R. B. Hinson, A. D. Beaulieu, G. L. Allee, J. F. Patience, J. E. Pettigrew, and H. H. Stein. 2013. Effects of dietary soybean hulls and wheat middlings on the body composition, nutrient and energy retention, and the net energy of diets and ingredients fed to growing and finishing pigs. J. Anim. Sci. 91:2756-2765.

Urriola, P. E., G. C. Shurson, and H. H. Stein. 2010. Digestibility of dietary fiber in distillers co-products fed to growing pigs. J. Anim. Sci. 88:2373-2381.

Weber, T. E., S. L. Trabue, C. J. Ziemer, and B. J. Kerr. 2010. Evaluation of elevated dietary corn fiber from corn germ meal in growing female pigs. J. Anim. Sci. 88:192-201.

Widmer, M. R., L. M. McGinnis, and H. H. Stein. 2007. Energy, phosphorus, and amino acid digestibility of high-protein distillers dried grains and corn germ fed to growing pigs. J. Anim. Sci. 85:2994-3003.

TABLES

Table 3.1. Analyzed nutrient composition of corn, wheat, sorghum, soybean meal (SBM), canola meal, conventional distillers dried grains with solubles (DDGS-CV), low fat distillers dried grains with solubles (LF-DDGS), corn germ meal (CGM), corn bran, wheat middlings (WM), and soybean hulls, as-fed basis

	Ingredient										
Item	Corn	Wheat	Sorghum	SBM	Canola meal	DDGS-CV	LF-DDGS	CGM	Corn bran	WM	Soybean hulls
GE, kcal/kg	3,990	3,858	3,850	4,272	4,259	4,782	4,378	4,195	4,281	4,109	3,640
DM, %	91.73	90.49	88.16	90.49	89.12	88.77	88.44	88.81	91.09	89.72	87.03
CP, %	9.17	12.73	10.01	50.33	35.83	29.34	33.28	21.95	10.25	16.13	9.97
AEE[1], %	3.96	1.86	4.33	0.43	2.42	12.2	7.99	3.73	4.09	5.18	1.14
Ash, %	1.17	1.61	1.20	6.17	7.84	4.64	6.17	3.05	0.89	5.81	4.36
OM, %	90.56	88.88	86.96	84.32	81.28	84.13	82.27	85.76	90.20	83.91	82.67
Ca, %	0.01	0.04	0.01	0.33	1.01	0.03	0.04	0.02	0.01	0.10	0.54
P, %	0.23	0.32	0.26	0.68	1.07	0.84	0.97	0.75	0.12	1.20	0.10
Cl, %	<0.10	<0.10	<0.10	<0.10	0.20	0.20	0.20	0.20	0.20	<0.10	<0.10
Mg, %	0.10	0.12	0.13	0.31	0.65	0.35	0.40	0.26	0.06	0.50	0.20
K, %	0.31	0.38	0.33	2.40	1.27	1.21	1.30	0.46	0.26	1.33	1.36
S, %	0.11	0.14	0.09	0.45	0.98	0.80	0.95	0.34	0.18	0.22	0.11
Na, (ppm)	8.00	<0.20	<0.20	55.0	219.0	1,025	2,332	166.00	38.00	34.00	5.00

Table 3.1 (cont.)

Cu, (ppm)	6.00	10.00	6.00	34.00	21.00	14.00	14.00	17.00	6.00	29.00	11.00
Fe, (ppm)	62.00	72.00	56.00	154.00	268.00	163.00	145.00	219.00	166.00	225.00	459.00
Zn, (ppm)	36.00	26.00	18.00	45.00	65.00	79.00	75.00	93.00	21.00	105.00	31.00
Mn, (ppm)	6.00	52.00	16.00	32.00	87.00	16.00	17.00	14.00	4.00	147.00	12.00
Se, (ppm)	<4.00	<4.00	<4.00	<4.00	<4.00	<4.00	<4.00	<4.00	<4.00	<4.00	<4.00
Carbohydrates, %											
Glucose	0.44	0.39	0.36	1.34	0.68	0.27	0.37	0.19	0.46	1.74	0.31
Fructose	0.47	0.33	0.18	0.79	0.65	0.08	0.10	0.68	0.54	1.31	1.25
Sucrose	1.02	0.47	0.04	7.51	5.47	0.03	0.00	0.09	0.00	0.69	0.36
Maltose	0.15	0.11	0.06	0.45	0.00	0.67	0.33	0.03	0.02	0.32	0.07
Raffinose	0.05	0.14	0.01	0.87	0.27	0.00	0.00	0.00	0.00	0.55	0.05
Stachyose	0.00	0.00	0.00	4.85	0.38	0.00	0.00	0.00	0.00	0.00	0.07
Verbascose	0.00	0.00	0.00	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Starch, %	64.50	69.54	67.28	1.02	0.00	5.57	5.60	11.93	22.20	19.27	0.00
NDF, %	12.71	11.79	7.72	8.28	25.90	29.79	30.87	55.06	49.65	40.99	61.30
ADF, %	2.51	2.36	4.26	4.48	17.21	8.17	8.09	13.03	12.37	12.32	45.90
Lignin, %	0.62	0.78	0.58	0.31	6.45	0.74	0.75	2.44	0.97	3.73	1.85
Bulk density, g/L	748.7	772.3	787.1	773.5	582.6	534.4	562.4	642.5	256.8	335.3	441.0
Particle size, µ	447.0	735.5	805.0	786.0	602.5	619.0	301.0	620.0	919.5	552.5	549.0

Table 3.1 (cont.)

WBC[2], g/g	1.29	1.15	1.11	2.93	3.18	1.94	1.94	3.67	3.13	4.06	5.05
Indispensable AA, %											
Arg	0.39	0.54	0.31	3.42	2.11	1.15	1.24	1.63	0.38	1.17	0.41
His	0.23	0.25	0.19	1.27	0.95	0.70	0.78	0.68	0.33	0.45	0.25
Ile	0.28	0.36	0.35	2.24	1.42	1.00	1.10	0.85	0.31	0.52	0.34
Leu	0.96	0.69	1.18	3.71	2.51	3.10	3.40	1.82	1.11	1.03	0.57
Lys	0.28	0.35	0.19	3.04	2.05	0.89	1.07	0.97	0.28	0.75	0.62
Met	0.18	0.17	0.14	0.64	0.70	0.51	0.58	0.42	0.15	0.24	0.09
Phe	0.39	0.45	0.45	2.43	1.39	1.29	1.41	1.05	0.45	0.63	0.34
Thr	0.28	0.31	0.27	1.79	1.49	1.00	1.08	0.85	0.37	0.53	0.31
Trp	0.06	0.13	0.05	0.62	0.44	0.18	0.18	0.16	0.06	0.16	0.06
Val	0.39	0.48	0.45	2.40	1.86	1.33	1.44	1.36	0.46	0.78	0.43
Dispensable AA, %											
Ala	0.59	0.39	0.81	2.04	1.54	1.82	2.07	1.43	0.63	0.79	0.38
Asp	0.53	0.54	0.56	5.28	2.51	1.62	1.89	1.68	0.51	1.18	0.79
Cys	0.17	0.23	0.13	0.63	0.82	0.49	0.56	0.31	0.20	0.30	0.14
Glu	1.42	2.62	1.71	8.14	5.63	3.62	4.42	3.00	1.55	2.77	0.92
Gly	0.31	0.44	0.28	1.99	1.74	1.01	1.12	1.27	0.39	0.88	0.82
Pro	0.68	0.88	0.70	2.37	2.11	2.01	2.36	1.15	0.96	0.98	0.45

Table 3.1 (cont.)

Ser	0.38	0.46	0.38	2.05	1.30	1.18	1.35	0.90	0.40	0.66	0.45
Tyr	0.27	0.29	0.31	1.77	0.99	1.05	1.10	0.69	0.31	0.44	0.38
Total AA	7.79	9.58	8.46	45.83	31.56	23.95	27.15	20.22	8.85	14.26	7.75

[1] AEE= acid hydrolyzed either extract.

[2] WBC= water binding capacity

Table 3.2. Ingredient composition of experimental diets containing corn, wheat, sorghum, soybean meal (SBM), canola meal, conventional distillers dried grains with solubles (DDGS-CV), low-fat distiller dried grains with solubles (LF-DDGS), corn germ meal (CGM), corn bran, wheat middlings (WM), and soybean hulls, as-fed basis

	Diet										
Item	Corn	Wheat	Sorghum	SBM	Canola meal	DDGS-CV	LF-DDGS	CGM	Corn bran	WM	Soybean hulls
Ingredients, %											
Corn	97.1	-	-	72.1	61.0	45.9	45.8	57.5	57.6	57.9	57.6
Wheat	-	97.7	-	-	-	-	-	-	-	-	-
Sorghum	-	-	97.1	-	-	-	-	-	-	-	-
SBM	-	-	-	25.5	-	-	-	-	-	-	-
Canola meal	-	-	-	-	37.0	-	-	-	-	-	-
HF-DDGS	-	-	-	-	-	52.0	-	-	-	-	-
LF-DDGS	-	-	-	-	-	-	52.0	-	-	-	-
Corn germ meal	-	-	-	-	-	-	-	40.0	-	-	-
Corn bran	-	-	-	-	-	-	-	-	40.0	-	-
Wheat middlings	-	-	-	-	-	-	-	-	-	40.0	-
Soybean hulls	-	-	-	-	-	-	-	-	-	-	40.0
Ground limestone	0.95	1.25	1.00	0.94	0.55	1.36	1.35	1.24	0.47	1.40	0.35
Monocalcium P	1.25	0.36	1.10	0.80	0.80	-	0.15	0.55	1.25	-	1.35
Salt	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin mineral premix[1]	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 3.2 (cont.)

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

Table 3.3. Chemical composition of experimental diets containing corn, wheat, sorghum, soybean meal (SBM), canola meal, conventional distillers dried grains with solubles (DDGS-CV), low-fat distiller dried grains with solubles (LF-DDGS), corn germ meal (CGM), corn bran, wheat middlings (WM), or soybean hulls, as-fed basis

	Diet										
Item	Corn	Wheat	Sorghum	SBM	Canola meal	DDGS-CV	LF-DDGS	CGM	Corn bran	WM	Soybean hulls
GE, kcal/kg	3764	3764	3760	3866	3888	4229	4090	3820	3904	3814	3728
DM, %	87.9	88.6	87.3	88.4	88.7	88.9	88.8	89.1	89.5	88.2	89.4
CP, %	9.61	13.2	8.46	20.0	19.3	18.7	19.6	18.3	8.56	11.6	9.14
AEE[1], %	1.78	1.59	1.81	2.15	2.49	7.61	4.93	1.84	3.39	3.72	4.37
Ash, %	3.61	3.71	3.99	4.79	6.11	5.15	5.30	3.74	2.81	4.31	4.40
Carbohydrates, %											
Glucose	-	-	-	0.48	-	-	-	-	-	-	0.48
Fructose	-	-	-	0.54	-	-	-	-	-	-	0.83
Sucrose	-	-	-	2.40	-	-	-	-	-	-	0.61
Maltose	-	-	-	0.12	-	-	-	-	-	-	0.11
Raffinose	-	-	-	0.16	-	-	-	-	-	-	0.05
Stachyose	-	-	-	0.26	-	-	-	-	-	-	0.03
Verbascose	-	-	-	0.00	-	-	-	-	-	-	0.00
NDF%	11.6	11.7	19.3	12.0	17.6	23.7	22.3	29.7	37.0	24.4	29.4
ADF%	3.07	2.39	4.04	3.31	7.97	5.27	5.53	6.40	7.93	5.42	18.1

[1] AEE= acid hydrolyzed ether extract.

Table 3.4. Comparative digestive utilization of corn, wheat, or sorghum diets between gestating sows and growing pigs[1]

	Corn		Wheat		Sorghum			*P*-value		
Item	Sows	Pigs	Sows	Pigs	Sows	Pigs	SEM	diet	Stage	diet*stage
ATTD of GE, %	88.23	85.84	90.85	89.26	88.88	85.94	1.09	<0.01	<0.01	0.70
ATTD of CP, %	84.96	66.98	91.97	85.67	73.30	61.85	3.20	<0.01	<0.01	0.14
ATTD of ADF, %	56.99[a]	53.66[a]	16.79[c]	30.72[b]	65.28[a]	64.58[a]	6.17	<0.01	0.55	<0.05
ATTD of NDF, %	76.24[b]	66.24[c]	66.16[c]	72.55[b]	89.38[a]	86.99[a]	2.14	<0.01	0.22	<0.01
DE, kcal/kg, as-fed basis	3,321	3,231	3,420	3,360	3,342	3,231	41	<0.01	<0.01	0.71
ME, kcal/kg, as-fed basis	3,223	3,037	3,296	3,212	3,278	3,093	51	<0.05	<0.01	0.33
DE, kcal/kg, DM basis	3,780	3,678	3,858	3,790	3,830	3,703	47	<0.05	<0.01	0.70
ME, kcal/kg, DM basis	3,669	3,457	3,718	3,623	3,757	3,545	58	<0.05	<0.01	0.33
ME/DE, %	85.26	82.45	85.42	84.60	84.58	83.37	1.18	0.40	0.07	0.54

[a-c] Least square means within a row lacking a common superscript letter are different ($P < 0.05$).

[1] Data are means of 8 observations.

Table 3.5. Comparative digestive utilization of diets containing soybean meal (SBM), canola meal (CM), conventional distillers dried grains with solubles (DDGS-CV), or low-fat distillers dried grains with solubles (LF-DDGS) between gestating sows and growing pigs[1]

	SBM		CM		DDGS-CV		LF-DDGS			*P*-value		
Item	Sows	Pigs	Sows	Pigs	Sows	Pigs	Sows	Pigs	SEM	diet	Stage	diet*stage
ATTD of GE, %	87.40	87.22	81.06	80.48	82.48	78.59	82.37	80.56	1.20	<0.01	<0.05	0.17
ATTD of CP, %	88.46	87.41	82.68	77.62	85.43	81.08	85.36	80.64	1.48	<0.01	<0.01	0.34
ATTD of ADF, %	50.44^{bc}	59.57^{a}	27.84^{e}	34.60^{de}	47.85^{bc}	42.11^{cd}	48.21^{bc}	54.84^{ab}	4.04	<0.01	0.08	<0.05
ATTD of NDF, %	76.07^{a}	73.43^{ab}	54.45^{e}	61.34^{d}	70.35^{b}	59.48^{de}	69.05^{bc}	63.41^{cd}	2.70	<0.01	0.07	<0.01
DE, kcal/kg, as-fed basis	3,341	3,365	3,151	3,122	3,488	3,317	3,369	3,288	51	<0.01	0.05	0.08
ME, kcal/kg, as-fed basis	3,165	3,203	2,950	2,969	3,279	3,143	3,164	3,202	71	<0.01	0.83	0.35
DE, kcal/kg, DM basis	3,779	3,807	3,554	3,522	3,924	3,732	3,796	3,705	57	<0.01	0.05	0.08
ME, kcal/kg, DM basis	3,581	3,624	3,328	3,349	3,689	3,536	3,565	3,607	80	<0.01	0.83	0.35
ME/DE, %	83.71	84.05	83.58	83.86	83.55	84.00	83.36	86.15	1.17	0.76	0.24	0.61

$^{a-e}$Least square means within a row lacking a common superscript letter are different ($P < 0.05$).

[1] Data are means of 8 observations.

Table 3.6. Comparative digestive utilization of diets containing corn germ meal (CGM), corn bran, wheat middlings (WM), or soybean hulls (SBH) between gestating sows and growing pigs[1]

	CGM		Corn bran		WM		SBH			*P*-value		
Item	Sows	Pigs	Sows	Pigs	Sows	Pigs	Sows	Pigs	SEM	diet	Stage	diet*stage
ATTD of GE, %	82.73^{ab}	83.94^{a}	79.45^{bcd}	79.23^{bcd}	84.13^{a}	78.91^{cd}	80.75^{abc}	75.76^{d}	1.53	<0.01	<0.05	<0.05
ATTD of CP, %	80.60	77.18	71.53	70.21	82.98	71.36	63.09	57.50	2.47	<0.01	<0.01	0.16
ATTD of ADF, %	61.72^{b}	75.38^{a}	55.49^{b}	60.47^{b}	34.18^{c}	34.66^{c}	79.48^{a}	53.51^{b}	3.26	<0.01	0.43	<0.01
ATTD of NDF, %	82.19^{a}	85.84^{a}	67.77^{bc}	72.41^{b}	65.66^{c}	66.70^{bc}	81.10^{a}	62.11^{c}	2.32	<0.01	0.15	<0.01
DE, kcal/kg, as-fed basis	$3{,}160^{a}$	$3{,}206^{a}$	$3{,}102^{ab}$	$3{,}092^{ab}$	$3{,}208^{a}$	$3{,}010^{b}$	$3{,}010^{b}$	$2{,}825^{c}$	58	<0.01	<0.05	<0.05
ME, kcal/kg, as-fed basis	$3{,}009^{ab}$	$3{,}086^{a}$	$3{,}000^{abc}$	$2{,}947^{abc}$	$3{,}094^{a}$	$2{,}850^{cd}$	$2{,}924^{bc}$	$2{,}703^{d}$	61	<0.01	<0.05	<0.05
DE, kcal/kg, DM basis	$3{,}548^{abc}$	$3{,}600^{ab}$	$3{,}466^{bcd}$	$3{,}455^{bcd}$	$3{,}637^{a}$	$3{,}411^{cd}$	$3{,}369^{d}$	$3{,}161^{e}$	65	<0.01	<0.05	<0.05
ME, kcal/kg, DM basis	$3{,}379^{ab}$	$3{,}465^{a}$	$3{,}352^{ab}$	$3{,}293^{b}$	$3{,}507^{a}$	$3{,}230^{b}$	$3{,}272^{b}$	$3{,}026^{c}$	69	<0.01	<0.05	<0.05
ME/DE, %	80.60	77.18	71.53	70.21	82.98	71.36	63.09	57.50	2.51	<0.01	<0.01	0.16

$^{a\text{-}d}$Least square means within a row lacking a common superscript letter are different ($P < 0.05$).

[1] Data are means of 8 observations.

Table 3.7. Prediction of apparent total tract digestibility of energy and nutrients, and DE and ME of diets for gestating sows from values in growing pigs[1]

Item[2]	Equation	R^2	*P*-value
ATTD of GE, %	$22.7553 + 0.7506*ATTDGE_{pig}$	0.78	<0.001
ATTD of CP, %	$27.2137 + 0.7232*ATTDCP_{pig}$	0.72	<0.001
ATTD of ADF, %	$-2.8492 + 1.0192*ATTDADF_{pig}$	0.55	<0.01
ATTD of NDF, %	$28.4391 + 0.6276*ATTDNDF_{pig}$	0.36	0.05
DE, kcal/kg DM	$911.57 + 0.7727*DE_{pig}$	0.78	<0.001
ME, kcal/kg DM	$1267.29 + 0.6587*ME_{pig}$	0.54	<0.01

[1] A total of 11 diets were used.

[2] ATTD = apparent total tract digestibility.

Table 3.8. Correlation coefficients (r) between chemical components and digestibility of energy and nutrients and DE and ME in 11 diets fed to growing pigs or gestating sows, DM basis[1]

	Correlation coefficient, r					
Item[2]	GE Kcal/kg	CP g/kg	AEE g/kg	Ash g/kg	ADF g/kg	NDF g/kg
Sows						
ATTD of GE, %	-0.27	-0.14	-0.53	-0.21	-0.80**	-0.67*
ATTD of CP, %	0.37	0.60	-0.10	0.27	-0.69*	-0.81**
ATTD of ADF, %	-0.18	-0.35	0.11	-0.28	0.45	0.53
ATTD of NDF, %	-0.29	-0.35	-0.18	-0.41	0.09	0.10
DE, kcal/kg DM	0.52	0.29	0.12	0.18	-0.66*	-0.80**
ME, kcal/kg DM	0.28	-0.03	-0.02	-0.08	-0.62*	-0.76**
Growing pigs						
ATTD of GE, %	-0.24	0.10	-0.69*	-0.22	-0.75**	-0.76**
ATTD of CP, %	0.47	0.79**	0.05	0.32	-0.39	-0.58
ATTD of ADF, %	-0.09	-	-0.19	-0.34	0.41	0.12
ATTD of NDF, %	-0.39	-0.14	-0.66*	-0.48	0.01	-0.35
DE, kcal/kg DM	0.42	0.47	-0.15	0.12	-0.67*	-0.88**
ME, kcal/kg DM	0.42	0.50	-0.17	0.15	-0.61*	-0.84**

**P* < 0.05, ***P* < 0.01.

[1] A total of 11 diets were used.

Table 3.9. Effects of diet composition (g/kg of DM) on digestibility of energy and nutrients and the concentration of DE and ME (kcal/kg, DM) in growing pigs and gestating sows[1]

			Parameter estimate										
Item	Stage	Intercept	GE, kcal/kg	CP, g/kg	AEE,[3] g/kg	Ash, g/kg	ADF, g/kg	NDF, g/kg	C(p)	R^2	AIC	RMSE	*P*-value
ATTD of GE, %	Sow	97.53	-	-0.0248	-0.0192	-	-0.0264	-0.0282	4.75	0.85	17.43	1.90	<0.05
ATTD of GE, %	Pig	101.34	-	0.0353	-0.0563	-0.2833	-0.0364	-	5.03	0.93	13.15	1.56	<0.01
ATTD of CP, %	Sow	286.00	-0.0503	0.1051	0.3434	-	-	-0.2018	4.71	0.91	29.93	3.35	<0.01
ATTD of CP, %	Pig	158.91	-0.0209	0.1886	0.2043	-0.4122	-0.0211	-0.0775	7.00	0.85	42.05	5.93	<0.05
ATTD of ADF, %	Sow	-507.11	0.1445	-0.0557	-0.7759	-1.1915	-0.0636	0.5078	7.00	0.50	68.65	19.88	0.69
ATTD of ADF, %	Pig	-473.17	0.1322	0.0676	-1.0023	-1.0632	0.0092	0.3120	7.00	0.60	59.23	12.96	0.53
ATTD of NDF, %	Sow	-20.04	0.0300	-0.0046	-0.1650	-0.6287	-0.0385	0.1208	7.00	0.23	59.96	13.40	0.96
ATTD of NDF, %	Pig	52.70	0.0057	0.0152	-0.3624	-0.0837	0.0518	-0.0678	7.00	0.66	50.00	8.52	0.42
DE, kcal/kg DM	Sow	2750.28	0.3294	-0.4031	2.9577	-2.7199	-1.1788	-1.7808	7.00	0.91	100.66	85.17	<0.01
DE, kcal/kg DM	Pig	-859.82	1.2275	0.9246	-5.3221	-10.8080	-1.4293	0.1322	7.00	0.96	95.26	66.64	<0.01
ME, kcal/kg DM	Sow	3360.92	0.1884	-1.1757	3.2946	-3.3369	-1.1621	-1.9782	7.00	0.85	105.48	106.04	<0.05
ME, kcal/kg DM	Pig	-1739.9	1.3693	0.8217	-7.3042	-8.9457	-1.1202	0.4537	7.00	0.90	104.28	100.45	<0.01

[1] Candidate models are those where C(p) is similar to p. P is the number of variables in the model +1. The optimal model is the prediction equation with the lowest AIC (measure of fit) and root mean square error (RMSE; measure of precision).