NONRUMINANT NUTRITION SYMPOSIUM:
Controlling feed cost by including alternative ingredients into pig diets: A review1,2

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ABSTRACT: Sustained price increases for traditional cereal grain and protein meal feed commodities have forced the pork industry to consider the dietary inclusion of alternative feedstuffs. Crop seed may serve as feedstuffs but their demand as feedstock for human food, biofuel, and bioindustrial products has increased. Together with these products, coproducts such as distillers dried grains with solubles, wheat millrun, and canola meal are produced. As omnivores, pigs are ideally suited to convert these non-human-edible coproducts into high-quality food animal protein. Therefore, coproducts and other low-cost alternative feedstuffs such as pulses and oilseeds can be included in pig diets to reduce feed cost per metric ton of feed. However, inclusion of alternative feedstuffs in pig diets does not necessarily reduce feed cost per kilogram of gain. Therefore, the use of novel and existing feedstuffs in pig diets must be optimized following their characterization for energy and AA profile. Alternative feedstuffs generally have a high content of at least 1 of the following antinutritional factors (ANF): fiber, tannins, glucosinolates, and heat-labile trypsin inhibitors. Several methods can optimize nutrient use of pigs fed alternative feedstuffs by reducing effects of their ANF. These methods include 1) particle size reduction to increase nutrient digestibility, 2) dehulling or scarification to reduce tannin and fiber content of pulses and oilseeds, 3) air classification to create fractions that have a greater content of nutrients and lower content of ANF than the feedstock, 4) heat treatments such as extrusion, toasting, roasting, and micronization to reduce heat-labile ANF, 5) dietary supplementation with fiber-degrading enzymes or predigestion of fibrous feedstuffs or diets with fiber-degrading enzymes to increase dietary nutrient availability, and 6) formulation of diets based on bioavailable AA coefficients. In conclusion, the feeding of alternative ingredients may reduce feed cost per unit of pork produced provided that their price per unit NE or digestible lysine is less than that of the traditional feedstuffs and that negative effects of their ANF are controlled.

Key words: alternative feedstuff, feed cost, nutritional value, pig

INTRODUCTION

Feed is the single greatest cost of pork production (Niemi et al., 2010). Drastic increases in feed cost over the last decade have reduced profit margins of pork production (Schmit et al., 2009). In pig diets, corn and wheat are the most widely fed energy sources in North America, Europe, and Australia. However, prices of these feed grains have soared due to their increased demand by the food and ethanol industry (Tyner and Taheripour, 2007), increased crude oil prices (Avalos, 2013), and recently the 2012 U.S. drought. The price of soybean meal (SBM), the most widely fed protein source, has soared also due to increased acreage used to grow corn at the expenses of soybean acreage (Schmit et al., 2009; Avalos, 2013) and the 2012 U.S. drought. Prices of U.S. corn and SBM more than doubled over the last 7 yr (Patience, 2013). Therefore, a need exists for cost-effective alternative feedstuffs.

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Cereal grains such as triticale and sorghum, cereal grain coproducts, oilseeds, oilseed coproducts, and pulses are alternatives for corn, wheat, and SBM although availability depends on local circumstances. The nutritive value of an increasing array of alternative feedstuffs has been determined for pigs (Jezierny et al., 2010; Liu et al., 2013) and added to databases (Sauvant et al., 2004; CVB, 2007; NRC, 2012). Moreover, their impact on growth performance and carcass and pork quality was reviewed (Shurson et al., 2012; Zijlstra and Beltranena, 2013a,b).

Effects of including alternative feedstuffs in pig diets on feed cost changes have not been reviewed. Our objective was to review the nutritive value of alternative feedstuffs for pigs, the effect of including these feedstuffs in pig diets on growth performance vs. feed cost, and optimizing their use in pig diets. Also, we suggested areas that need further research to optimize their use. Other items, such as effects of harvest and storage conditions and mycotoxins, were beyond the scope of this review.

### NUTRITIVE VALUE OF ALTERNATIVE FEEDSTUFFS FOR PIGS

Alternative feedstuffs can be good sources of energy, AA, and minerals in pig diets. However, their dietary inclusion might be limited by several factors. The availability, nutritional value, and limitations of alternative feedstuffs are discussed.

### Cereal Grains

Corn and wheat remain the traditional sources of energy in pig diets. Corn is the major energy source in the United States and eastern Canada whereas wheat is the major energy source in Europe, Australia, and western Canada. Other “small” cereal grains can also be used as dietary energy source. For example, alternatives that are available in temperate regions such as Canada, northern United States, and northern Europe include barley and triticale (AAFC, 2005; McGoverin et al., 2011), while sorghum is an alternative in tropical regions such as Mexico. The nutritive values of corn and wheat are well characterized; hence, the nutritive values of the other 3 cereal grains are discussed.

**Barley.** Barley is grown mainly for malt and livestock feed (Fairbairn et al., 1999). Two types of feed barley are hulled and hullless. Hulled barley contains less starch and more fiber than wheat or corn (Table 1), whereas hullless barley contains more starch and less fiber than hulled barley. Fiber is negatively correlated with energy value of cereal grains (Fairbairn et al., 1999; Zijlstra et al., 1999) whereas starch is positively correlated (NRC,
Therefore, hulled barley contains less NE than wheat whereas the NE value of hulless barley and wheat are close (Table 1). The ADG of grower pigs but not of finisher pigs fed hulled barley-based diets was less than of pigs fed wheat grain-based diets that were formulated to similar DE value and total AA content (Blair et al., 1990). However, this switch in cereal grain did not affect G:F of pigs in either phase (Blair et al., 1990). Hence, the greater fiber content in hulled barley may not reduce growth performance of pigs under all circumstances. Replacing hulled barley with hulless barley in diets formulated to similar DE value and standardized ileal digestibility (SID) AA content increased growth performance of grower pigs by 27% (Woyengo et al., 2012a). Replacing hulless barley with corn in diets formulated to similar DE value and SID AA content did not affect growth performance of grower–finisher pigs (Wu et al., 2000). Therefore, small cereal grains can increase flexibility in pig feed formulation. Finally, the ratio of amylose to amylopectin varies among hulled and hulless barley cultivars (Jha et al., 2011). Amylose has less energy digestibility in pigs than amylopectin (Regmi et al., 2011); therefore, the energy value of barley can vary among cultivars.

**Triticale.** Triticale is a hybrid of wheat and rye and has better agronomic attributes than wheat (McGoverin et al., 2011). Triticale is grown mainly for livestock feed with some destined for human food. Triticale contains similar starch and fiber as wheat and corn; therefore, triticale, wheat, and corn have similar NE values (Table 1). The ADFI, ADG, and G:F did not differ between weaned pigs fed triticale- or corn grain-based diets formulated to similar ME value and total AA content (Myer and Brendemuhl, 2009) or fed triticale- or wheat grain-based diets formulated to similar NE value and SID AA content (Beltranena et al., 2008). Therefore, triticale can replace cereal energy sources in pig diets without reducing growth performance. However, effects of dietary inclusion of triticale on carcass traits and pork quality require research.

**Sorghum.** Sorghum is grown for livestock feed, human food, and ethanol production and is more drought tolerant than corn (Liu et al., 2013). Sorghum contains similar CP, starch, and fiber than corn (Table 1) but also contains more tannins that reduce nutrient utilization (Liu et al., 2013). The content of tannins and, hence, sorghum nutritive value varies among cultivars. For example, G:F of grower–finisher pigs (20 to 93 kg BW) and ileal and total tract digestibility of N and GE of grower pigs (50 kg BW) was reduced when high-tannin sorghum replaced corn but not when low-tannin sorghum was fed (Cousins et al., 1981). Replacing high-tannin with low-tannin sorghum (i.e., 3.7 vs. 0.1% of DM, respectively) reduced ADG by 0.03 kg and G:F by 0.05 of weaned pigs (9 kg BW) fed diets formulated to similar ME value (Myer and Gorbet, 1985).

**Cereal Grain Coproducts**

Cereal grains are processed into ethanol biofuel, flour, and other products for human food or industrial application, resulting in coproducts that can be fed to livestock. Dried distillers grain with solubles (DDGS) is the primary coproduct from ethanol production. The DDGS is now readily available in North America and Europe as a commodity feedstuff as a result of government production subsidies and legislations that stipulated a minimum amount of ethanol in gasoline, thereby rapidly increasing ethanol and DDGS production (Tyner and Taheripour, 2007). Coproducts of wheat flour milling are also available as commodity feedstuffs, because mainly wheat is used by the milling industry to produce flour for bread production (FAO, 2009). Wheat millrun is one of the milling coproducts that are used to formulate pig diets.

**Dried Distillers Grains with Solubles.** The DDGS produced in the United States and eastern Canada are mainly derived from corn whereas DDGS produced in western Canada and Europe are mainly derived from wheat (Nyachoti et al., 2005; Cozannet et al., 2010). However, some ethanol plants cofermented wheat and corn, depending on price and availability. The nutritive value of DDGS has been reviewed previously (Stein and Shurson, 2009). Briefly, DDGS contain around 3 times more protein, AA, fat, fiber, and minerals than the parent cereal grain (Table 1) but potentially also 3 times more mycotoxins (Zhang and Caupert, 2012). Starch in cereal grains is fermented into alcohol and CO₂ that are removed so that distillers grain is left to which the solubles are added and then dried together. The high fiber content in DDGS reduces nutrient utilization. The 10 to 12% of unsaturated fat in corn DDGS reduces pork fat hardness. Recent processing changes that recover oil produce low-oil DDGS with 6 to 9% fat, but feeding such DDGS continues to cause problems with softer pork fat (Graham et al., 2013). Finally, DDGS can have protein damage during the drying of DDGS. Specifically, the SID in pigs was 27% less for CP and 50% for Lys in corn DDGS than in corn (Almeida et al., 2011). Similarly, the SID in pigs was 16 to 21% less for CP and 36 to 43% for Lys in wheat DDGS (Lan et al., 2008; Cozannet et al., 2010) than in wheat (Hennig et al., 2008).

Feeding of DDGS may affect growth of pigs. In nursery pigs, increasing corn DDGS inclusion from 0 to 30% in diets formulated to similar ME and SID AA content reduced ADFI by 17 and ADG by 10% (Tran et al., 2010). Increasing wheat DDGS from 0 to 15% in diets formulated to similar NE and SID AA content marginally reduced ADG by 10 to 12% and ADG by 5 to 10% (Tran et al., 2010). Increasing wheat DDGS from 0 to 15% in diets formulated to similar NE and SID AA content marginally reduced ADG by 10 to 12% and ADG by 5 to 10% (Tran et al., 2010). Increasing wheat DDGS from 0 to 15% in diets formulated to similar NE and SID AA content marginally reduced ADG by 10 to 12% and ADG by 5 to 10% (Tran et al., 2010). Increasing wheat DDGS from 0 to 15% in diets formulated to similar NE and SID AA content marginally reduced ADG by 10 to 12% and ADG by 5 to 10% (Tran et al., 2010).
SID AA content reduced ADG by 100 g but not ADFI of grower pigs (Agyekum et al., 2013). Increasing corn DDGS from 0 to 45% in diets formulated to similar ME and SID AA content reduced ADG by 32 g but not ADFI of grower–finisher pigs (Cromwell et al., 2011), indicating that DDGS reduces efficiency of utilization of ingested nutrients. Increasing dietary DDGS inclusion from 0 to 30% increased viscera mass and decreased dressing percentage of pigs (Agyekum et al., 2012). The greater gut mass increased gut energy expenditure (Ferrell, 1988), indicating that dietary DDGS increases energy use for maintenance at the expense of growth. Regarding pork quality, increasing corn DDGS inclusion from 0 to 20% in corn-based diets increased pork PUFA content (Benz et al., 2010; Wang et al., 2012). However, inclusion of up to 30% of corn DDGS in barley-based diets formulated to similar NE value and SID AA content did not affect growth performance or carcass traits of grower–finisher pigs (Beltranena et al., 2009a,c). In summary, dietary DDGS may reduce performance of younger pigs. However, considerable DDGS can be included in diets of grower–finisher pigs without affecting growth performance and carcass quality, provided that shipping weight is increased by 1 to 2 kg to mitigate the reduced dressing percentage due to gut fill and increased viscera weight. 

**Wheat Millrun and Middlings.** Wheat millrun and middlings contain less starch and more nonstarch components (i.e., fiber, CP, and ether extract) than wheat due to endosperm removal during milling (Table 1). Replacing 40% wheat with wheat millrun in diets formulated to similar ME value and SID AA content reduced ADG and G:F of grower pigs by 7% (Nortey et al., 2007). Similarly, inclusion of 30% wheat middlings in corn–SBM based diets formulated to similar ME value and SID AA content reduced ADG, G:F, and dressing percentage of grower pigs (25 to 55 kg BW) and increased full and empty visceral weight (Stewart et al., 2013). However, dietary inclusion of wheat middlings for finisher pigs (85 to 125 kg BW) reduced dressing percentage and increased gut fill but did not affect growth performance or empty viscera weight (Stewart et al., 2013). Therefore, inclusion of 40% wheat middlings in diets for grower pigs formulated based on ME system can reduce growth performance and increase viscera mass, but finisher pigs can adapt better. Whether reduced growth performance and increased visceral weight of weaned pigs fed diets containing 30% wheat middlings can be compensated for with compensatory gain requires research, including diets formulated to similar NE value.

**Pulses**

Pulses are nonoilseed legumes that are produced mainly for human consumption. Pulses fed to pigs include field pea, faba bean, and lentil. Cultivars that are well adapted to cool climates have been developed (Duc et al., 1995; Jezierny et al., 2010). Therefore, pulses may serve as alternative to SBM in pig diets in temperate regions, where soybean does not grow well.

**Field Pea.** Field pea contains less CP and Lys than SBM and less starch than corn or wheat (Table 1) but more fiber than SBM, corn, or wheat. As a legume, field pea contains antinutritional factors (ANF; Jezierny et al., 2010). For example, trypsin inhibitor activity was greater for SBM than for raw field pea samples (5.8 vs. 0.2 to 5.0 mg of trypsin inhibitor/g of CP; Jezierny et al., 2011). The SID of Lys of field pea is similar to SBM and its NE value is similar to that wheat.

Replacing corn and SBM with more than 36% raw field pea in diets formulated to similar ME value and SID AA content reduced the ADG of weaned pigs (9 to 24 kg BW) by 3% (Stein et al., 2010). Likewise, 30% raw field pea in diets formulated to similar DE value and total AA content decreased the ADG of weaned pigs by 6% (Friesen et al., 2006). Partial replacement of SBM with 20% field pea in diets formulated to similar DE value and CP content did not affect growth performance and meat quality of finisher pigs (55 to 160 kg BW) used for Parma ham (Gatta et al., 2013). Replacing 14% SBM and 16% corn with 30% field pea did not affect growth performance and carcass traits of grower–finisher pigs (Smith et al., 2013). Therefore, grower–finisher pigs can be fed field pea almost without limits in diets formulated to similar NE value and SID AA content without affecting growth performance and carcass traits.

**Faba Bean.** Faba bean contains more CP, Lys, and fiber and less starch than field pea (Table 1). Raw faba bean contain 0 to 7.0 g condensed tannin/kg of DM and <0.2 to 3.9 mg of trypsin inhibitor activity/g of CP (Jezierny et al., 2011). Faba bean has a SID of Lys value slightly greater than that of field pea but less NE value (Table 1) likely due to the greater CP and lower starch content of faba bean vs. field pea.

Replacing SBM with 40% zero-tannin faba bean in diets formulated to similar NE value and SID AA content did not affect performance of weaned pigs (Beltranena et al., 2009b). Replacing 14% SBM and corn with 30% faba bean in diets formulated to similar NE value and SID AA content did not affect growth performance and carcass traits of grower–finisher pigs (Smith et al., 2013). Inclusion of 18% faba bean in diets fed to grower–finisher pigs did not change pork quality (Gatta et al., 2013). Similarly, replacing SBM and wheat with barley and 30% zero-tannin faba bean in diets formulated to similar NE value and SID AA content did not affect growth performance of grower–finisher pigs (35 to 115 kg BW); however, dressing percentage and carcass loin thickness were reduced (Zijlstra et al., 2008). Faba bean and bar-
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Therefore, 30% faba bean can be included in diets fed to grower–finisher pigs without affecting growth performance, but research is required to achieve equal AA utilization and carcass traits for pigs fed in high fiber diets.

**Lentil.** Lentil contains similar CP, Lys, and starch and less fiber than faba bean (Table 1). Lentil ranged from 0.4 to 1.0 g condensed tannin/kg of DM whereas raw lentil ranged from 2 to 3 mg of trypsin inhibitor activity/g of CP (Wang and Duan, 2006). The SID of Lys of lentil is less than that of field pea or faba bean, and its NE value is between field pea and faba bean (Table 1). Inclusion of 22.5% lentil in diets formulated to similar NE and SID AA content did not affect performance of weaned pigs (Landero et al., 2012d).

**Oilseed Meals**

Oilseed meals are coproducts of the oilseed-crushing industry that extracts oil for human consumption or for biofuel and can serve as dietary protein supplements. Oilseed meals other than SBM include canola, cotton, sunflower, copra, and camelina. Of these, canola meal is the most widely used alternative (Bell, 1993) and a focus of this review.

The most common canola is *Brassica napus* whereas *Brassica juncea* is a newly developed species that is grown in warmer and drier areas of the Canadian prairies. Solvent extraction, expeller pressing, or cold pressing can extract oil from canola seed. Solvent extraction is the most common method and produces solvent-extracted canola meal (SECM) with less than 1% residual oil (Spragg and Mailer, 2007; CCC, 2009; Table 1), but gums (phospholipids) are added back to the meal, increasing its ether extract content to 3 to 4%. Expeller pressing produces expeller-pressed canola meal (EPCM) with 10 to 12% residual oil whereas cold pressing produces cold-pressed canola cake (CPCC) with 12 to 20% residual oil (Spragg and Mailer, 2007; Table 1). Therefore, EPCM and CPCC are not only protein sources but also better energy sources than SECM due to their residual oil (Woyengo et al., 2010; Seneviratne et al., 2011a).

Generally, canola meal contains less CP and AA and more fiber than SBM (Table 1) and contains glucosinolates that can reduce feed intake and nutrient utilization in pigs. In SECM, EPCM, and CPCC, the glucosinolates content varies depending on the glucosinolates content in canola seed and extent of their degradation by heat during toasting (Woyengo et al., 2011). Juncea canola meal has a thinner seed coat and therefore contains less fiber than Napus canola meal (Slominski et al., 2012). However, Juncea canola meal contains more glucosinolates than Napus canola meal (Landero et al., 2012c) that are bitter glucosinolates (3-butenyl) that reduce preference of weaned pigs in favor of Napus vs. Juncea canola meal (Landero et al., 2012c).

The SECM and EPCM are similar in AA digestibility (Table 1). The CPCC has less AA digestibility than SECM or EPCM, which could be attributed to the lack of heating seed with steam before oil extraction. Mild, short-time heat treatment and pressing can disrupt cell walls and de-nature protein, increasing AA digestibility (Vande Ginste and De Schrijver, 1998). The CPCC has the greatest NE value followed by EPCM and last SECM, following the same ranking for their ether extract content. Napus canola meal has less SID of Lys than Juncea canola meal (Trindade Neto et al., 2012). Canola meals have less AA digestibility than SBM and SECM has less NE value than SBM. However, EPCM and CPCC have greater NE values than SBM due to greater residual oil content than SBM.

Napus SECM or EPCM can be included in diets for pigs without affecting growth performance. Specifically, replacing SBM with 20% Napus SECM (Landero et al., 2011a) or 20% Napus EPCM (Landero et al., 2012a) in diets formulated to similar NE and SID AA content did not affect performance of weaned pigs. Inclusion of 22.5% Napus SECM in diets formulated to similar NE and SID AA content did not reduce growth performance of grower pigs (29 to 65 kg BW; Montoya and Leterme, 2010). However, increasing Juncea SECM inclusion from 0 to 24% in diets formulated to similar NE and SID AA reduced ADFI and ADG of weaned pigs (Landero et al., 2013a). The greater content of glucosinolates (i.e., 3-butenyl) in Juncea canola meal than Napus canola meal may explain the poor performance of weaned pigs fed Juncea SECM. Similarly, increasing Napus EPCM meal inclusion from 0 to 22.5% in diets formulated to similar NE and SID AA reduced ADG of grower–finisher pigs (Seneviratne et al., 2010). The EPCM (Seneviratne et al., 2010) contained more glucosinolates than Napus SEC (23 vs. 4 μmol/g; Landero et al., 2011b). The greater content of total glucosinolates in Napus EPCM than Napus SEC may explain the poor performance of grower–finisher pigs fed EPCM. Effects of including low-glucosinolate EPCM and Juncea canola meals in diets for grower–finisher pigs on growth performance and carcass traits requires further research.

**Oilseeds**

Oilseeds such as soybean and canola produce oil for human food consumption. However, oilseeds can also be fed to livestock as full-fat seed when off-grade or not destined for human oil production. Compared with their
meals, oilseeds contain more oil and less CP and fiber (Table 1) due to dilution with oil. Full-fat soybean and canola are the most common oilseeds fed to pigs.

**Full-Fat Soybean.** Full-fat soybean (FFSB), similar to SBM, is a good source of AA and energy. The Lys content and SID of Lys of FFSB are greater than for canola meal (Table 1). Also, FFSB has a NE value 34% greater than that of SBM due to its 22% oil content. The FFSB contains 18% more fiber than SBM because SBM, unlike FFSB, is dehulled. Most oil in soybean is unsaturated, which can reduce pork quality. Soybean contains ANF, such as trypsin inhibitors, that can reduce nutrient utilization. These ANF are reduced drastically during the desolventizing–toasting step to produce SBM, which supports unrestricted inclusion of SBM in diets for pigs. Inclusion of FFSB may be limited due to intact ANF. Therefore, FFSB is micronized, roasted, or extruded to reduce ANF to levels in SBM.

Inclusion of 30% toasted, extruded, or roasted FFSB in diets fed to grower–finisher pigs (30 to 100 kg BW) did not affect growth performance and carcass weight (Zollitsch et al., 1993) but increased pork linoleic and linolenic acids. Similarly, inclusion of 20% extruded FFSB in diets fed to grower–finisher pigs did not affect growth performance and carcass traits (Cannon et al., 1992). Therefore, 30% of FFSB can be included in diets for grower–finisher pigs without reducing growth performance and with limited effect on carcass traits. Notably, effects of heat treatments on ANF levels in FFSB can vary, causing variable nutritive value of FFSB. Therefore, inactivation of ANF in FFSB should be ensured before its use as feedstuff for pigs.

**Full-Fat Canola.** Full-fat canola (FFC), similar to canola meal, is a good source of AA for pigs with similar Lys content and digestibility as pulses (Table 1) and DE and NE values that are close to corn and wheat. The FFC contains less fiber than canola meal due to oil dilution, but FFC contains similar glucosinolates to canola meal. Also, FFC contains double the oil of FFSB that is mostly unsaturated; thus, FFC reduces pork quality at one-half the dietary inclusion of FFSB.

Increasing inclusion of FFC from 0 to 15% in diets formulated to similar NE and SID AA content decreased ADFI and increased G:F of grower pigs (Montoya and Leterme, 2010) whereas ADG was not affected. Similarly, increasing inclusion of FFC from 0 to 24% in diets formulated to similar DE value and total AA content did not affect performance of weaned (10 to 28 kg BW) or grower–finisher pigs (23 to 91 kg BW; Brand et al., 1999); however, dressing percentage was decreased by 4%. Recently, increasing inclusion of FFC from 0 to 15% in diets formulated to similar NE and SID AA content linearly decreased G:F and carcass dressing percentage of grower–finisher pigs (Woyengo et al., 2012b). Simultaneously increased dietary FFC and fiber may decrease dressing percentage (Brand et al., 1999; Woyengo et al., 2012a). Formulations were not consistent among studies; FFC was replaced with wheat (Brand et al., 1999), wheat and SBM (Montoya and Leterme, 2010), or wheat and SBM balanced with barley (Woyengo et al., 2012b). Barley contains more fiber than SBM or wheat so that dietary fiber increased more when partially replacing wheat with FFC and barley than when replacing wheat with only FFC. Therefore, effects of dietary FFC to reduce G:F may be enhanced by simultaneous cereal changes.

**FEED COST VERSUS BENEFIT OF ALTERNATIVE FEEDSTUFFS IN PIG DIETS**

We have studied effects of including alternative feedstuffs in pig diets on growth performance. Some studies included an economic analysis of feed cost vs. benefit (Table 2). Others were designed to evaluate responses to progressive feedstuff inclusions and not to optimize gross income margin over feed cost. In all studies, diets within phase were formulated to similar NE value and SID AA content.

Inclusion of 15% wheat DDGS in diets for weaned pigs decreased feed cost by US$14.60/t but increased feed cost per kilogram of BW gain only at 20% inclusion because of reduced performance (Jha et al., 2010). However, inclusion of 30% corn DDGS in diets fed to grower–finisher pigs did not affect feed cost, feed cost per kilogram of BW gain, or income over feed cost (Beltranena et al., 2009a). Instead, inclusion of 25% corn DDGS in diets for grower–finisher pigs (20 to 120 kg BW) reduced feed cost by 13% (Skinner et al., 2012).

Replacing 20% SBM with Napus SECIM in diets for weaned pigs reduced feed cost $11.90/t and feed cost 2 cents/kg BW gain (Landero et al., 2011b). Replacing 20% SBM with Napus EPCM in diets for weaned pigs reduced feed cost by $29.80/t and feed cost by 4.2 cents/kg BW gain (Landero et al., 2012b). However, replacing 24% SBM with Juncea SECIM in diets for weaned pigs increased feed cost per metric ton and per kilogram BW gain due to reduced performance (Landero et al., 2013a). For grower–finisher pigs, dietary inclusion of 15% ECPM reduced feed cost by 2.0 cents/kg BW gain (Seneviratne et al., 2009). However, dietary inclusion of ECPM reduced ADG, indicating that pigs would remain longer in the barn before reaching market weight. Dietary inclusion of 10, 20, or 30% Napus or Juncea SECIM increased feed cost per metric ton and per kilogram BW gain even though G:F was increased (Seneviratne et al., 2011b). In this study, the wheat DDGS that was partially replaced with canola meal was priced less than canola meal, indicating that replacing one coproduct with another does not necessarily reduce feed cost even though the data was interesting nutritionally.
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For pulses, inclusion of lentil in diets for weaned pigs decreased feed cost by $4.13/t and reduced feed cost per kg BW gain by 0.64 cents/kg BW gain (Landero et al., 2011c). For oilseeds, inclusion of FFC in diets for grower–finisher pigs reduced feed cost by $5.50/t and reduced feed cost per kg BW gain by 2.0 cents/kg BW gain (Woyengo et al., 2012b).

In summary, up to 20% Napus SECM and EPCM and 22.5% lentil can be included in diets for weaned pigs to reduce feed cost per kilogram BW gain. For grower–finisher pigs, diets can include up to 15% Napus EPCM to reduce feed cost and up to 30% corn DDGS without affecting growth performance and feed cost if effects on pork fat hardness are ignored.

The increased knowledge about the nutritional quality and impact of growth performance and carcass traits of alternative feedstuffs has increased the comfort zone of using these feedstuffs in feed formulation. Therefore, characterization of alternative feedstuffs has reduced their risk for dietary inclusion and thereby increased flexibility of feed formulation. As discussed previously, large quantities of feedstuffs can be replaced with minimal effects on growth performance although limits to maintain lean growth, carcass traits, and pork quality may exist. Presently, barley is priced less than wheat in Canada ($260 vs. $284/t, respectively; Statistics Canada, 2013) and sorghum is priced less than corn in the United States ($251 vs. 267/t, respectively; USDA, 2013a), indicating that replacing wheat and corn with barley and sorghum reduces feed cost. Although field pea ($322) is priced higher than corn or wheat and FFC ($619) and FFB (S$479) are priced higher than SBM ($340; Statistics Canada, 2013; USDA, 2013b), pulses and oilseeds fed to pigs are generally off-grade and fetch a lower price than food commodities and may therefore be attractive for pig feeding purposes.

Prices of traditional and alternative feedstuffs keep changing depending on supply and demand. For instance, prices of corn, SBM, corn DDGS, wheat middlings, and vegetable oil increased by 358, 203, 518, 378, and 212%, respectively, over the last 7 yr (Patience, 2013) and thereby increased the cost per megacalorie NE accordingly (Table 3). Notably, the cost of NE in corn DDGS was less than that in corn in 2005 but subsequently increased more for corn DDGS than corn, resulting in a greater cost of NE in DDGS than corn grain in 2012. The current cost of corn DDGS might be attributed partly to increased knowledge about feeding DDGS, thereby increasing the demand for DDGS by the feed industry. Changes in price and availability of feedstuffs can affect the cost–benefit analyses of including alternative feedstuffs in pig diets.

### OPTIMIZE USE OF ALTERNATIVE FEEDSTUFFS IN PIG DIETS

In some of our studies, dietary inclusion of alternative feedstuffs did not reduce feed cost. The primary objective of these studies was not to reduce feed cost but to evaluate responses to increasing dietary inclusion of alternative feedstuffs. Occasionally we did not reduce feed cost; therefore, a need exists to optimize the use of alternative feedstuffs is discussed subsequently.

### Table 2. Effect of including alternative feedstuffs in pig diets on performance and economic viability of pig production

<table>
<thead>
<tr>
<th>Alternative feedstuff</th>
<th>BW, kg</th>
<th>Feedstuff level, %</th>
<th>Effect on ADG</th>
<th>Change in feed cost</th>
<th>Source</th>
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<tr>
<td>Lentil</td>
<td>Initial Final ADG G:F Per t Per kg gain</td>
<td>Lentiel et al. (2011c)</td>
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<td>nEPCM</td>
<td>7.3 % 20 None None –$29.80 –4.2 ¢</td>
<td>Landero et al. (2012b)</td>
<td></td>
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<td></td>
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<tr>
<td>nSECM</td>
<td>8.1 % 20 None None –$11.90 –2.00 ¢</td>
<td>Landero et al. (2011b)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>jSECM</td>
<td>7.7 % 25 Reduced Reduced ND ND</td>
<td>Landero et al. (2013b)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>wDDGS</td>
<td>6.2 % 17.3 Reduced Reduced –$14.60 –2.07 ¢</td>
<td>Jha et al. (2010)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grower–finisher pig</td>
<td>FFC</td>
<td>Reduced Reduced</td>
<td>Reduced Reduced</td>
<td>Reduced</td>
<td>Reduced</td>
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<tr>
<td>FFC</td>
<td>25 % 15 None None –$5.50 –2.00 ¢</td>
<td>Woyengo et al. (2012b)</td>
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<tr>
<td>nEPCM</td>
<td>25 % 15 Reduced Increased NR Reduced</td>
<td>Seneviratne et al. (2009)</td>
<td></td>
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<tr>
<td>nSECM</td>
<td>33 % 40 Reduced Increased Increased Increased</td>
<td>Seneviratne et al. (2011b)</td>
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<tr>
<td>jSECM</td>
<td>33 % 40 Reduced Increased Increased Increased</td>
<td>Seneviratne et al. (2011b)</td>
<td></td>
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</tr>
<tr>
<td>cDDGS</td>
<td>30 % 30 None None None None</td>
<td>Beltranena et al. (2009e)</td>
<td></td>
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</tbody>
</table>

1. nEPCM = Napus expeller-pressed canola meal; nSECM = Napus solvent-extracted canola meal; jSECM = Juncar solvent-extracted canola meal; wDDGS = wheat dried distillers grains with solubles; FFC = full-fat canola; cDDGS = corn dried distillers grain with solubles.
2. Feedstuff level = dietary level of alternative feedstuff.
3. Reduced = dietary inclusion of the alternative feedstuff reduced ADG or G:F; None = dietary inclusion of the alternative feedstuff did not affect ADG or G:F; Increased = dietary inclusion of the alternative feedstuff increased ADG or G:F.
4. ND = not determined; NR = not reported.
5. Mkt wt = market weight.
Energy and AA are the most costly components of pig diets (de Lange and Birkett, 2005; Patience, 2013) with energy constituting approximately 87% of their total cost (Patience, 2013). Therefore, optimizing diets based on available energy and AA by matching their supply and requirements will reduce feed cost. For pigs, AA availability in feedstuffs is typically expressed as SID (Stein et al., 2007). The DE and ME systems overestimate energy availability in protein- and fiber-rich feedstuffs (Moehn et al., 2005) and the error compounds with increasing dietary inclusion. The NE system is not perfect, but it is presently the best available to manage the energetic risk of dietary inclusion of alternative feedstuffs (Zijlstra and Beltranena, 2013b).

Most alternative feedstuffs are rich in fiber or protein; therefore, formulating diets based on NE and SID AA values may optimize dietary inclusion. Other factors contributed, but increasing dietary inclusion of 

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>Energy content, Mcal NE/kg</th>
<th>Year 2005</th>
<th>Year 2012</th>
</tr>
</thead>
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<tr>
<td>Corn</td>
<td>2.67</td>
<td>65</td>
<td>298</td>
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<td>Soybean meal</td>
<td>2.09</td>
<td>200</td>
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<td>Corn DDGS</td>
<td>2.34</td>
<td>50</td>
<td>309</td>
</tr>
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<td>Wheat middlings</td>
<td>2.12</td>
<td>60</td>
<td>287</td>
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<tr>
<td>Fat:AV blend</td>
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1 Adapted from Patience (2013).
2 DDGS = dried distillers grains with solubles; AV blend = animal–vegetable blend.

**Formulation using Net Energy and Available Amino Acids**

The NE values for feedstuffs in North America (NRC, 2012) were estimated from their DE value and analyzed content of starch, ether extract, CP, and ADF using an equation (Noblet et al., 1994). However, the equation was developed from complete diets; hence, whether or not the NE value of individual feedstuffs is predicted accurately remains unclear (NRC, 2012). Increasing dietary inclusion of alternative feedstuffs will compound the error of under- or overestimating NE value. Moreover, the impact of starch, ether extract, CP, and ADF on actual NE values of feedstuffs may vary depending on their characteristics. For example, efficiency of starch utilization varies depending on its amylose to amylopectin ratio: 1) Amylose has less digestibility than amylopectin in the small intestine but is highly fermentable in the hindgut of pigs and 2) VFA that are metabolites of starch fermentation are used less efficiently as NE sources than glucose that is the end product of starch digestion (Regmi et al., 2011). Therefore, the NE values of feedstuffs that contain fermentable starch (e.g., pulses and specific cultivars of barley) can be overestimated using NE prediction equations. Therefore, we need to determine 1) NE values of alternative feedstuffs, 2) ileal and total tract digestibility values of their energy-yielding macronutrients, and 3) factors that affect digestibility of these macronutrients. Then NE predictions for alternative feedstuffs can become more accurate.

The SID assay does not consider endogenous AA losses that are dependent on diet composition (Stein et al., 2007). Dietary fiber, tannin, and protease inhibitors are ANF that increase these ingredient-specific endogenous AA losses in pigs (Nyachoti et al., 1997; Myrie et al., 2008), thereby increasing maintenance requirement of AA. True ileal digestibility corrects for ingredient-specific endogenous AA losses (Stein et al., 2007). Therefore, formulation of pig diets based on true ileal digestibility AA values can further optimize the use of alternative feedstuffs. Likewise, inclusion of alternative feedstuff in pig diets formulated based on SID AA, the essential AA in ingredient-specific endogenous losses, should be supplemented. Dietary fiber increases endogenous losses of threonine (Myrie et al., 2008); hence, extra threonine should be added when feeding high-fiber alternative feedstuffs to meet Thr requirements (NRC, 2012).

Lysine is the most limiting AA in pig diets. In alternative feedstuffs that are subjected to heat during processing, such as oilseed meals and DDGS, Lys is chemically modified into forms that are absorbed but not used by pigs (Rutherfurd and Moughan, 2012). Chemically modified Lys may be partly converted back into intact Lys during the HCl hydrolysis step of AA analysis, thereby overestimating Lys availability in heat-processed feedstuffs in diets formulated based on SID AA values. In cotton seed meal, true ileal digestible total Lys content exceeded true ileal digestible chemically available Lys content by 25% (Rutherfurd and Moughan, 2012). Therefore, formulation of diets containing heat-processed feedstuffs based on chemically available AA values can further optimize their use. Chemically available Lys can be determined using fluorodinitrobenzene and guanidination assays (Rutherfurd and Moughan, 2012).

**Feedstuff Processing**

**Particle Size Reduction.** Reduction of particle size for feedstuffs increases nutrient digestibility in pigs because surface area of particles for digestive enzyme action is increased (Liu et al., 2013). For instance, reducing particle size of wheat DDGS by grinding from 571...
to 383 μm increased apparent total tract digestibility of GE and SID of Lys for wheat DDGS-based diets fed to grower pigs (Yáñez et al., 2011), similar to particle size reduction of barley and field pea (Oryschak et al., 2002). However, feeding diets based on finely ground barley (785 to 434 μm) from 31 kg BW to slaughter increased stomach ulceration in pigs (Morel and Cottam, 2007). Therefore, proper particle size to optimize use of each alternative feedstuff should be established.

**Dehulling, Scarification, and Air Classification.** Tannins and fiber are concentrated in seed hulls and reduce nutrient utilization. Thus, dehulling of feedstuffs reduces the content of these ANF and may increase their nutrient utilization in pigs. For example, replacing 30% hulled faba bean with dehulled faba bean increased starch digestibility in diets fed to grower pigs from 95 to 98% (Van der Poel et al., 1992). Scarification of cereals using pearling mills reduces hull fiber content and also reduces mold and mycotoxins that adhere to the hulls of grains (House et al., 2003).

Air classification can separate finely ground feedstuffs into fractions that have a higher or lower density and content of nutrients and ANF than their feedstock (Zhou et al., 2013). For SECM, air classification produced a low-fiber, light-particle fraction and a high-fiber, heavy-particle fraction with equal glucosinolate content (Zhou et al., 2013). Performance of weaned pigs fed the light-particle fraction was 3% greater than those fed SECM. Dry fractions such as air classification, sieving, or gravity separation or their combinations require research to determine opportunities for tail-end processing to optimize alternative feedstuff use in pig diets.

**Increasing Bulk Density.** Cereal coproducts, such as wheat millrun, are bulky due to their high fiber content. Consequently, the cost of transporting and storing these fibrous coproducts is greater than for low-fiber feedstuffs. Feed processing, such as air classification to separate high-fiber from low-fiber particles or pelleting, may increase bulk density of fibrous feedstuffs, thereby reducing their handling cost. Pelleting and regrinding increased bulk density of corn DDGS from 456 to 482 kg/m³ (Fahrenholz et al., 2013). Notably, increasing bulk density of alternative feedstuffs using processing will increase their cost. Therefore, effects of increasing bulk density of fibrous alternative feedstuffs on cost of producing pork need to be determined.

**Heat Treatment.** Some ANF such as trypsin inhibitors that are present in alternative feedstuffs for pigs are heat labile. Therefore, heat treatments can reduce these ANF (Jezierny et al., 2010). For example, FFSB can be extruded, toasted, roasted, and micronized. Specifically, extrusion of faba bean at 156°C reduced trypsin inhibitor activity from 4.47 to 0.05 IU/mg (Alonso et al., 2000), and extrusion of field pea at 135°C fed to weaned pigs increased SID of CP and AA (Owusu-Asiedu et al., 2002). Excessive drying of corn DDGS reduces Lys availability but also increases P digestibility by releasing phytate-tied P (Widyaratne and Zijlstra, 2007; Stein and Shurson, 2009). Similarly, desolventizing SECM at >100°C reduces Lys availability but also reduces glucosinolate content (Newkirk et al., 2003). Therefore, targeted heat treatment for alternative feedstuffs to increase their nutritive value can optimize their use in pig diets.

**Use of Feed Enzymes**

Plant-based alternative feedstuffs have a high proportion of P in phytate that is poorly digested by pigs (Woyengo and Nyachoti, 2011). Phytate reduces utilization of other dietary nutrients by binding to them or digestive enzymes (Woyengo and Nyachoti, 2013). Plant-based alternative feedstuffs also contain fiber, which limits nutrient use in pigs (Woyengo and Nyachoti, 2011). Therefore, adding supplemental phytase and fiber-degrading enzymes (carbohydrases) to diets can increase the nutritive value of alternative feedstuffs (Zijlstra et al., 2010). Phytase increases availability of P, which is the third most costly nutrient in pig diets, while supplementation of carbohydrases may increase energy digestibility but also AA availability. Supplementation of phytase or carbohydrases to pig diets containing alternative feedstuffs indeed increased nutrient digestibility in pigs (Nortey et al., 2007; Woyengo et al., 2008). But enzymes do not consistently increase nutrient digestibility of DDGS. For instance, carbohydrase supplementation of pig diets based on wheat and corn DDGS did not increase nutrient digestibility (Yáñez et al., 2011). Therefore, efficacy of enzymes to increase nutrient use and reduce feed cost of diets containing DDGS or other alternative feedstuffs requires unraveling.

**Enzyme Predigestion.** Use of supplemental enzymes for high-fiber feedstuffs might be limited by digesta passage. Indeed, supplemental carbohydrases increased degradation DDGS in vitro (Jha et al., 2012) but not in pigs (Yáñez et al., 2011). Steeping feed or predigestion of fibrous diets with exogenous enzymes before feeding to pigs (Columbus et al., 2010) may increase nutrient availability of feedstuffs and thereby optimize their use in pig diets.

**Summary and Conclusions**

Barley, triticale, and low-tannin sorghum can replace corn or wheat in diets without reducing growth performance of pigs and can reduce feed cost. Pulses and full-fat oilseeds can partly or fully replace traditional sources of energy and protein without reducing performance. Some pulses and oilseeds are sold at a dis-
counted price; therefore, their use can reduce feed cost. Napus canola meal and DDGS can be included in pig diets to replace SBM leading to reduced feed cost. However, inclusion of Juncea canola meal can reduce growth performance; hence, its use in diets should be based on targeted growth performance.

Feed processing of alternative ingredients and supplemental enzymes added to pig diets containing alternative feedstuffs may increase nutrient utilization, but their effects on feed cost should be determined. Lastly, we need to determine 1) true ileal digestible AA content of alternative feedstuffs, 2) effects of formulating pig diets containing alternative feedstuffs based on NE and true ileal digestible AA values, 3) effects of various ANF on dietary AA requirements by pigs, and 4) factors (other than CP, starch, ether extract, and ADF) that affect NE values of alternative feedstuffs for pigs to create more accurate predictions of ingredient NE values.

LITERATURE CITED


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