Effects of feed processing on the nutritional value of feed ingredients or diets fed to pigs

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ABSTRACT:

A conventional diet based on corn and soybean meal fed to pigs is usually provided in a mash form and in most cases processing other than grinding and mixing is not used. However, due to the high cost of energy in pig diets, use of high fiber ingredients such as soybean hulls, distillers dried grains with solubles, and wheat middlings has increased. High fiber concentrations in the diet usually results in reduced energy and nutrient digestibility due to the low capacity of pigs to digest fiber, which negatively impacts growth performance and carcass composition of the pigs. Feed processing technologies such as changes in grinding procedures, expansion, extrusion, pelleting, use of enzymes or chemical treatments may, however, be used to solubilize some of the cellulose and hemicellulose fractions that form the cell wall of plants in the ingredients, and therefore, increase nutrient availability. This may have a positive effect on energy digestibility, and therefore, also on pig growth performance and carcass composition, but effects of different feed technologies on the nutritional value of feed ingredients and diets fed to pigs are not fully understood. It has however, been demonstrated that reduced particle size of cereal grains usually results in increased digestibility of energy, primarily due to increased digestibility of starch. Extrusion or expansion of ingredients or diets may also increase energy digestibility and it appears that the increase is greater in high fiber diets than in diets with lower concentrations of fiber. Chemical treatments have not consistently improved energy or nutrient digestibility, but a number of different enzymes may be used to increase the digestibility of phosphorus, calcium, or energy. This, there are several opportunities for using feed technology to improve the nutritional value of diets fed to pigs.

Keywords:

Chemical treatments, Enzymes, Particle size, Pig, Processing, Starch

Introduction

In the swine industry, the cost of feed has a high impact on the total production costs of pork. This is more notable when prices of feed are high than when costs are lower. Therefore, maximizing the utilization of nutrients that are provided from the feed to the pig is among the strategies that can be used to reduce the impact of high feed prices on production costs.

Feed ingredients are usually processed using one or more feed processing techniques before feed is consumed. Most ingredients are ground before being consumed, which reduces the particle size and increases digestibility (Wondra et al., 1995d). Feed ingredients are also sometimes heated, which may reduce concentrations of antinutritional factors, but effects of heating on energy and nutrient digestibility have not been consistent (Herkelman et al., 1992). Other processing techniques that may be used include expander processing (Lundblad et al., 2011; Thomas et al., 1997), pelleting (Hancock and Behnke, 2001; le Gall et al., 2009), and extrusion (Lundblad et al., 2011; Stein and Bohlke, 2007). Chemical and enzyme treatments may be used to solubilize the cellulose and hemicellulose fractions that form the cell wall of plants. Some of the chemicals used to increase fiber digestibility are sodium hydroxide (NaOH; Fahey et al., 1993; Felix et al., 2012; Morrow et al., 2013),

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ammonium (Mosier et al., 2005; Realff and Abbas, 2004), calcium oxide (CaO; Cobianchi et al., 2012), and calcium hydroxide (Ca(OH)2; Lesoing et al., 1981). Benefits of microbial phytase in terms of increasing the digestibility of phosphorus (Almeida and Stein, 2010; 2013) and calcium (Gonzalez-Vega et al., 2013; 2015) are well documented. However, other exogenous enzymes such as cellulase, hemicellulase, xylanase, β-glucanase, α-galactosidase, or carbohydrase mixtures may also be used to increase energy and fiber digestibility in feed ingredients and diets (Adeola and Cowieson, 2011; Bals et al., 2006; Emiola et al., 2009; Park et al., 2003; Yañez et al., 2011; Casas and Stein, 2016). There is, however, a lack of information about effects of many of these processing techniques on energy and nutrient digestibility and the utilization of feed by pigs. There is also a lack of information about how combinations of different processing techniques may impact feed utilization by pigs.

Particle size of feed ingredients

1. Measuring Particle Size

Determining the mean particle size of feedstuffs that are commonly used in diets fed to pigs is not a well-established practice in feed mills. However, energy and nutrient digestibility may be increased as the particle size of feedstuffs decreases (Fastinger and Mahan, 2003; Kim et al., 2002; Mavromichalis et al., 2000; Rojas and Stein, 2015; Wondra et al., 1995a,c). Therefore, it is important to determine the optimal particle size of feed ingredients to maximize energy and nutrient digestibility.

The American Society of Agricultural Engineers has published a procedure for determining particle size and calculating the fineness of feedstuffs (ASAE, 2008). Particle size distribution and mean particle size of feedstuffs are determined using 100 g of feedstuff that is placed on the top of a stack of test sieves (i.e., U.S sieve # 4, 6, 8, 12, 16, 20, 30, 40, 50, 70, 100, 140, 200, 270, and a solid metal pan), which are stacked from the biggest to the smallest aperture size sieve. The test sieves are located in a vibratory sieve shaker for 10 min. The amount of feedstuff that is accumulated in each of the test sieves is recorded and weighed to calculate particle size distribution and mean particle size. After determination of particle size, the surface area is calculated using the mean particle size of the feedstuff as a reference (ASAE, 2008).

2. Mills Used for Grinding

Grinding is used to reduce the particle size of a feed ingredient and it is accomplished with the use of different types of mills. The most common mills used in the industry are roller mills and hammer mills. Ingredients such as distillers dried grain with solubles (DDGS) and soybean meal (SBM) are often ground during the production process, and in most cases, no further grinding is needed for these ingredients before diets are mixed. In contrast, cereal grains and pulse crops are usually not ground prior to entering the feed mill, and these ingredients, therefore, need to be ground.

In the feed industry, there are different preferences for use of roller mills or hammer mills. These preferences are often based on the grinding capacity needed, electricity efficiency and types of feedstuffs used (Hancock and Behnke, 2001). However, roller mills require more oversight and they are more complicated to operate and manage than hammer mills, but they have improved energy efficiency, and provide a more uniform particle size compared with hammer mills. Thus, there is less variation among the size of particles if a roller mill is used compared with a hammer mill (Hancock and Behnke, 2001; Wondra et al., 1994b). Hammer mills increase losses of moisture from the grain, are more noisy, and are more costly to maintain than roller mills (McEllhiney, 1983), but a hammer mill system can be installed for about 50% of the cost of a roller mill (Vermeer, 1993). Corn that is ground with a roller mill compared with a hammer mill contains more uniform edges and the shape of the particles tends to be more spherical (Reece et al., 1985). However, a more uniform particle size distribution is also observed with the same mean particle size if a roller mill rather than a hammer mill is used, which results in a greater digestibility of dry matter (DM), gross energy (GE), and N, but this does not affect growth performance (Wondra et al., 1995b). Roller mills may be stacked so the grain is rolled not only once, but 2, 3, or even 4 times (Stark, 2013). This procedure allows roller mills to produce an end-product with a particle size of less than 500 μm.

Historically, most feed mills have used either roller mills or hammer mills, but not both, but recently, advances in milling technology have introduced systems where ingredients are first rolled using 1, 2, or 3 sets of rollers and then processed in a hammer mill. This technology is known as “multiple stage grinding”, and it is believed that this results in a more uniform particle size and reduced cost of grinding, but no comparative data between multiple stage grinding and single stage grinding have been reported. It is also possible to sieve the material after the rollers so that only the larger particles are guided to the hammer mill, whereas smaller particles by-pass the hammer mill. Use of this procedure will minimize electricity usage and results in the most uniform particle size.

Electricity used to process feedstuffs is an important component in a feed mill's budget. Corn milled in a hammer mill at 600 μm rather than 1000 μm increased energy usage, and when particle size was decreased from 1,000 to 400 μm, the energy usage increased almost 2.5 times (Wondra et al., 1995¬a). The production rate (ton/h) also decreases as particle size is reduced (Healy et al., 1994). Likewise, electricity costs are more expensive for hammer mills compared with roller mills (Vermeer, 1993). Energy usage is also affected by the type of cereal that is ground (Hancock and Behnke, 2001).

3. Effect of Particle Size on Digestibility of Energy and Nutrients in Cereal Grains

Research to identify an optimal particle size of cereals has been conducted and effects of particle size on energy and nutrient digestibility have been reported (Amaral et al., 2014; Fastinger and Mahan, 2003; Kim et al., 2002; Lawrence et al., 2003; Mavromichalis et al., 2000; Rojas and Stein, 2015; Wondra et al., 1995a,b,c,d;). Most recommendations for optimal particle size were generated between the 1960s and the 1990s depending on the type of cereal grain, type of milling, and physiological state of the pig (e.g., weanling pig, growing pig, finishing pig, or sow). However, in most cases, a reduction in the mean particle size to a range between 485 to 600 μm had a positive effect on nutrient and energy digestibility and growth performance (Rojas and Stein, 2015; Wondra et al., 1995b).

A reduction of particle size of wheat from 920 to 580 μm increased apparent total tract digestibility (ATTD) of starch, but not of GE (Kim et al., 2005). However, pigs fed a barley-field pea diet with a particle size of 400 μm had an increase in ATTD of GE, DM, crude protein (CP), and GE compared with pigs fed the same diet ground to 700 μm (Oryschak et al., 2002). A linear increase in ATTD of GE and CP and in the SID of AA also has been observed when particle size of lupins was decreased from 1304 to 567 μm (Kim et al., 2009). Likewise, reduction of the mean particle size of field peas results in an increase in the digestibility of starch and energy and therefore also in an increase in DE (Montoya and Leterme, 2011). The ATTD of DM and GE, and the concentration of metabolizable energy (ME), increased when pigs were fed DDGS ground to 308 μm compared with pigs fed DDGS ground to 818 μm, but particle size did not affect the ATTD of N and P (Liu et al., 2012). Reduction of particle size of corn from 500 to 332 μm also increased the rate of phytate degradation (Ton et al., 2014), but generally, particle size of corn gran or corn DDGS does not affect P digestibility (Liu et al., 2012; Rojas and Stein, 2015).

Several experiments have focused on evaluating corn particle size because corn is one of the most common ingredients used in pig diets. The ATTD of DM, N, and GE in corn increased 5, 7, and 7 percentage units, respectively, when particle size was reduced from 1,200 to 400 μm (Wondra et al., 1995d), but the type of mill used to grind the corn may have an effect on energy and nutrient digestibility (Wondra et al., 1994b). A reduction of the mean particle size of corn from 865 to 339 μm increased linearly the apparent ileal digestibility of starch and GE and the concentration of DE and ME, but this was not the case for the standardized total tract digestibility of P and the standardized ileal digestibility (SID) of AA (Rojas and Stein, 2015). Similar results were observed by Giesemann et al. (1990), who reported that finishing pigs fed a corn-based diet with a particle size of 641 μm had an increased ATTD of DM, N, and GE compared with pigs fed a diet with a mean particle size of 1,500 μm. Likewise, a reduction in particle size from 900 to 300 μm in corn and sorghum improved the ATTD of GE (Healy, 1992; Healy et al., 1994), and an improved ATTD of GE and ether extract was observed as the particle size of corn grain was reduced (Huang et al., 2015). The use of pelleting in combination with grinding also may increase ATTD of DM, GE, and N (Wondra et al., 1995a). In a 24 d experiment, energy and DM digestibility was determined on d 9 and pigs fed corn ground to 1000 μm had a reduced ATTD of DM and GE compared with pigs fed corn ground to 500 μm (Kim et al., 2002). Other observations reported by Wondra et al. (1995c) indicated that ATTD of GE, DM, and N improved as the particle size of corn was reduced from 1,200 to 400 μm. However, particle size did not affect urine N excretion, but as particle size of corn was reduced from 1,200 to 400 μm, the ME of corn increased from 3,399 to 3,745 kcal/kg (Wondra et al., 1995c).

The ATTD of GE also is improved linearly when particle size of sorghum is reduced (Healy et al., 1994). A reduction of particle size of SBM from 949 to 185 μm had no effect on average SID of indispensable AA or dispensable AA, but a linear increase in the SID of isoleucine, methionine, phenylalanine, and valine was observed as particle size was reduced (Fastinger and Mahan, 2003). However, energy digestibility of SBM was not affected by decreasing the particle size of SBM from 949 to 185 μm. Nevertheless, it was suggested that SBM ground to 600 μm will have the best AA and energy digestibility (Fastinger and Mahan, 2003).

The ATTD of N and DM in wheat also increase as particle size is reduced from 1,300 to 600 μm (Mavromichalis et al., 2000), but this is not the case for barley because the ATTD of organic matter (OM), energy, or CP is not affected by particle size (Medel et al., 2000). This indicates that the effect of reduction in particle size is unique and depends on each specific ingredient.

4. Effect of Particle Size on Growth Performance and Sow Productivity

Reduction of cereal grain particle size may increase enzyme surface action, which leads to increased energy and nutrient digestibility (Fastinger and Mahan, 2003; Kim et al., 2002; Rojas and Stein, 2015). However, this increase in digestibility is not always translated into a positive effect on growth performance because pigs may compensate for a low digestibility by eating more feed. The best results on growth performance are obtained in weanling pigs and finishing pigs if wheat is ground to 600 and 1,300 μm, respectively (Mavromichalis et al., 2000).

Carcass dressing percentage was increased linearly in pigs fed corn ground from 865 to 339 μm (Rojas and Stein, 2016a) and there was a tendency for a greater carcass dressing percentage when pigs were fed a diet containing sorghum ground to 319 μm compared with pigs fed a diet containing sorghum ground to 724 μm (Paulk et al., 2015). Likewise, pigs fed corn ground to 400 μm compared with pigs fed corn ground to 1,000 μm had an increase in carcass dressing percentage (Wondra et al., 1995a). The reason for this observation may be that the weight of the intestines is reduced with reduced particle size of corn (Rojas and Stein, 2016a). In contrast, Mavromichalis et al. (2000) reported that there was no effect on carcass dressing percentage when pigs were fed wheat ground to 600 μm compared with pigs fed wheat ground to 1,300 μm. Thus, it appears that the positive effect of smaller particle size on dressing percentage that is observed for corn and sorghum, may not always be seen for other cereal grains and more research to investigate effects of particle size on dressing percentage of pigs fed wheat, barley, triticale, and rye is needed.

Feed intake may be improved if particle size of wheat is reduced from 1,200 to 980 μm, but this did not have an effect on overall gain to feed (G:F; Seerley et al., 1988). Likewise, pigs (93 to114 kg) fed wheat that was ground to 600 μm had improved G:F compared with pigs fed wheat ground to 1,300 μm (Mavromichalis et al., 2000), but the same effect was not observed from 67 to 93 kg. In contrast, Hancock and Behnke (2001) reported that for each 100 micron decrease in particle size of corn, the G:F ratio in growing pigs will be improved by 1.3%. Likewise, Wondra et al. (1995b) reported that the G:F ratio was 7% greater in pigs fed corn ground to 400 μm compared with pigs fed corn ground to 800 μm. These observations are in agreement with data reported by Amaral et al. (2014) and Rojas et al. (2016a). Pigs have a greater preference for corn when the particle size is reduced than for sorghum that was ground to the same particle size as corn (Healy et al.,1994), and Kim et al. (2005) hypothesized that reduction of particle size does not have the same effect among all cereals grains. Pigs fed corn ground to 1,000 rather than 400 μm had reduced average daily feed intake and increased G:F, which is likely a result of the greater energy value in corn ground to 400 μm compared with corn ground to 1,000 μm (Wondra et al., 1995a). Similar results were reported by Paulk et al. (2015) who observed that finishing pigs fed diets containing sorghum ground to 319 μm improved G:F compared with pigs fed a diet containing sorghum ground to a mean particle size of 724 μm. In contrast, growth performance of pigs fed SBM that was ground to 639 μm or 444 μm was not different from that of pigs fed SBM ground to 965 or 1,226 μm (Lawrence et al., 2003). It was hypothesized that the reason for this observation is the low inclusion level of SBM in the diet (Lawrence et al., 2003). Thus, the effect of reduced particle size may only be measurable if a high inclusion rate of the ingredient is used in the diet.

Relatively little research investigating the effect of particle size on sow BW and litter performance has been reported. A reduction in particle size of corn from 1,200 to 400 μm does not affect BW or back fat losses in lactating sow (Wondra et al., 1995d). However, there was a linear decrease in ADFI of sows as particle size of corn was increased from 400 to 1,200 μm and a decrease in litter BW gain was also observed (Wondra et al., 1995d).

5. Effect of Particle Size on Ulcer Development

The stomach of the pig has 4 different regions (esophageal region, cardiac region, fundic region, and pyloric region; Yen, 2001). The esophageal region is the non-glandular region, whereas, the cardiac, fundic, and pyloric regions are the glandular regions. Each region has specific characteristics to maintain the function of the stomach. However, the functions of the stomach may be interrupted if pigs develop ulcers, and it is possible that particle size of feed ingredients impact the risk of pigs developing ulcers. There are different types of ulcers such as peptic ulcers and esophagogastric ulcers that may affect the glandular area and the non-glandular esophageal portion of the stomach (Mahan et al., 1966). However, the esophageal region is the region that is most at risk of developing gastric ulcers if pigs are fed ingredients with a reduced particle size (Mahan et al., 1966; Maxwell et al., 1970; Pickett et al., 1969; Reimann et al., 1968;) because the mucus in the glandular portion of the stomach has a protective function (Ohara et al., 1993; Varum et al., 2010). However, a reduced particle size of grain is not the only factor that may trigger development of ulcers. There are other factors such as type or intensity of production (Kowalczyk, 1969; Ramis et la., 2004) and type of housing (Amory et al., 2006) that also may increase the risk of pigs developing ulcers. The development of ulcers increases as pigs are fed pelleted diets that contain corn ground to 400 µm compared with pigs fed non-pelleted diets (Wondra et al., 1995a,b). However, growth performance may not always be affected by the presence of ulcers, and pigs fed pelleted diets usually have greater average daily gain and G:F than pigs fed unpelleted diets.

Development of ulcers is considered one of the major economical losses in the swine industry (Friendship, 2003) and the presence of esophagogastric ulcers have increased lately in the U.S. pork industry due to increased use of pelleting (Hancock and Behnke, 2001). In the UK, 79% of pigs from 60 farms had some level of ulcers (Swaby and Gregory, 2012) and in a survey related to the presence of gastric ulcers in pigs on 16 commercial farms in the UK, it was observed that 19.1% of the commercial farms had some prevalence of ulcers (Amory et al., 2006). It is hypothesized that the formation of ulcers starts within 7 d after pigs are provided a diet ground to a small particle size and it is also assumed that keratinization and erosions of stomach tissue may be ameliorated when pigs are fed a coarse diet for 7 d (Maxwell et al., 1970). It has also been proposed that this may be achieved if pigs are fed coarse diets 40 h prior to slaughter (Reimann et al., 1968). Development of ulcers is followed by colonization of Helicobacter spp and the presence of this microorganism is more evident in the fundic and pyloric regions than in the esophageal and cardiac regions (Rodriguez et al., 2009). Pigs fed either a finely ground diet or a pelleted diet have a greater secretion of chloride in the stomach compared with pigs fed a coarsely diet or a non-pelleted diet (Mobeler et al., 2010), which promote the presence of Helicobacter spp in the stomach (Eaton et al., 1995; Morgan et al., 1991).

One of the reasons for developments of ulcers is that fine grinding may result in reduced pH in the stomach (Mahan et al., 1966). Pepsin activity is also increased as particle size of corn decreases (Maxwell et al., 1970). Pigs fed diets that are either finely ground or pelleted have greater concentrations of chloride in the esophageal region of the stomach compared with pigs fed either coarse or unpelleted diets (Mobeler et al., 2010). This may be due to an increased mixing in the stomach and more watery digesta, which results in an increase in HCL secretion.

There is evidence that pigs fed corn with less variation in particle size tend to have less keratinization in the stomach (Wondra et al., 1995b) and pigs fed corn ground to 400 µm have more ulcers and keratinization in the esophageal region compared with pigs fed corn ground to 1,200 µm (Wondra et al., 1995a). A linear increase in the severity of parakeratosis in the esophageal region of the stomach in finishing pigs was observed as particle size of corn was reduced from 865 to 339 µm, but this observation did not impact pig growth performance (Rojas et al., 2016). Likewise, when sows are fed corn ground to 1,200 µm, only 25% of the sows developed ulcers, but if sows are fed corn ground to 400 µm, 77% of the sows developed ulcers (Wondra et al., 1995a). Pigs fed diets containing wheat ground to 600 µm developed more ulcers and had more tissue keratinization compared with pigs fed diets containing wheat ground to 1,300 µm, but this did not have an effect on G:F (Mavromichalis et al., 2000).

6. Effect of Particle Size on Feed Flowability and Handling

There is relatively little information about the effect of particle size on feed flowability and handling, but it has been hypothesized that reduced particle size may result in poor flowability (Appel, 1994). This concurs with observations indicating that flowability of diets is reduced as particle size of DDGS or corn is reduced (Liu et al., 2012; Rojas et al., 2016a). Likewise, SBM ground to 639 µm had a greater angle of repose than SBM ground to 965 µm (Lawrence et al., 2003). However, if a bowl type feeder is used and if feed is added twice daily, a reduced particle size does not reduce flowability of the diet (Wondra et al., 1995d). Likewise, pelleting of diets will also prevent the bridging problems, dustiness, ingredient segregation, and increased bulk density that are common problems when diets are ground to less than 600 µm (Skoch et al., 1983a; Wondra et al., 1995a). The palatability of corn with a particle size of 444 µm was not less than that of corn ground to 619 µm when fed to lactating sows (Pettigrew et al., 1985).

Thermal treatments

Most diets fed to pigs are provided in a mash form after the ingredients have been ground and mixed. These types of diets are relatively inexpensive to produce compared with diets that are pre-processed with steam conditioning followed by pelleting, or expansion or extrusion, or a combination of expanding or extrusion and pelleting. Effects of these processing techniques on energy and nutrient digestibility of diets or feed ingredients have been investigated (Jha et al., 2011; Liu et al., 2013; Ohh, et al., 2002; Rehman and Shah, 2005; Rojas et al., 2016b; Stein and Bohlke, 2007). The objectives of using processing technologies are to improve energy and nutrient digestibility in ingredients (Hancock and Behnke, 2001) as well as to stimulate feed intake in the case of weanling pigs (Zijlstra et al., 2009). Thus, it is believed, that the nutritional value of ingredients and diets may be improved by feed processing (Zijlstra et al., 2009).

Feed processing often involves application of a source of heat, but excessive heat may result in the Maillard reaction (Gerrard, 2002). The Maillard reaction takes place between an amino group in an AA and a carbonyl group of a reducing sugar (Nursten, 2005), which reduces the availability and digestibility of AA (Almeida et al., 2013; Fontaine et al., 2007; Gonzales-Vega et al., 2011). Heating followed by cooling may also result in retrogradation of the starch, which will then become less digestible and, therefore, the energy value may be reduced (Sauber and Owens, 2001).

Addition of phytase to feed is a common technique used in pig diets to hydrolyze the bond between P and the phytate molecule. However, pelleting or expansion or extrusion of diets may reduce the efficiency of phytase and other exogenous enzymes because of the heat that is applied (Slominski et al., 2007). Therefore, phytase and other enzymes need to be thermostable at the temperature used during feed processing to avoid loss of activity. Alternatively, phytase and other enzymes that are available in a liquid form may also be sprayed on the pellets after production.

1. Steam Conditioning

The main objective of steam conditioning is to establish conditions that will result in production of a durable pellet (Hancock and Behnke, 2001). During conditioning, the temperature increases to 75°C and the moisture increases 3 to 4 percentage units in the feed mixture for approximately 1 min (Svihus and Zimonja, 2011). Addition of either steam or water results in formation of a liquid layer on top of the ingredients that helps bind certain particles in the mixture (Obernberger and Thek, 2010). It is believed that the durability of the pellet is increased and the heat damage of the starch is reduced if ingredients are conditioned prior to pelleting (Zijlstra et al., 2009). Therefore, the conditioning step is important because there are several factors that may impact the quality of the pellet such as particle size of ingredients and the type of ingredients included in the diet (Hancock and Behnke, 2001).

Steam conditioning may be completed by a single pass or a 2-pass conditioner, which influences the length of time the ingredients will be in the conditioner. The longer feedstuffs are exposed to the steam and the greater the temperature is, the greater is the starch gelatinization and protein denaturation (Hancock and Behnke, 2001; Lewis et al., 2015a), because the granules in the starch become hydrated and swell due to absorption of water (Fellows, 2000). However, rapid cooling after heating may lead to formation of retrograded starch, which leads to formation of crystals that reduce enzymatic starch digestibility (Brown, 2004; Htoon et al., 2009) and cooling needs therefore to be controlled to reduce the risk of creating retrograded starch.

2. Pelleting

Use of steam and pressure are the principles behind the pelleting technology. Steam increases the temperature of the feed and the steamed ingredients are subsequently pelleted to a determined pellet size using pressure (Zijlstra et al., 2009). Effects of different pellet sizes have been investigated, but it has been suggested that diets for nursery and finishing pigs may be processed using a single die with 4 to 5 mm holes without affecting growth performance (Hancock and Behnke, 2001). The effect of die thickness was investigated on the SID of AA in corn and wheat fed to pigs and no significant effects were observed on AA digestibility when the size of the die increased from 16 to 24 mm and from 16 to 20 mm, respectively (Lahaye et al., 2007). Pellet hardness and pellet durability index are acceptable indicators of pellet quality (Thomas and van der Poel, 1996) and it is believed that expansion or extrusion prior to pelleting may increase the pellet durability index in diets based on cereal grains (Traylor et al., 1999). Pelleting changes the physico-chemical characteristics of the ingredients due to the heat that is applied during the process (Zijlstra et al., 2009), and pelleting usually improves feed intake of weanling pigs compared with diets provided in a mash form (Steidinger et al., 2000).

Starch in cereals grains that are pelleted is more likely to be digested in the small intestine due to the gelatinization of starch that may be accomplished by pelleting (Jensen and Becker, 1965). Likewise, a decrease in dustiness and increased handling properties, bulk density, and reduction in segregation of components in feed ingredients are some of the advantages of using pelleting (Hancock and Behnke, 2001; Svihus and Zimonja, 2011). However, the acquisition and maintenance of equipment for pelleting may be expensive (Svihus and Zimonja, 2011).

In terms of applicability, pelleting often results in an increase in feed conversion by 4 to 12 percentage units (Lewis et al., 2015b; Paulk and Hancock, 2016; Steidinger et al., 2000; Walker, 1989; Xing et al., 2004). Likewise, ADG is also often increased by pigs fed pelleted diets compared with pigs fed diets in a meal form (Laitat et al., 1999; Overholt et al., 2016; Ulens et al., 2015; Xing et al., 2004). The main reason for these observations is that feed wastage is reduced and digestibility of energy is improved because of gelatinization of starch (NRC, 2012; Richert and DeRouchey, 2010) that occurs when cereal grains are processed in the presence of heat. Therefore, pelleting may also impact feed intake and gut function of the pig (Svihus and Zimonja, 2011). Pelleting a corn-soybean meal diet increased digestibilities of DM, N, and GE by 5 to 8% compared with feeding the same diet in a meal form (Wondra et al., 1995a). This concurs with observations by Rojas et al. (2016b) who reported that pelleting different types of diets regardless of the level of fiber (i. e., 7, 11, or 20% NDF) improved the apparent ileal digestibility of GE, DM, and most indispensable AA and the ATTD of GE compared with un-pelleting diets. Likewise, Lahaye et al. (2008) reported that pelleting a wheat-canola meal diet improved the ileal digestibility of CP and AA and this is also the case if field peas are pelleted (Stein and Bohlke, 2007). Similar results by pelleting diets containing wheat and SBM compared with un-pelleted diets also were reported (van de Ginste and de Schrijver, 1998). Diets fed to growing and finishing pigs based on corn and wheat middlings that were pelleted increased the digestibility of GE and G:F (Skoch et al., 1983b). Recently, it was reported that pigs fed pelleted diets had a greater feed efficiency compared with pigs fed meal diets, and reduced performance of pigs fed diets containing high-fiber by-products was ameliorated if the diet was pelleted (Fry et al., 2012). This observation concurs with recent data demonstrating that the ME of diets is increased by pelleting (Rojas et al., 2016b).

3. Extrusion

In association with pelleting, extrusion is a technology that is often used in the feed production industry. In the United States, only 5% of the pet feed is not extruded (Spears and Fahey, 2004), which demonstrates the importance of this technology for the pet feed production industry. The extrusion process consists of pressuring the feed material through a barrel by the use of single or twin-screw extruders, which results in generation of heat (Hancock and Behnke, 2001; Fellows, 2000; Richert and DeRouchey, 2010). Both types of extruders may be used on the whole diet or on individual ingredients. The objective of extrusion is to increase energy and nutrient digestibility in cereal grains, which is expected to have a positive effect on feed conversion rate and possibly growth performance of pigs (Hancock and Behnke, 2001). Extrusion results in a more severe change in the physico-chemical characteristics of the feedstuff compared with pelleting (Zijlstra et al., 2009) because of the change in temperature, pressure, friction, and attrition of the feedstuffs inside the extruder (Hancock and Behnke, 2001). Extrusion of the entire diet compared with pelleting improved feed conversion by 8% and DM and CP digestibility by 3 and 6%, respectively (Sauer et al., 1990). However, feed intake of pigs is not always improved when diets containing wheat or sorghum are extruded (Durmic et al., 2002). Ileal digestibility of DM is improved by extrusion of corn, but AA digestibility is not different between extruded and non-extruded corn (Muley et al., 2007). However, the ileal digestibility of CP may be greater in extruded soybean meal compared with non-extruded soybean meal (Chae et al., 1997), but that is not always the case (Navarro et al., 2014). Extrusion of field peas has a positive effect on the

ATTD of GE and on the apparent ileal digestibility of most indispensable AA (Htoo et al., 2008; Stein and Bohlke, 2007) and GE (Muley et al., 2007) and the DE of field peas is improved by 4.8% by extrusion (Stein and Bohlke, 2007). Extrusion or extrusion in combination with pelleting of a diet containing corn, soybean meal, DDGS, and soybean hulls improved the ileal digestibility of GE, starch, DM, CP, and most indispensables AA compared with the un-processing diet (Rojas et al., 2016b). Therefore, there is an opportunity for increasing energy and nutrient digestibility if ingredients that have high concentrations of fiber are extruded, but it may not always be economical to extrude diets for growing-finishing pigs (Hancock and Behnke, 2001). Apparent total tract digestibility of DM and CP was not different when a flaxseed-field pea mix was extruded using either a twin-screw extruder or a single-screw extruder (Htoo et al., 2008). However, ATTD of GE and the concentration of DE were greater in the diet extruded using a single-screw compared with the diet extruded using a twin-screw extruder (Htoo et al., 2008). Likewise, extrusion also may increase the solubility of dietary fiber, which in turn may result in an increased energy digestibility because soluble fibers are much more fermentable by pigs than insoluble fibers (Urriola et al., 2010). As a result of the positive effects of extrusion on digestibility and feed efficiency, some feed companies in Europe extrude diets for pigs and most of the compound feed in Europe is pelleted.

4. Expansion

Expansion is also known as a shear conditioning process. The reduced temperature and retention time that feed ingredients are exposed to in the expansion process are the main differences between this process and the extrusion technology (Fancher et al., 1996). This is the reason there is less starch gelatinization if feed ingredients are processed using the expansion technology compared with using the extrusion technology (Liu et al., 2013). It is unusual that expanded feed is offered to pigs in mash form. Instead, most expanded feed also goes through a steam condition step and pelleting (Johnston et al., 1999; Laurinen et al., 1998; Lundblad et al., 2009). It has been proposed that pelleting may be replaced by expansion (Zijlstra et al., 2009), because during expansion, the physico-chemical characteristics of the feed are modified (van der Poel et al., 1998) due to the high pressure that is used in the process (Hancock and Behnke, 2001). However, nutrient and energy digestibility were not improved by pigs fed expanded diets based on wheat and barley compared with pigs fed un-expanded diets (Callan et al., 2007), but fiber digestibility may be improved by expansion (van der Poel et al., 1998). In contrast, Traylor et al. (1999) reported that there was an increase in energy and nutrient digestibility when growing pigs were fed an expanded corn-SBM based diet compared with pigs fed an un-expanded corn-SBM based diet. However, digestibility of DM, neutral detergent fiber (NDF), and CP were not improved if pigs were fed an expanded diet containing barley and wheat bran-wheat middlings (Laurinen et al., 1998). Usually a complex phase 1 diet contains corn, SBM, soybean oil, and animal protein. Expansion of different portions of a complex diet (e.g., corn, corn-SBM, or corn-soybean meal-oil) in combination with highly digestible animal protein results in an increase in average daily again when fed to weanling pigs compared with pigs fed a whole complex diet that was expanded (Johnston et al., 1999). However, when a wheat-fish meal-SBM based diet was either expanded or extruded and fed to weanling pigs for 36 d, the greater G:F in pigs fed the extruded diet compared with pigs fed the expanded diet was mainly due to a greater digestibility of starch in the extruded diet (Lundblad et al., 2011). However, Millet et al. (2012) reported and increased G:F ratio for feed fed an expanded diet compared with pigs fed the same diet in meal form, but no difference in ADG was observed, which indicates that expansion may have improved energy digestibility. The pellet durability index of a corn- and barley-based diet was improved by adding water into the mixer followed by expansion of the diet (Lundblad et al., 2009). It is, thus, possible that expansion in combination with pelleting may result in a better quality pellet (Hancock and Behnke, 2001).

Chemical treatments

Chemical processes that may be used to increase the nutritional value of feed ingredients include hydrolytic and oxidative agents (Fahey et al., 1993). Most research using chemical treatments has been conducted using ruminant animals because it is believed that mainly high fiber ingredients will benefit from chemical treatments. However, some high fiber feed ingredients fed to pigs such as DDGS and other corn co-products have become important ingredients in diets fed to pigs due to their relatively low cost (Stein, 2012). Almost 90% of the total fiber in DDGS is insoluble fiber and only 40% of insoluble fiber in DDGS is fermented (Urriola et al., 2010). In contrast, more than

90% of the soluble dietary fiber is fermented, but soluble fiber accounts for only 10% of the total fiber in DDGS (Urriola et al., 2010). Therefore, any treatment that can solubilize some of the insoluble fibers in DDGS or other corn co-products is expected to result in increased energy contribution from the fibers because of the increased fermentability of soluble fiber.

1. Sodium Hydroxide

Sodium hydroxide is considered a hydrolytic agent that may solubilize the hemicellulose, lignin, and silica constituents of the plant cell wall. The solubilization is mainly due to changes in the lignin-hemicellulose matrix that takes place when the cell wall is in contact with NaOH (Fahey et al., 1993). Changes in the plant cell wall may improve access of microbial enzymes to the constituents of the plants (Fahey et al., 1993). Sodium hydroxide has also been used to remove feathers from hens as an alternative procedure compared with rubber picking fingers, but the nutritional value of the feathers removed with this procedure was not improved compared with the conventional method (Kim and Patterson, 2000).

There is limited information about the effect of NaOH treatments on energy and nutrient digestibility of ingredients fed to pigs, whereas much research has been conducted with ruminant animals (Braman and Abe, 1977; Felix et al., 2012; Hunt et al., 1984; Miron et al., 1997; Morrow et al., 2013). Treatment with NaOH increases rumen digestibility of OM in barley straw from 52 to 76% and the digestibility of DM by 22% in other crop residues (Fahey et al., 1993). Dairy cows fed a diet that contain sorghum grain treated with 4% NaoH had a greater digestibility of NDF compared with dairy cows fed a diet with untreated sorghum grain (Miron et al., 1997). Sodium hydroxide also has been used to reduce the acidity of DDGS in an attempt to prevent the increase in acidosis that is sometimes observed if DDGS is fed to ruminants. Felix et al. (2012) reported that there is an increase in rumen pH in heifers fed DDGS treated with NaOH compared with heifers fed un-treated DDGS, which is expected to reduce the incidence of rumen acidosis and may increase NDF degradation in the rumen. Pigs fed bird-proof sorghum treated with NaOH increased nitrogen and energy digestibility (Kemm and Ras, 1985). Likewise, pigs fed Leucaena leucocephala leaf meal that was treated with NaOH had improved N retention compared with pigs fed untreated Leucaena leucocephala meal (Echeverria et al., 2002), which may be due to a reduction in the concentration of tannins in Leucaena leucocephala leaf meal treated with NaOH (Acamovic and D' Mello, 1994). However, pigs fed cooked soybeans that were treated with NaOH had reduced growth performance compared with pigs fed untreated cooked soybeans (Young and Smith, 1973). It is possible that the reason for this observation is that NaOH reduced the palatability of the diet (Young and Smith, 1973). There is, however, limited information about effects of treating co-products from cereal grains with NaOH and it is also not known if oilseed meals other than SBM may benefit from treatment with NaOH.

2. Ammonia

Anhydrous ammonia, ammonium hydroxide, thermoammoniation, and urea also have been used to treat fibrous materials. A combination of ammonia and high pressure may improve solubilization and fermentability of fiber if fed to ruminants (Bals et al., 2006; Realff and Abbas, 2004;), because this treatment may result in hydrolyzing the hemicellulose and cellulose fractions of the cell wall (Bals et al., 2006; Mosier et al., 2005;), which make the cell wall more susceptible to be fermented by microbes (Oji et., 2007). There is, however, no information about effects of these procedures on the fermentability of fiber by pigs. It is possible that ammonia treatment may be used to increase the energy value of fibrous ingredients fed to pigs, but to our knowledge no research has been reported to test this hypothesis. Sheep fed a diet containing a mix of corn cobs, corn husks, and corn stalks treated with 3% aqueous ammonia had improved digestibility of N, DM, NDF, acid detergent fiber, and OM compared with sheep fed a diet with an untreated mix (Oji et al., 2007). Aqueous ammonia has also been used to remove the negative effects of aflatoxins B1 in corn fed to pigs (Jensen et al., 1977).

3. Calcium Oxide and Calcium Hydroxide

Calcium oxide or Ca(OH)2 also may be used to treat fibrous materials, but it is a less common treatment. However, castor seed meal treated with CaO may replace up to 330 g/kg of SBM in diets for dairy cows without affecting milk production or growth performance (Cobianchi et al., 2012). ¬An experiment conducted by Lesoing et al. (1981) demonstrated that digestibility of DM, OM, cellulose, and hemicelluloses increased in lambs fed wheat straw treated with Ca(OH)2 in combination with NaOH compared with lambs fed a diet with untreated wheat straw. Feedlot cattle fed diets containing Brix sugar cane treated with CaO also had increased digestibility of NDF (Magalhaes et al., 2012), further indicating that CaO treatment may be used to increase the digestibility of OM and GE in ruminants. A combination of ammonia treatment and treatment with Ca(OH)2 resulted in improved nutritive value of rice straw when fed to beef cattle (Polyorach and Wanapat, 2015). However, growth performance was not improved if feedlot cattle were fed corn stover and modified wet distillers grains with solubles treated with CaO compared with cattle fed untreated corn stover and modified wet distillers grains with solubles (Duckworth, 2013). Treatment of fibrous materials with either CaO, Ca(OH)2, or NaoH solubilize more of the hemicellulose fraction than the cellulose fraction of the cell wall (Lesoing et al., 1981). Calcium hydroxide also has been used to decontaminate corn infected with fusarium mycotoxins (Rempe et al., 2013).

Enzyme treatments

Exogenous enzymes are commonly used in Northern European pig diets because most diets in Northern Europe are based on barley or wheat instead of corn. These ingredients have high concentrations of β-glucans and arabinoxylans (Li et al., 1996a; Mavromichalis et al., 2000), but exogenous β-glucanases and xylanases may contribute to the hydrolysis of these fractions (Owusu-Asiedu et al., 2010).

The effect of dietary exogenous carbohydrate digesting enzymes (hemicellulases, cellulases, xylanases, pectinases, β-glucanases, and α-galactosidases) on digestibility of energy and nutrients in corn and wheat DDGS fed to pig has been studied (Emiola et al., 2009; Yañez et al., 2011), but results have been inconsistent. Pigs fed a barley-SBM diet supplemented with β-glucanases had increased energy and CP digestibility, but this was not the case if pigs were fed wheat-SBM, corn-SBM, or rye-SBM diets with addition of β-glucanases (Li et al., 1996b). However, pigs that were fed a wheat-DDGS based diet that was supplemented with carbohydrase enzymes (xylanase, β-glucanase, and cellulase) had a greater GE digestibility compared with pigs fed diets that were not supplemented with enzymes (Emiola et al., 2009). In contrast, when xylanase was added to a corn-DDGS based diet, no improvement in energy digestibility was observed (Yañez et a., 2011). However, addition of xylanase to full fat or defatted rice bran resulted in a significant improvement in DE and ME of the ingredients, but that was not the case if xylanase was added to brewers rice, presumably due to a lack of substrate in brewers rice (Casas and Stein, 2016). Addition of cellulase to DDGS may theoretically result in release of glucose that may be absorbed in the small intestine (Bals et al., 2006), but data to demonstrate this effect under practical conditions are lacking. Pigs fed a sorghum-SBM diet supplemented with the cellulase enzyme did not have improved growth performance or digestibility of DM, N, or GE compared with pigs fed a non-supplemented diet (Kim et al., 1998; Park et al., 2003). However, addition of enzymes as cocktails tends to have a better effect compared with addition of single enzymes. Kim et al. (2003) reported that pigs fed a corn-SBM based diet with addition of a cocktail of enzymes that contained α-galactosidase, β-mannanase, and β-mannosidase had improved energy and AA digestibility and improved G:F compared with pigs fed the same diet without enzymes. A similar response was reported by Omogbenigun et al. (2004) who demonstrated that addition of enzymes (i.e., cellulase, galactanase, mannanase, and pectidase) as a cocktail had a positive effect on GE, starch, non-starch polysaccharides, and CP digestibility in diets containing corn, SBM, canola meal, barley, peas, wheat, and wheat by-products fed to pigs.
Exogenous enzymes usually are added during the diet mixing process. Therefore, these enzymes need to be thermo stable if any thermal treatment is used. The enzymes also need to be stable in the conditions of the gastro intestinal tract of the pig to avoid reducing activity. However, if exogenous enzymes are used to treat ingredients before they are included in the diet, less variables need to be considered (e.g., thermal treatment, stomach PH, and time). Pigs fed a diet containing pretreated SBM with protease enzyme had no change in G:F compared with pigs fed the untreated SBM (Rooke et al., 1998). This is likely a result of the fact that no improvement in CP and AA digestibility is observed in protease-treated SBM compared with untreated SBM (Caine et al., 1997).

Conclusions

Fiber is the most indigestible nutrient in pig diets. Therefore, feed technology needs to target this fraction to increase the utilization by pigs. Physical treatments available include roller and hammer mills. Thermal treatments available include pelleting, extrusion, and expansion. Chemicals treatments such as NaOH, ammonia, CaO, and Ca(OH)2 may also be used. Carbohydrate digesting enzymes may also be used individually or as cocktails to improve fermentation of the indigestible fraction of the diets. There is, however, a lack of knowledge about the ideal particle size that provides the best utilization of energy and nutrients from ingredients by pigs. Likewise, interactions among type of diet and physical or thermal treatments have not been investigated and effects of chemical treatments and enzymes additions in diets fed to pigs containing high fiber ingredients, are not well understood.

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