10 Alternative Feedstuffs in Swine Diets

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Introduction

For sustainable swine production, alternative feedstuffs play a key role for three main reasons. First, for economic sustainability alternative feedstuffs, and co-products in particular, have become an important option to control rapidly increasing feed costs (Zijlstra and Beltranena, 2009). The novel industrial demand for feed grains, in part for biofuel production, has elevated the long-term price forecasts for feed grains to another price plateau. Alternative feedstuffs are a short-term solution for commercial swine production to control feed costs, with proper risk management strategies, including modern feed quality evaluation, as key components. Second, for agronomic sustainability, alternative crops with unique agronomic features might be important (Miller et al., 2002). For example, the drought tolerance of sorghum and triticale may support a switch from traditional feed grains that are less drought-tolerant such as wheat and corn. Triticale requires 14% less crop inputs than wheat (David-Knight and Weightman, 2008).

Increased use of pulse (non-oilseed legume) crops because of efficiency of N-use may support, at least, a partial switch from feed grains. Similarly, a crop rotation may reduce disease pressure on crops (Krupinsky et al., 2002). An important criterion for sustainable success is that the newly included crops have a market as alternative feedstuff if quality targets for the primary market cannot be met. Finally, for societal and environmental sustainability, the use of co-products as feedstuffs for swine addresses the argument that pigs compete with humans for food (Nonhebel, 2004). The conversion of inedible residues from the food, bio-fuel, and bioprocessing industries into high-quality animal protein food mitigates the impact of these industries on the environment. For example, behind every food product in a supermarket, there is at least 1 useful co-product that is overlooked, even though certain global regions already use co-products from the food industry effectively to produce pork that is less reliant on feed grains. Pigs, as an omnivorous species (Stevens and Hume, 1995), are ideally suited to consume a wide variety of feedstuffs and, thus, can be an integral part of sustainable livestock-production systems.

The use of alternative feedstuffs in the swine industry is not new. In traditional swine production, pigs were housed in small numbers, and high growth rates were less important. Pigs were actually fed feedstuffs that currently are regarded as alternative, such as leftover human food products (Pond and Lei, 2001). Such traditional production is still common practice in global small-scale swine production, particularly in Asia (Chen, 2009). The development of modern swine-production

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Sustainable Swine Nutrition, First Edition. Edited by Lee I. Chiba.

systems that demand high growth rates, safe, and consistent pork products resulted from a reliance on a supply of affordable feed grains and a few protein sources to produce pork competitively (Pond and Lei, 2001). Currently in North America, the inclusion of alternative feedstuffs in the commercial swine industry is considered advantageous solely during periods of price increases for common feed grains or protein sources.

The lack of a consistent supply of co-products played a large role. In the last five years, only one alternative feedstuff, corn dried distillers grains with solubles (DDGS), has reached commodity status within the North American swine industry (Patience et al., 2007). Across the world, few regions have a solid logistical system in place for the commercial swine industry to rely on co-products as main feedstuffs in swine diets. However, some European countries with a small land base, such as The Netherlands, have historically been heavily dependent on a large array of alternative feedstuffs (FEFAC, 2005). Finally, alternative feedstuffs are considered for the production of organic pork (Partanen et al., 2006), perhaps to either avoid the use of corn and soybeans that have been genetically modified for herbicide resistance and other traits or the required use of homegrown organic feedstuffs.

The introduction of alternative feedstuffs is a risk for consistent growth performance and predictable pork quality. The risk should be managed partly using modern feed evaluation techniques. This chapter describes three categories of alternative feedstuffs: (1) developments in traditional crops, (2) alternative crops, and (3) co-products resulting from the biofuel and food industry, and crop fractionation. Details of alternative feedstuffs have been summarized previously (Thacker and Kirkwood, 1990; Chiba, 2001; Myer and Brendemuhl, 2001; Sauber and Owens, 2001), so the focus of the present chapter will be on new developments within the last decade.

Feed Formulation and Risk Management

Nutrients

The introduction of alternative feedstuffs into swine diets not only provides an opportunity to improve the economic sustainability of swine production, but also poses a risk that must be managed properly. This risk can be divided into a range of factors: nutritional, such as variability and a wider macronutrient range; chemical, such as residues; biological, such as mycotoxins and antinutritional factors (ANF), and the potential for a negative impact on pork quality (De Lange, 2000; Smits and Sijtsma, 2007).

Some of the countries in the European Union, such as The Netherlands, are heavily dependent on alternative feedstuffs (FEFAC, 2005). Alternative feedstuffs not only enlarge the raw material matrix but also introduce a wider range in the macronutrient profile, especially non-starch polysaccharides (NSP) and protein. Indisputably, the choice of energy evaluation system will alter the relative values placed on feeds (Noblet et al., 1993). For energy evaluation, the DE and ME systems overestimate the energy contribution to support maintenance and growth (Black, 1995), while the NE system offers a more accurate ranking of feedstuffs (Whittemore, 1997). Values have been reported widely for an array of feedstuffs in tables (CVB, 2007; Sauvant, 2004). The feed industry in The Netherlands has been relying on the NE system since 1970 (CVB, 1993), partly to manage the risk of a wide ingredient matrix (Zijlstra and Payne, 2007).

The difference in approach to energy evaluation among scientists and countries is reflected in the selected approach in research deliverables. Regularly, the inclusion of new co-products, for example corn DDGS and wheat DDGS, was tested by feeding grower–finisher pigs diets that were formulated to an equal DE or ME content with incremental concentrations of the test feedstuff. Not surprisingly, this approach resulted in reduced growth performance (e.g., Roth-Maier et al., 2004; Friesen et al., 2006; Thacker, 2006; Whitney et al., 2006; Widyaratne and Zijlstra, 2007). Inclusion of high fiber or high protein feedstuffs into diets that have been formulated to equal DE or ME actually results in a lower dietary NE content. Subsequently, the test feedstuff was blamed in studies that observed a reduced growth performance, rather than the feed quality evaluation system used to analyze dietary energy and amino acid (AA) content.

In Europe, obtaining an accurate prediction of the NE content of alternative feedstuffs is considered important (Smits and Sijtsma, 2007) to assure equivalent growth performance following the introduction of alternative feedstuffs or co-products. However, European validation studies with alternative feedstuffs in swine diets formulated to an equal NE content are either rarely conducted or published in the scientific literature. As a rare example, incrementally increasing levels up to 18% of canola meal in diets formulated for grower–finisher pigs to equal NE and digestible AA did not change growth performance in a study done in France (Albar et al., 2001). In North America, this approach to formulate diets to equal NE content might also result in less difference in growth performance observed, following the introduction of single alternative feedstuffs, such as the zero-tannin faba bean (Zijlstra et al., 2008). Feed intake would then be the major factor impacting growth (Seneviratne et al., 2010). Feed-quality evaluation for energy likely plays the most important role in the successful introduction of new feedstuffs.

A final risk associated with feedstuffs is intrinsic nutrient variability due to genetic expression in crops impacted by agronomic, weather, harvest, and storage conditions. With co-products and fractions, an additional source of variability is introduced by processing (Zijlstra et al., 2001). For example, one of the main risks associated with the use of DDGS in swine diets is variability in quality, in particular for the first-limiting AA lysine because of drying that uses heat (Zijlstra and Beltranena, 2008). The risk of protein damage by overheating feedstuffs is well understood (e.g., Van Barneveld et al., 1994), and a wide range in lysine damage has been confirmed for DDGS (Fontaine et al., 2007). Apart from heat damage, oil extraction of oil seeds using a range of processing techniques (solvent extraction, expeller press, and cold press) may result in a range of residual oil and, therefore, variability in energy content of the resulting meal or cake (Spragg and Mailer, 2007).

Other Risks

Residues are also a risk associated with alternative feedstuffs, especially of unknown or less reputable sources. A worst-case scenario was the introduction of polychlorinated biphenyls (PCB)/dioxin via contaminated feedstuff into the feed (Bernard et al., 2002; Covaci et al., 2008). Monitoring systems have identified that a low level of exposure to swine via feed exists (Glynn et al., 2009). Residues such as PCB can accumulate in pork (Hoogenboom, 2004), and, thereby, pose a significant risk for the consumer. A recent example was the melamine-contaminated feedstuffs into pet food (Thompson et al., 2008) and human diets that might have been preceded by contaminations of swine feed (González et al., 2009). These incidents point to the importance of prevention procedures such as Hazard Analysis and Critical Control Point (HACCP) and immediate recall procedures to be implemented rigorously by the feed industry (den Hartog, 2003). New co-products such as crude glycerol may also contain residues that should be monitored carefully. Specifically, crude glycerol may contain residual methanol that at high dietary levels may cause metabolic acidosis, vomiting, blindness, or gastrointestinal problems (Kerr et al., 2007).

Mycotoxins may occur naturally in crops and, therefore, also in their co-products. Some mycotoxins are resistant to processes such as fermentation and drying and are, thus, not inactivated. In fact, some processes such as ethanol production from grain actually concentrate the mycotoxin deoxynivalenol (DON) threefold in the co-product DDGS (Schaafsma et al., 2009) due to starch removal. Apart from DON, the concentration of the mycotoxins aflatoxins, fumonisins, and zearalenone also increase in DDGS compared to the feedstock (Wu and Munkvold, 2008). Although some studies indicate that mycotoxin contamination in DDGS may not be a regular phenomenon (Zhang et al., 2009), the fact that mycotoxin concentration occurs makes it a risk that should be managed, because DON, even at low concentrations, may severely impact growth and reproductive performance (House et al., 2002; Dänicke et al., 2004). Knowledge about the geographical location of harvest of the feedstock grain combined with information about agronomic conditions during growth and harvest of the cereal would be beneficial. These conditions relate directly with DON content in grain used for ethanol production and thus concentrations in the co-product DDGS (Schaafsma et al., 2001).

Crops

Cereal

Traditionally, the driver for a competitive swine industry has been extensive, low-cost grain production, especially in North America. The grain standard will differ locally because of agronomic conditions. Within grains, alternative cultivars are being developed mostly to enhance yield, but also to enhance density of digestible nutrients.

Corn

Corn is globally the cereal standard grain and is the basis for commercial swine production in the United States and Latin America. The nutritional value of hybrid yellow, dent corn is well defined (e.g., Sauber and Owens, 2001). Within the last decade breeding efforts improved, apart from yield, the nutritional or agronomic characteristics of alternative corn cultivars with unique traits such as low phytate (Spencer et al., 2000; Veum et al., 2001; Hill et al., 2009), herbicide-resistance (Hyuan et al., 2004), rootworm resistance (Hyun et al., 2005; Stein et al., 2009), short season (Opapeju et al., 2006), phytase-containing (Nyannor et al., 2007), or enhanced oil (energy) and AA density (Pedersen et al., 2007).

Small Grains

Of the small grains, barley, sorghum, and wheat are also important feed grains for the swine industry within specific geographic locations. For example, barley and wheat are major feedstuffs in western Canada and Australia, whereas sorghum is a major feedstuff in Mexico because of their local production. The nutritional value of these grains has been well defined (Sauber and Owens, 2001), although the perception exists that barley and wheat have a higher variability in DE content (Fairbairn et al., 1999; Zijlstra et al., 1999) than corn. The impact of variability in wheat quality on subsequent growth performance in weaned pigs can be reduced by enzyme application (Cadogan et al., 2003). Similar to corn, unique traits have been developed such as low phytate in barley (Veum et al., 2002; Htoo et al., 2007a,b) and starch profile in sorghum and barley (Shelton et al., 2002; Bird et al., 2004), but these advances have been achieved to a lesser extent compared with corn. Although breeding programs have placed emphasis on yield increases for small grains, yield increases in corn have been much larger than for small grains (Alston et al., 2009) in recent decades. The yield of corn in areas with sufficient heat and water is much greater than barley or wheat, and is the main reason that production of small grains in the United States has been largely replaced with corn.

Triticale

Water and N are key drivers for successful grain production. In semi-arid areas such as parts of western Canada and Australia, water supply and drought are recurring issues. Enhanced drought tolerance and N-use efficiency in corn and small grains might be an approach to increase grain yield. However, cultivation of feed grains with a higher yield and lower crop input requirements (Davis-Knight and Weightman, 2008) in areas with marginal growing conditions should also be part of a solution package to maximize pork produced per hectare. Crops such as triticale, a hybrid of wheat and rye (Radecki and Miller, 1990), may improve feed grain yield in marginal growing conditions (McLeod et al., 2001) and require 14%-less crop inputs compared to wheat (Davis-Knight and Weightman, 2008). Traditionally, growth performance of pigs fed triticale has been assumed lower, because studies conducted in a distant past indicated that triticale might reduce growth performance of young pigs relative to corn (Hale and Utley, 1985). Ergot tolerance has also been enhanced (Salmon, 2004). However, modern triticale cultivars are low in trypsin inhibitors and palatability of pigs fed triticale is, thus, less of a concern (Radecki and Miller 1990). Indeed, weaned pigs fed diets containing either 60% of wheat or 60% of modern varieties of triticale achieved an identical growth performance (Figure 10.1; Beltranena et al., 2008).

Pulse

Because of their high N efficiency, pulse (non-oilseed legume) crops are an attractive alternative for sustainable crop production in moderate climates. Atmospheric N is fixated by Rhyzobia bacteria living in symbiotic association with pulse roots that reduce the demand for fertilizer even for subsequent crops in the crop rotation systems involving cereal grain and oilseeds in alternating

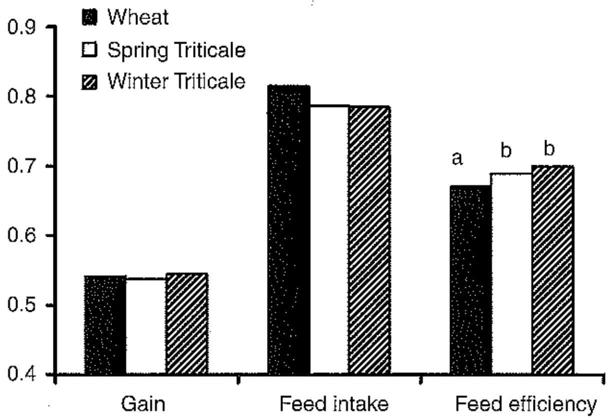

Figure 10.1 The replacement of 66% wheat with spring or winter triticale in diets for weaned pigs did not affect gain (kg/d; SEM = 0.013) or feed intake (kg/d; SEM = 0.022), but improved feed efficiency ($P < 0.05$; SEM = 0.01); adapted from Beltranena et al., 2008.

years. Pulse seeds used as feedstuffs include crops such as field pea, faba bean, lentil, chickpea, and white bean (Rochfort and Panozzo, 2007). In comparison to the oilseeds, pulse seeds contain less protein, but contain major quantities of starch, so that pulses are an alternative feedstuff with a dual purpose: provide energy and protein. Traditionally, legume seeds contain varying quantities of ANF that interfere with the digestion, absorption, and utilization of nutrients (Huisman and Jansman, 1991). Crop breeding has reduced the quantities of ANF substantially for some legume seeds such as field pea and faba bean (Clarke and Wiseman, 2000); however, processing to inactivate ANF is required for other crops such as soybean and common bean (e.g., Van der Poel et al., 1990). Phytochemicals in pulse seeds may stimulate health benefits (Rochfort and Panozzo, 2007); however, such benefits have not been determined in swine.

Field Pea

Field pea has become an important energy and protein source for swine in specific geographical locations in Europe and Canada, although its affordability depends on demands from human food markets. Modern cultivars of field pea have a low content of ANF and can, therefore, be included in diets for grower–finisher pigs without limitations for inclusion (Gunawardena et al., 2007). The digestibility value of energy is generally lower than corn and AA is generally lower than soybean meal (Mariscal-Landín et al., 2002; Sauvant et al., 2004; Stein et al., 2004). Digestibility of starch in field pea is 90% by the end of the ileum (Fledderus et al., 2003; Stein et al., 2007) and can be improved by extrusion technology (Mariscal-Landín et al., 2002; Stein et al., 2007). Specific field pea proteins differ in digestion along the gastrointestinal tract (Le Guen, 2007), indicating that not all field pea proteins are digested well and there are opportunities to enhance digestibility of field pea. Field pea NSP and oligosaccharides contain unique fermentation characteristics (Leterme et al., 1998). Digestibility of P is hindered by phytate, similar to other legume seeds (Stein et al., 2007).

Grower–finisher pigs fed diets containing field pea can achieve identical growth performance, carcass characteristics (Stein et al., 2004; 2006; Gunawardena et al., 2007), and pork quality (Gunawardena et al., 2007) as pigs fed soybean meal as the main protein source. Results are less conclusive for weaned pigs. Field pea was included up to 18% in phase-three diets without affecting growth performance (Stein et al., 2004), whereas up to 30% field pea linearly decreased growth performance in a three-phase nursery program starting four days after weaning (Friesen et al., 2006). Combined, field pea can be used in diets for grower–finisher and later-stage weaned pigs without limitations for inclusion, provided that modern feed evaluation methods are used for energy, amino acids, and P. Inclusion should perhaps be limited to below 20% for early stage weaned pigs.

Zero-Tannin Faba Bean

The faba bean is an emerging pulse crop in western Canada and parts of Northern Europe. With adequate rainfall, seed yield and atmospheric N fixation are higher than for field pea (Strydhorst et al., 2008); thus, zero-tannin faba bean might be even more environmentally sustainable. Following plant-breeding efforts, zero-tannin faba bean contains less than 1% residual tannin, and a digestibility trial determined that zero-tannin faba beans are well digested by pigs (Van der Poel et al., 1992a), and that the NE content is similar and standardized ileal digestible (SID) AA content is greater than with field pea (Zijlstra et al., 2008). In late-stage nursery diets, zero-tannin faba bean entirely replaced soybean meal without reducing growth performance (Figure 10.2; Beltranena et al., 2009). In grower–finisher pigs, zero-tannin faba bean entirely replaced soybean meal in diets for grower–finisher pigs without affecting growth performance, carcass quality, or pork quality (Gunawardena et al., 2007), provided that diets were balanced for NE and SID AA content.

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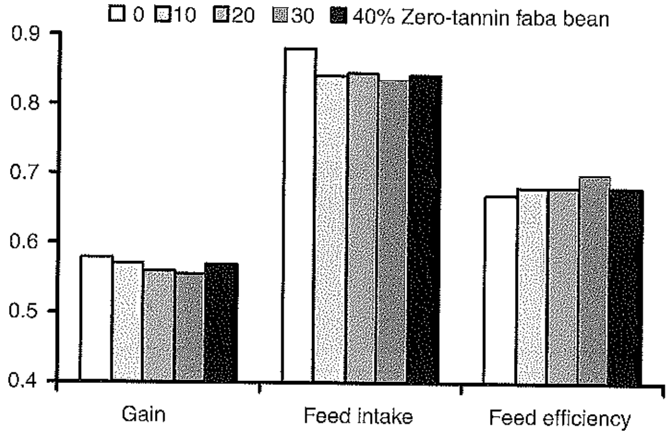

Figure 10.2 The lack of effect of replacing soybean meal with zero-tannin faba bean in diets fed to weaned pigs on gain (kg/d; SEM = 0.011), feed intake (kg/d; SEM = 0.019), and feed efficiency (SEM = 0.01); adapted from Beltranena et al., 2009.

Lupin

In particular in Australia and Europe, three main species of lupin are cultivated: *Lupinus albus*, *L. angustifolius*, and *L. luteus*. Pigs can effectively utilize *L. angustifolius* and *L. luteus*, but less efficient utilization of diets containing *L. albus* remains poorly understood (Van Barneveld, 1999; Písaříková and Zralý, 2009). Sweet lupin (*L. angustifolius*) has a reduced alkaloid content and high energy and AA digestibility (Kim et al., 2008, 2009), and can be included in swine diets at high inclusion levels without hampering growth performance (Van Barneveld et al., 1999), although its nutritional quality may vary (Kim et al., 2009). Sweet lupin may also contain functional properties that alter fat metabolism in pigs (Martins et al., 2005). For yellow lupin (*L. luteus*), a dietary inclusion of up to 15% in the diet is recommended for weaned pigs (Kim et al., 2008).

Others

An array of other pulse crops exists, such as chickpea, lentil, and common bean. Generally, care should be taken to ensure that concentrations of anti-nutritional factors such as trypsin inhibitors, lectins, and tannin is low in the crop or has been reduced to tolerable levels using processing (Van der Poel et al., 1990; Rubio, 2005). Following this assurance, (processed) seeds of other pulse crops may serve well as an alternative feedstuff (Mustafa et al., 2000).

Oilseed

Crops such as soybean, canola seed, and flaxseed can be used as feedstuffs for pigs. Generally, these crops have too much economic value for inclusion in swine diets, but their co-product meal is used as a protein source. Seed that does not meet grading specifications might be included in swine diets. One economically sustainable exception might be the use of flaxseed to produce omega-3 pork. Co-extrusion of flaxseed with field pea will improve digestibility of nutrients including fatty acids (Figure 10.3; Htoo et al., 2008). Then, dietary omega-3 fatty acids can be incorporated effectively in fat (Juárez et al., 2010) to enhance opportunities to introduce value-added pork such as bacon, ham, and processed pork products (Musella et al., 2009) into human food markets.

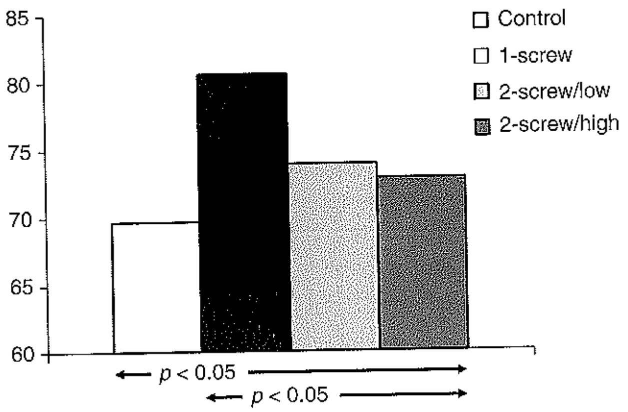

Figure 10.3 Effect of co-extrusion of flax seed and field pea using a single-screw or twin-screw extruder at low or high intensity on the apparent total tract digestibility of energy (SEM = 1.9); adapted from Htoo et al., 2008.

Co-products

A range of technologies exists to fractionate crop seeds into their components for human food, bio-products, or feed application (Zijlstra et al., 2004; Zijlstra and Beltranena, 2007; Vasanthan and Temelli, 2008). Traditionally, crop seeds were subjected to a dry (without solvent) fractionation processes to extract a valuable component using physical characteristics for human food application. Examples include oil extraction using a press, milling, sieving, and protein and starch separation using air classification. The co-products that were produced could be used as feedstuffs. Advantages of such dry fractionation separation techniques are continuous instead of batch-processing, lower processing costs, and the absence of solvents or slurry (Hemery et al., 2007). Disadvantages of dry fractionation are that the fractionation into components is not absolute and that properties of the products may not reach the superior value attributes required by some end users for human food or bio-industrial applications. Consequently, wet fractionation processes were developed using water, acids, bases, salts, or organic solvents to separate valuable components using chemical characteristics (Vasanthan and Temelli, 2008). Advantages of wet fractionation include the ability to achieve greater purity of high-value fractions. Furthermore, soluble ANF (e.g., glucosinolates, phenolics) can be washed away in the slurry, and pH or enzymes can be used to dephytinize co-products, resulting in the conversion of phytate-P into available P (Drew, 2004). However, processing costs of wet fractionation are greater and drying of the main product and co-products is required for long-distance transportation, long-term storage, and dry-feed application. Although drying that uses heat might be advantageous to inactivate ANF and increase mineral availability, drying may also damage the protein contained in co-products and thereby hamper nutritional quality. Spray drying is far more costly than traditional drying methods, but it avoids protein damage in co-products and, therefore, maintains their nutritional and functional properties. Co-products have become increasingly attractive for use in swine diets as alternative feedstuffs to reduce feed costs and enhance economic sustainability of the swine industry (Jha et al., 2010; Zijlstra et al., 2010). Co-products tend to be high in NSP, therefore, NSP-degrading enzymes might be used to enhance nutrient digestibility (Zijlstra et al., 2009b); however, feed processing of co-products will not be discussed in detail.

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Liquid feeding systems allow the incorporation of wet co-products into swine diets, and, thereby, entirely avoid drying and associated energy costs. Therefore, liquid feeding can be regarded as more environmental and economically sustainable, especially if the swine farm is nearby a processing plant, otherwise transportation becomes an issue. Liquid feeding may also allow for modification of feed characteristics using steeping to enhance nutrient digestibility (Choct et al., 2004; Niven et al., 2007) and fermentation to enhance gut health and growth performance (Scholten et al., 1999), although these opportunities might be less for co-products resulting from a fermentation process.

Biofuel Industry

Fossil fuels are a main source of energy for anthropogenic activity. Considerable incentives and demands exist for a variety of reasons to replace fossil fuels with renewable fuel sources such as biodiesel and ethanol. As a result, DDGS, canola cake, and crude glycerol have become available as alternative feedstuffs for swine; however, variability in nutritional quality of these co-products is a major concern (Zijlstra and Beltranena, 2008). The use of cereal grains in livestock diets and biofuel production has received considerable attention in discussions around global food supply (Blaxter, 1983; Avery, 2006; Dale, 2008). The biofuel industry directly competes with the livestock and food industries for grain supply, thereby, increasing local grain prices. In turn, the biofuel and food industries also produce co-products that are available for incorporation into livestock diets. If a decision to produce biofuels has been made, markets for the co-products are needed. Thus, inclusion of the biofuel co-products in swine feeds might be cost-attractive to swine producers (Lammers et al., 2010).

Dried Distillers Grains with Solubles

Of the alternative feedstuffs, corn DDGS has reached global commodity status. The nutritional value of corn DDGS for swine has been reviewed recently (Stein and Shurson, 2009). Briefly, the fermentation of starch sugars into ethanol results in a co-product with increased density of the other macronutrients and minerals. In the instance of corn, which contains more oil than wheat, the co-product corn DDGS may reach a similar DE and ME content than corn grain because of increased density of ether extract, and it will reach a higher protein density than the feedstock. Therefore, corn DDGS is an attractive feedstuff for swine as both an energy and AA source. Up to 30% corn DDGS can be included in diets for grower-finisher pigs without changes in growth performance (Xu et al., 2010a). However, inclusion of DDGS does not always result in consistent growth performance (Stein and Shurson, 2009). Differences might be related to variability in quality among samples of corn DDGS (Zijlstra and Beltranena, 2008) because of fermentation, drying, and different ratios between distillers grain and solubles and differences in dietary energy, macronutrients, and AA profiles among diets. Increasing dietary inclusion of DDGS in corn–soybean meal diets balanced for energy and AA does not affect carcass lean and backfat (Xu et al., 2010a). However, increasing dietary DDGS will increase dietary fiber and polyunsaturated fatty acid (PUFA) contents that consequently will decrease dressing percentage and increase carcass PUFA content, respectively (Xu et al., 2010a). Dietary fiber increases gut weight (Jørgensen et al., 1996) and dietary PUFA are directly deposited into carcass fat depots (Averette Gatlin et al., 2002). To reduce the negative impact of corn DDGS on pork fat hardness, a three-week withdrawal of corn DDGS prior to slaughter should be implemented (Xu et al., 2010b; Beltranena et al., 2010; Beltranena and Zijlstra, 2010).

In the instance of wheat and other small grains, the oil content of wheat is lower than corn, resulting in wheat DDGS having a much lower energy content than wheat grain (Widyaratne and Zijlstra, 2008, 2009). Compared to corn DDGS, wheat DDGS is more useful as a protein source than as an energy source. For both corn and wheat DDGS, P content and digestibility are greater than for the parent grain. Initially, results of feeding wheat DDGS to pigs were not positive in Canada. The growth performance of grower–finisher pigs fed 100 g/kg or more of wheat DDGS was reduced (Thacker, 2006) even when diets were formulated to equal DE and SID AA content (Widyaratne and Zijlstra, 2007). However, wheat DDGS used for these studies had been overheated during drying (Zijlstra and Beltranena, 2008). Recently, ethanol-processing plants with improved fermentation and drying technologies produce a wheat DDGS of a likely higher quality. Indeed, 15% of this wheat DDGS could be included in diets fed to weaned pigs with limited effects on growth performance (Avelar et al., 2010). Furthermore, up to 30% of the wheat DDGS could be included in diets fed to grower–finisher pigs in a commercial grow-out facility, but reduced performance should be expected at higher dietary inclusion levels (Beltranena and Zijlstra, 2010). Enzymes may provide an opportunity to increase nutrient digestibility of wheat-based DDGS (Yanez et al., 2009) and diets including wheat DDGS (Emiola et al., 2009).

Crude Glycerol

Crude glycerol may serve as an energy source for pigs. Apparent total tract energy digestibility of diets containing 0–20% crude glycerol originating from soybean oil ranged from 89% to 92%, indicating that crude glycerol is digested well by grower pigs (Lammers et al., 2008a). To produce biodiesel, oil extracted from oilseeds or fat from animal origin is hydrolyzed using an alcohol such as methanol and a catalyst such as Na or KOH, thereby, producing methyl esters (biodiesel) and crude glycerol (Kerr et al., 2007). The production of 1 L of biodiesel may yield 79 g of crude glycerol. The large-scale production of biodiesel was started in Europe, particularly in Germany. The average daily gain (ADG) of grower pigs was increased by 8% by replacing 10% dietary barley with crude glycerol originating from rapeseed oil (Kijora and Kupsch, 1996). In the United States, replacing up to 6% of corn grain with crude glycerol originating from soybean oil increased ADG of nursery pigs (Groesbeck et al., 2008). These results indicate that crude glycerol may replace part of the energy contribution for cereal grains in swine diets on an equal-mass basis for 5–10% of the diet (Figure 10.4; Lammers et al., 2008b; Zijlstra et al., 2009a).

Concerns also exist regarding feeding crude glycerol. For example, crude glycerol may contain impurities such as methanol and NaCl that remain as a residue after processing. Methanol content

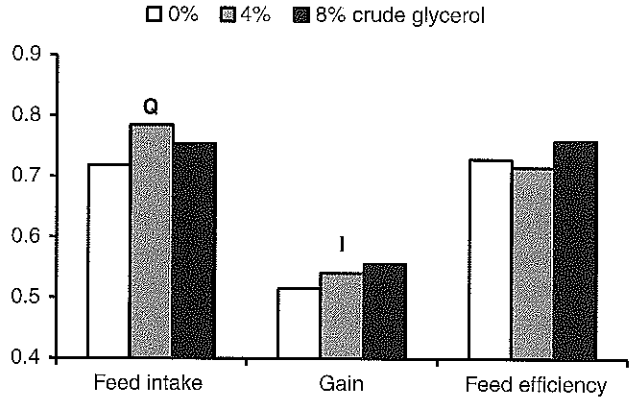

Figure 10.4 The addition of crude glycerol to pelleted wheat-based diets fed to weaned pigs will increase feed intake (kg/d) quadratically (Q; $P < 0.05$; SEM = 0.02) and may enhance gain (kg/d) linearly (l; $P < 0.10$; SEM = 0.01); adapted from Zijlstra et al. 2009.

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Food Industry

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should not exceed 150 ppm in glycerol used as a feedstuff, because higher levels may cause metabolic acidosis, vomiting, blindness, or gastrointestinal problems (Kerr et al., 2007). Increased NaCl may limit dietary inclusion of glycerol to avoid exceeding dietary Na and Cl recommendation levels. Finally, glycerol is a viscous gel that may present problems for feed mixing and flow (Kerr et al., 2007), but it increased pellet durability and lowered amperage, motor load, and improved pellet-mill production efficiency (Groesbeck et al., 2008).

Food Industry

Behind every food product in the supermarket, there should be at least 1 co-product. These co-products cover a wide range: beet pulp, canola meal, citrus pulp, whey, bakery waste, co-products from flour milling, meat-and-bone meal, etc. The livestock industry is an ideal platform to convert these low-value co-products into high-quality animal protein.

Oilseed Meal

The primary reason for the creation of oilseed meal is oil extraction for human food markets, although biodiesel and bio-products are becoming increasingly important. Rapeseed oil was the third leading vegetable oil in the world in 2008–2009, after soybean and palm oil, and rapeseed meal was the world's second-leading source of protein meal, around one-fifth of the production of the leading soybean meal (USDA, 2010). Most of rapeseed in North America and Europe is low in glucosinolates and erucic acid, and is also known as canola; thus, a major nutritional quality distinction exists between rapeseed and canola seed.

In canola, oil constitutes 45% of the seed and is its most valuable component. Solvent extraction, expeller pressing, and cold pressing can extract oil to produce raw canola oil and solvent-extracted canola meal, expeller-processed canola meal, and cold-pressed canola cake, respectively, as alternative feedstuffs (Leming and Lember, 2005). Practical inclusion of solvent-extracted canola meal is limited to 15% in diets for grower–finisher pigs, despite a suggested maximum inclusion of 25% (Canola Council of Canada, 2009). In diets containing 50% canola meal as replacement for soybean meal, growth performance and carcass characteristics could not be maintained equal to a soybean meal diet (Shelton et al., 2001); however, the canola-meal diet contained much less ME than the soybean-meal diet. The main reason for limitations in dietary inclusion of canola meal is lower content of available energy and AA, mainly because of less digestible fiber and CP compared to soybean meal (Bell, 1993).

Extraction of oil from canola seed is mostly conducted in solvent-extraction plants due to high extraction efficiency (>95%), but results in canola meal with a low DE content (Spragg and Mailer, 2007). Expeller pressing without solvents is efficient in oil extraction (75%). Hence, expeller-pressed canola meal contains 10–15% oil (Leming and Lember, 2005), and thus a greater digestible energy content and lower digestible AA content than solvent-extracted canola meal (Woyengo, 2010; Seneviratne et al., 2010). Compared to solvent-extracted canola meal, the higher energy content might, thus, make expeller-pressed canola meal a better alternative feedstuff for the energy-dependent phase of the growth cycle of grower–finisher pigs, although residual glucosinolates might slightly reduce voluntary feed intake (Seneviratne et al., 2010).

Using a screw press, canola press cake can be produced that will contain 18–20% residual oil (Schöne et al., 2002). Dietary inclusion of 15% canola press cake reduced feed intake and weight gain, with residual glucosinolates likely being a contributing factor (Schöne et al., 2002). A maximal glucosinolate content of 2 mmol/kg diet seems a prerequisite for using canola products in pig feeding (Schöne et al., 1997).

Flaxseed (or linseed) meal is a co-product of the flax crushing industry. Depending on the oil extraction, flaxseed meal may contain 3–7% residual oil in the case of solvent extraction (Batterham et al., 1991; Bell and Keith, 1993; Farmer and Petit, 2009), and expeller-pressed flaxseed meal may contain 13% residual oil (Eastwood et al., 2009). Because of its low residual oil, the feeding of flaxseed meal did not affect fatty acid profiles in plasma and milk of sows (Parmer and Petit, 2009), whereas feeding of flaxseed or flax oil does increase α-linolenic acid. Because of its high residual oil, the feeding of expeller-pressed flaxseed meal does increase the α-linolenic acid content in backfat and loin tissue (Eastwood et al., 2009). Expeller-pressed flaxseed meal might be included at 15% in diets for grower–finisher pigs (Eastwood et al., 2009).

Wheat Co-products

Dry milling of wheat removes much of the starch fraction in the grain to produce flour for human consumption and leaves wheat by-products as a residual (Holden and Zimmerman, 1991). The wheat co-products include wheat bran, middlings, shorts, and screenings and can either be purchased separately or combined as wheat millrun. The contaminants that are separated from whole-wheat seeds before flour milling are collectively called wheat screenings and typically consist of malformed wheat kernels, foreign seeds, and other contaminants. Generally, wheat screenings contain less than 7% crude fiber and not less than 35% broken or shrunken grain (Audren et al., 2002). The wheat bran is the coarse outer covering of the wheat kernel that is separated from cleaned and scoured wheat in the process of commercial flour milling; it contains 12% crude fiber (AAFCO, 1988). Wheat shorts are the layer of the wheat kernel just inside the outer bran layer covering the endosperm (Huang et al., 1999) and usually contain 5–10% crude fiber and 15–20% crude protein (CP). Wheat middlings consist mostly of fine particles of bran and germ and contain at least 15% CP (O'Hearn and Easter, 1983). Wheat millrun consists of coarse bran, shorts, screenings, and middlings (AAFCO, 1988) and contains approximately 9.5% crude fiber (Dale, 1996). These co-products vary in nutrient profiles, but also a large variability in nutrient profile exists within each category (Cromwell et al., 2000).

Wheat co-products from flour milling are variable in composition. For example, wheat short varies in composition because of different proportions of bran and endosperm (Huang et al., 1999). The neutral detergent fiber (NDF) content among wheat co-products is negatively correlated with AA digestibility (Huang et al., 2001). Insoluble dietary fibers of wheat bran increase digesta viscosity and may thereby reduce nutrient digestibility (Sakata and Saito, 2007). Nutrient digestibility of wheat co-products may be enhanced by using xylanase supplementation (Nortey et al., 2007; 2008).

Sugar Beet Pulp

Processing of sugar beet for sugars also produces the co-product sugar beet pulp. Sugar beet pulp is high in NSP, particularly pectin (Spagnuolo et al., 1999). Sugar beet pulp is fermented well by pigs, even though the rate of fermentation is much lower than for other rapidly fermentable NSP, such as inulin (Awati et al., 2006). Fermentable NSP such as sugar beet pulp interferes with nutrient digestibility. However, the functional properties of these fermentable NSP have also received considerable interest regarding three main purposes for sustainability: to alter N-excretion patterns, to improve gut health, and to influence animal welfare. Feedstuffs containing fermentable NSP, such as sugar beet pulp, shift N excretion from urine to feces (Zervas and Zijlstra, 2002a) by binding N into microbial protein (Bindelle et al., 2009), whereas feedstuffs containing non-fermentable NSP, such as oat hulls, do not (Figure 10.5; Zervas and Zijlstra, 2002b). The shift in N excretion combined with the reduced manure pH will decrease ammonia emission for swine manure (Canh et al., 1998),

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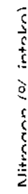

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Fractionation

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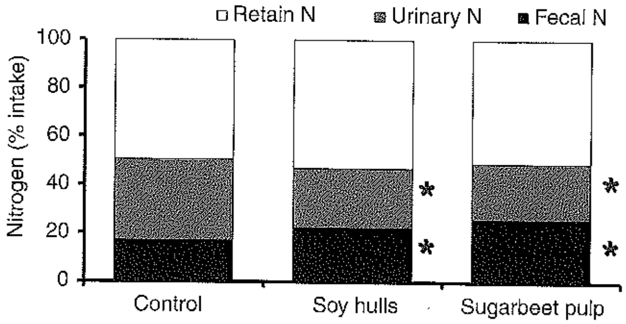

Figure 10.5 The effect of fermentable fiber contained in soy hulls or sugar beet pulp on N-excretion pattern ($P < 0.05$) between feces and urine in grower pigs; adapted from Zervas and Zijlstra, 2002b.

although odor emissions might not be reduced (Payeur et al., 2002). Sugar beet pulp stimulated growth of the gut and intestinal health in high-CP diets, but reduced gut health in low-CP diets (Hermes et al., 2009). Finally, the lower energetic utilization of fermented NSP compared with that of starch can be fully compensated in pigs by reducing their physical activity and, thus, by altering their behavior (Schrama et al., 1998). Feed intake of gestating sows can be increased by feed diets containing 45% sugar beet pulp, without negatively affecting reproductive performance (Van der Peet-Schwering et al., 2004).

Other Co-products

Apart from canola, flax, wheat, and sugar beet co-products, a large array of other co-products exists. Most of these have been discussed previously (Thacker and Kirkwood, 1990; Chiba, 2001; Myer and Brendemuhl, 2001; Sauber and Owens, 2001); however, new information was recently gathered for a few of these.

Corn germ meal, if solvent-extracted, will be low in fat (2%) and high in fiber (54% NDF), followed by 21% CP and 14% starch (Weber et al., 2010). In balanced diets, up to 40% corn germ meal can be included (Harbach et al., 2007). Corn germ meal is utilized well by pigs (Weber et al., 2010), although exact fermentation patterns have not been published.

For a sustainable poultry industry, the major waste product, feather meal, should be managed properly, similar to slaughter offal from hog slaughter. Proper management includes heat processing to eliminate pathogenic bacteria, and hydrolysis to improve AA digestibility. Pigs fed corn-based diets containing 10% hydrolyzed feather meal supplemented with required AA could utilize feed and AA for BW gain and lean gain as efficiently as pigs fed a corn–soybean meal diet (Divakala et al., 2009).

Pet food by-product is loosely described as pet food that has been rejected because it did not meet quality specifications, was damaged during handling, or was distributed to a retail outlet and not sold before the expiration date. Pet food by-products can effectively provide protein and fat in diets for weaned pigs (Jablonski et al., 2006), provided proper regulatory approval is obtained.

Fractionation

Fractionation is processing of crops or commodities so that the nutritional and functional characteristics of the individual fractions remain intact or are not further reduced, respectively. A specific strategy to fractionate crops into unique fractions using dry or wet fractionation might be advantageous to develop new crop products as feedstuffs for livestock with high nutritional demands, thereby accessing new markets to enhance crop value (Zijlstra et al., 2004; Zijlstra and Beltranena, 2007). Air classification of pulse crops seems such an opportunity, because pulse seeds contain both starch and protein that separate well in a stream of air. Specifically, dehulling of field pea followed by fine grinding and air classification allows the separation of the light, fine (pea protein concentrate) and the heavy, coarse (mainly starch) fractions that can be used in pig feeding (Wu and Nichols, 2005). Consequently, protein and starch concentrates can be produced at a fraction of the expense of wet fractionated protein concentrates or protein isolates. Oil fractionation has been strong traditionally for human food purposes, whereas fiber fractionation via dehulling has been strong traditionally with modern fractionation technologies implemented to extract fiber fractions with unique functional properties.

Protein Fractions

Protein concentrates containing around 60% CP and protein isolates containing around 90% CP have been developed from soybean meal. As a sustainable alternative, fractionation of field pea has a strong tradition among the pulse crops (Bramsnaes and Olsen, 1979), and a highly pure protein concentrate can also be effectively fractionated from zero-tannin faba bean using air classification (Gunawardena et al., 2010a). The pulse protein concentrates that are fractionated using air classification are an attractive alternative nutritionally for specialty protein sources in young pigs (Figure 10.6; Valencia et al., 2008; Gunawardena et al., 2010b). However, nutrient digestibility and digestible nutrient profile of pulse protein concentrates should be characterized prior to validation experiments because nutrient digestibility will be lower than in soy protein concentrate (Valencia et al., 2008). Field pea protein isolates can be produced using wet fractionation and could potentially be used as an alternative for spray-dried plasma protein. Field pea protein isolate is highly digestible, in part due to effective removal of ANF (Le Guen et al., 1993a,b). However, field pea protein isolate may have the nutritional quality, but it does not have the functional properties of plasma protein. Therefore, field pea protein isolate will have to be mixed with egg yolk antibodies from hyperimmunized laying hens containing specific anti-enterotoxigenic *Escherichia coli* (K88) antibodies to control an infection of the bacteria (Owusu-Asiedu et al., 2003a,b).

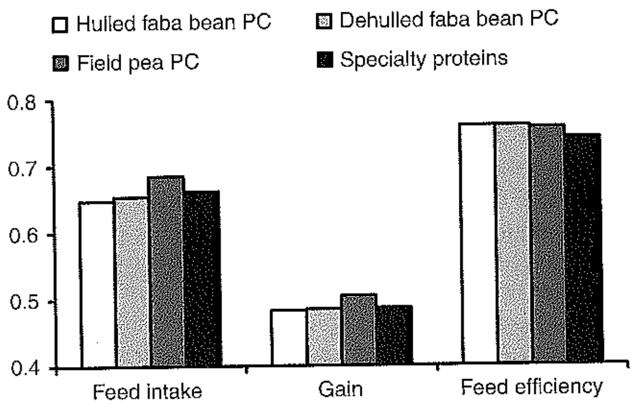

Figure 10.6 The lack of effect of protein source (PC = protein concentrate) included at 16–17.5% in the diet on feed intake (kg/d; SEM = 0.016), gain (kg/d; SEM = 0.012), and feed efficiency (SEM = 0.01) of weaned pigs; adapted from Gunawardena et al., 2010b.

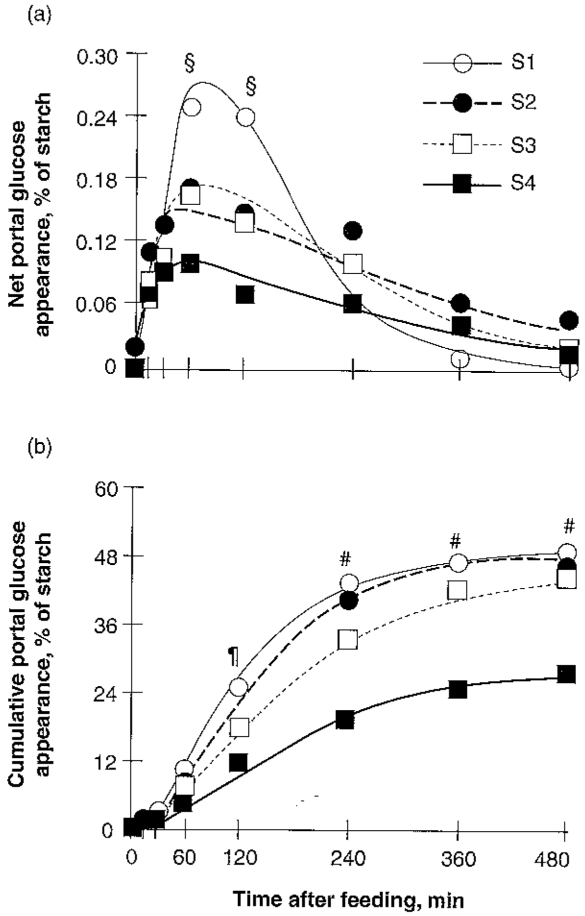

Figure 10.7 Portal appearance of glucose in pigs fed four diets containing S1 to S4 starch (i.e., starch sources ranging from rapidly to slowly digestible starch). A modified Chapman–Richards model was used to predict kinetics of portal glucose appearance from observed values ($R^2 = 0.96$); Panel A, net portal appearance of glucose; Panel B, cumulative portal glucose appearance; §, S1 vs. S2 and S3 vs. S4; ¶, S1 vs. S4; and #, S1, S2, and S3 vs. S4 means differ, $P < 0.05$; n = 4. In A, the SE ranged from 0.01 to 0.03; in B the SE ranged from 0.02 to 5.22%; adapted from Van Kempen et al., 2010.

Starch Fractions

Starch is a main energy source in pigs and is included as a component of feedstuffs. Starch isolates (90%) are produced for human food purposes, and are rarely included in commercial swine feed. However, starch isolates are used in swine nutrition to study the impact of starch chemistry on glycemic responses (Figure 10.7; Van Kempen et al., 2010). Starch concentrates may be produced using dry or wet fractionation. Air classification products are highly digestible field pea and zero-tannin faba bean starch concentrate that may serve as a feedstuff for young pigs (Gunawardena et al., 2010b). Extrusion may enhance nutrient utilization of this faba bean starch concentrate (Wierenga et al., 2008). Still, cooked rice might be a preferable starch source for young pigs (Parera et al., 2010). Wet fractionation of barley or oat for the purpose of extraction of β-glucan may also produce a starch concentrate that has a high digestibility for pigs (Johnson et al., 2006). Finally, raw potato starch might be included in diets for young pigs as a source of resistant starch (Bhandari et al., 2009).

Resistant starch has prebiotic activity and might be part of a solution to use feedstuff characteristics instead of feed additives to facilitate the removal of antibiotics from swine diets. Furthermore, dietary resistant starch is fermented similarly as fermentable fiber and might be part of a solution for reducing odor emissions from swine farms, because excretion of volatile nitrogenous compounds as a part of odor will be reduced (Willig et al., 2005). Finally, dietary resistant starch may reduce skatole formation, and might, thereby, form part of a solution to avoid castration of boars while continuing to produce pork (Lösel and Claus, 2005).

Fiber Fractions

Dehulling of cereal grains, pulse seeds, or oilseeds is generally considered advantageous for swine nutrition. Dehulled seed will have a higher energy value and nutrient digestibility than the entire seed. For example, dehulled faba bean, lupin, barley, oats, corn, and meal of dehulled canola seed have a greater nutrient digestibility than their hulled counterparts (e.g., Van der Poel, 1992b; Kracht, 2004; Hennig et al., 2006; Moeser et al., 2002). Hull NSP is generally insoluble and has less favorable fermentation characteristics in the porcine digestive tract (Williams et al., 2005). The feeding of hull NSP with a low ANF content increased diet bulk density, thereby, causing satiety in gestating sows with a restricted access to feed and reduced stereotypic behavior (Matte et al., 1994; Holt et al., 2006). However, fiber fermentation characteristics can differ among samples of the same grain, and high fermentability may create prebiotic effects (Pieper et al., 2009). The viscosity or prebiotic effects of NSP can be enhanced following wet fractions. For example, wet fractionation of β-glucan from oat or barley yields β-glucan concentrate with a high fermentability and a specific in vitro viscosity, depending on chain length of the β-glucan. These fractions have prebiotic activity (Metzler-Zebeli et al., 2010) and impact glycemic responses (Hooda et al., 2010).

Fat Fractions

Oil extracted from oil seeds has, after purification, a high value for its primary market, which is human food purposes. The crude plant oil after initial separation has value especially for young pigs with immature gastrointestinal tracts, because plant oil has a greater digestibility of ether extract than animal-based fat (Duran-Montgé et al., 2007). However, price or logistical considerations due to impeded material flow can prohibit high inclusion levels of liquid plant oils. Animal-based, saturated fat sources such as tallow seem to be more cost effective as energy sources for grower–finisher pigs and may not have an impact on pork fat softness as do unsaturated fatty acids, such as linoleic acid in corn DDGS (Stein and Shurson, 2009). Opportunities exist to enhance the omega-3 fatty acid content of pork by feeding flax oil (Health Canada 2004), but doing so may also reduce pork fat hardness unless conjugated linoleic acid is fed simultaneously (Dugan et al., 2004). Feeding flax oil in diets for gestating and lactating sows will increase α-linolenic acid in sow tissues and milk, and, thereby, increase α-linolenic acid in suckling piglets, especially after birth (Boudry et al., 2009). Increased α-linolenic acid in piglets may improve their health status via improved intestinal barrier function (Boudry et al., 2009) and immune resistance (Farmer et al., 2010). Finally, dietary intake of unsaturated fat will increase the requirement for vitamin E, which is a membrane-associated antioxidant (Schaefer et al., 1995); therefore, vitamin addition to diets high in unsaturated fatty acid is recommended (Lauridsen et al., 1999).

Summary

For sustainable swine production, economics, agronomy, societal acceptance, and the environment are key components. Alternative feedstuffs play a key role in these components, and the pig as an omnivorous species is suited to effectively convert alternative feedstuffs to pork products. Traditionally, alternative feedstuffs were solely viewed as an opportunity to reduce feed costs, but recently, modified crops have been used to reduce the environmental footprint of pork production. Alternative feedstuffs may have unique value attributes that allow manipulation of animal health, behavior, nutrient excretion patterns, and even pork quality. Alternative feedstuffs also provide some challenges. First, co-products add variability in macronutrient profiles in the feedstuff matrix beyond the variability intrinsic to the crops. Therefore, feed-quality evaluation for energy, AA, and P content and availability or digestibility is important, as is the system selected for evaluation. Second, co-products may contain chemical residues and mycotoxins that reduce voluntary feed intake and affect reproductive performance. Finally, co-product use may reduce carcass characteristics and pork quality. The high-fiber content of co-products reduces dressing percentage. The high-oil content of some co-products provides unsaturated fatty acids that soften pork fat. In conclusion, use of alternative feedstuffs may reduce feed costs per unit of pork produced but also provides challenges in achieving cost-effectiveness, predictable growth performance, animal health, reasonable environmental footprints, and desirable carcass characteristics and pork quality.

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