Introduction

Recently, several reviews articles and book chapters have been published about the feeding of co-product feedstuffs to swine, including co-products from the biofuel industries. These compilations included a review of distillers dried grains with solubles (DDGS), mostly from corn (Stein and Shurson, 2009) and an expanded review to include also North American co-products from the biodiesel industry (Shurson et al., 2012). These reviews state that co-products from the biofuel industry vary widely in nutritional composition (Zijlstra and Beltranena, 2009). Nonetheless, co-products from the biofuel industry provide additional feedstuffs that may further enhance flexibility of swine feed formulation. Their risks for inclusion in swine feeds are similar to other alternative feedstuffs tested (Zijlstra and Beltranena, 2013).

In this position paper, we do not rehash these previous writings entirely and not discuss the wisdom (or lack thereof) of converting grains and oilseeds into biofuels and their co-products. Rather, we discuss the new reality of increased availability of co-products within the context of unprecedented high feed grain prices and the use of swine to convert these and other co-products from food and biofuel industries into pork. Feed cost currently exceeds 72% of the overall cost of swine production. Finally, we place the use of co-products in the global context of improving the human-edible protein balance, which is edible protein output produced per unit of edible protein input required (FAO, 2011), as well as the impact on carbon or environmental footprint.

Co-products

Many technologies exist to fractionate crop seeds into their components for human food, bio-product, or feed application (Zijlstra et al., 2004; Zijlstra and Beltranena, 2007). Traditionally, crop seeds were subjected to 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 air classification. The produced co-products could be used directly as feedstuffs. Subsequently, wet fractionation processes were developed using water, acids, bases, salts, or organic solvents to achieve greater separation of valuable components using chemical characteristics (Vasanthan and Temelli, 2008). Advantages of wet fractionation include greater purity of high-value fractions; however, drying of the main product and co-products is required for long-distance transportation, long-term storage, and dry feed application. Although extended drying using heat may inactivate anti-nutritional factors and increase mineral availability, intensive drying may also damage the protein contained in co-products and thereby hamper nutritional quality, and is thus a concern for dried co-products (Fontaine et al., 2007).

Co-products have become increasingly attractive for use in swine diets as alternative feedstuffs to reduce feed costs and thereby enhance economic sustainability of the swine industry (Jha et al., 2010). Liquid feeding systems allow the incorporation of wet co-products into swine diets, and thereby entirely avoid drying and associated energy-costs. Thus, liquid feeding can be regarded as even more environmental and economically sustainable, especially if the swine farm is nearby a processing plant. Otherwise, transportation becomes an issue. Liquid feeding systems also improve the response to exogenous feed enzymes by solubilizing their substrates.

Implications

• As omnivores, pigs are ideally suited to convert non human-edible feedstuffs into high quality food animal protein. Dietary inclusion of co-products from food and bio-fuel production will considerably improve the human-edible protein balance (edible protein output/input) of swine production.
• Compared with traditional diets based on a single grain as an energy source and soybean meal as a protein source, feeding high inclusion levels of co-products has a greater risk. This risk can be managed using modern feed formulation, feed evaluation, feed enzymes, and feed processing to attain predictable swine growth performance, carcass characteristics, and pork quality.
• Dietary inclusion of co-products reduces feed cost per unit of pork produced and is part of an effort to create sustainable swine production systems. Fast adoption of feeding co-products is driven by unprecedented high corn and soybean meal prices.

Keywords: co-product, feed evaluation, pig, risk management, sustainability
Biofuel industry

Fossil fuels are a main source of energy for anthropogenic activity. Considerable incentives exist for a variety of reasons to replace fossil fuels with biofuel 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, 2009). The use of cereal grains in livestock diets and biofuel production has received considerable attention around global food supply (Blaxter, 1983; Dale, 2008). The biofuel industry directly competes with the livestock and food industry for grain supply, thereby increasing local grain prices. In turn, the biofuel and food industry also produce co-products that are available for incorporation into livestock diets. If a decision to produce bio-fuels has been made, markets for the co-products are needed. Thus, inclusion of the bio-fuel co-products in swine feeds might be cost-attractive to swine producers (Lammers et al., 2010).

Food industry

Behind every food product in the supermarket, there is a co-product. These co-products cover a wide range (e.g., beet pulp, citrus pulp, whey, bakery waste, co-products from flour milling, meat and bone meal). The livestock industry is an ideal platform to convert these low-value co-products into high quality animal protein (Zijlstra and Beltranena, 2013) and thereby reduce the overall cost of food production.

Change, Tradition, and Challenges

The use of co-products in the swine industry is not new. Traditionally, pigs in small-scale agriculture were fed feedstuffs that currently are regarded as alternative, such as leftover human food products (Pond and Lei, 2001). However, demands for high growth rates such as those achievable with current pig genotypes were also less important historically. Small-scale production practices are still common and produce large numbers of pigs in Asia.

In contrast, for decades, the large-scale North American swine industry heavily relied on the abundance of feed grains to produce pigs competitively for slaughter. The geographical association between the Corn Belt and hog production was thus strong in the Midwestern states of the U.S. In western Canada, subsidies for transporting grain from the Prairies to central Canada and the coasts disappeared in 1995, creating an abundance of cost-competitive feed grains for a decade. Combined with a favorable dollar exchange rate and other factors, an economic situation similar to the Midwestern U.S. developed in Western Canada that stimulated expansion of the swine industry. A shift toward less reliance on feed grains and increased inclusion of co-products was predicted (Zijlstra et al., 2004; FAO, 2012) to be essential for sustainable swine production systems into the future. The main reason for our predictions was the increased use of feed grains for non-food and non-feed uses, especially bioethanol. However, the speed of change in increased feed grain prices surprised us, because predicted changes in world grain market were fortified by changes in demands of grains for food purposes and occasional declines in grain production due to climate reasons, such as the drought in the U.S. in 2012.

In North America, the switch from diets with increased inclusion levels of grain to diets containing high concentrations of co-products has been recent (last two to three years). In part, risks for the inclusion of co-products in swine diets and general concurring loss of feed efficiency were accepted, because the pork industry had to survive economically, and other economic drivers such as feed costs per unit of gain became more important. Until recently, feeding strategies employed in North America differed drastically from feeding pigs elsewhere globally, but challenges were identified and solutions were adopted rapidly to achieve greater inclusion levels of co-products in swine diets.

Challenges and Paths to Solutions

Dietary inclusion of co-products poses risks and these must be managed properly to protect the value chain. For feed, these risks can be
Canola meal is one of the co-products that are used globally (photo credit: Canola Council of Canada).

overcome initial North American reluctance to adopt the NE system, and has partially adopted the French NE system (NRC, 2012).

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 (e.g., corn DDGS and wheat DDGS) was tested by feeding grower-finisher pig 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., 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 less dietary NE content because the DE and ME systems ignore energy losses due to heat increment. Subsequently, the test feedstuff was blamed in studies that observed a reduced growth performance, rather than the feed quality evaluation system used.

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 dietary inclusion of co-products. However, European validation studies with co-products in swine diets formulated to an equal NE content are either rarely conducted or published in scientific literature. As a rare example, incremental increasing levels of dietary content of canola meal up to 18% in diets formulated for grower-finisher pigs to equal NE and digestible amino acids did not change growth performance in a French study (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 being observed following the introduction of single co-product, such as expeller-pressed canola meal. Feed intake would then be the major factor impacting growth (Seneviratne et al., 2010). Feed quality evaluation for energy and amino acids is most important for the successful introduction of new co-products. Indeed, data on feed ingredient composition, especially their available nutrient and energy content, was identified as a research need by NRC (2012).

Variation in quality

Without question, co-products have a more variable nutrient profile than their feedstock. Crops vary in quality due to genetic variation and agronomic, weather, harvest, and storage conditions. For co-products, processing is an extra source of variation (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 amino acid lysine due to drying using heat (Zijlstra and Beltranena, 2009). The risk of protein damage by overheating, extended heating, or both is well understood and a wide range of lysine damage has been confirmed for DDGS (Fontaine et al., 2007). Apart from heat damage, oil extraction of oilseeds using a range of processing techniques (solvent-extraction, expeller-press, and cold press) causes a range of residual oil content and therefore variability in energy value of the resulting meal or cake (Spragg and Mailer, 2007). The variation can be predicted using chemical analyses (Zijlstra et al., 2001); however, long-term, near infrared spectroscopy calibrations must be developed so that the feed industry can mitigate this variability rapidly and effectively (Zijlstra et al., 2010b). The variation in quality can then be considered during feed formulation resulting in

Feed evaluation systems

Some European countries such as the Netherlands are heavily dependent on the use of co-products (EFAC, 2005). These co-products not only enlarge the raw material matrix, but also introduce a wider range in the macronutrient profile, especially fiber or non-starch polysaccharides (NSP) and protein. Indisputably, the choice of energy evaluation systems will alter the relative values placed on feeds (Noblet et al., 1993). For energy evaluation, the digestible energy (DE) and metabolizable energy (ME) systems overestimate the energy contribution of co-products high in fiber or protein to support maintenance and growth, while the net energy (NE) system offers a more accurate ranking of feedstuffs. Values have been reported widely for an array of feedstuffs in tables (Sauvant et al., 2004; CVB, 2007). The feed industry in the Netherlands has been reliant on the NE system since 1970 (CVB, 1993), partly to manage the risk of a wide ingredient matrix due to a greater array of available co-products (Zijlstra and Payne, 2007). The recent NRC committee has also

Variation in quality

Without question, co-products have a more variable nutrient profile than their feedstock. Crops vary in quality due to genetic variation and agronomic, weather, harvest, and storage conditions. For co-products, processing is an extra source of variation (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 amino acid lysine due to drying using heat (Zijlstra and Beltranena, 2009). The risk of protein damage by overheating, extended heating, or both is well understood and a wide range of lysine damage has been confirmed for DDGS (Fontaine et al., 2007). Apart from heat damage, oil extraction of oilseeds using a range of processing techniques (solvent-extraction, expeller-press, and cold press) causes a range of residual oil content and therefore variability in energy value of the resulting meal or cake (Spragg and Mailer, 2007). The variation can be predicted using chemical analyses (Zijlstra et al., 2001); however, long-term, near infrared spectroscopy calibrations must be developed so that the feed industry can mitigate this variability rapidly and effectively (Zijlstra et al., 2010b). The variation in quality can then be considered during feed formulation resulting in

Feed evaluation systems

Some European countries such as the Netherlands are heavily dependent on the use of co-products (EFAC, 2005). These co-products not only enlarge the raw material matrix, but also introduce a wider range in the macronutrient profile, especially fiber or non-starch polysaccharides (NSP) and protein. Indisputably, the choice of energy evaluation systems will alter the relative values placed on feeds (Noblet et al., 1993). For energy evaluation, the digestible energy (DE) and metabolizable energy (ME) systems overestimate the energy contribution of co-products high in fiber or protein to support maintenance and growth, while the net energy (NE) system offers a more accurate ranking of feedstuffs. Values have been reported widely for an array of feedstuffs in tables (Sauvant et al., 2004; CVB, 2007). The feed industry in the Netherlands has been reliant on the NE system since 1970 (CVB, 1993), partly to manage the risk of a wide ingredient matrix due to a greater array of available co-products (Zijlstra and Payne, 2007). The recent NRC committee has also

without question, co-products have a more variable nutrient profile than their feedstock. Crops vary in quality due to genetic variation and agronomic, weather, harvest, and storage conditions. For co-products, processing is an extra source of variation (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 amino acid lysine due to drying using heat (Zijlstra and Beltranena, 2009). The risk of protein damage by overheating, extended heating, or both is well understood and a wide range of lysine damage has been confirmed for DDGS (Fontaine et al., 2007). Apart from heat damage, oil extraction of oilseeds using a range of processing techniques (solvent-extraction, expeller-press, and cold press) causes a range of residual oil content and therefore variability in energy value of the resulting meal or cake (Spragg and Mailer, 2007). The variation can be predicted using chemical analyses (Zijlstra et al., 2001); however, long-term, near infrared spectroscopy calibrations must be developed so that the feed industry can mitigate this variability rapidly and effectively (Zijlstra et al., 2010b). The variation in quality can then be considered during feed formulation resulting in

Feed evaluation systems

Some European countries such as the Netherlands are heavily dependent on the use of co-products (EFAC, 2005). These co-products not only enlarge the raw material matrix, but also introduce a wider range in the macronutrient profile, especially fiber or non-starch polysaccharides (NSP) and protein. Indisputably, the choice of energy evaluation systems will alter the relative values placed on feeds (Noblet et al., 1993). For energy evaluation, the digestible energy (DE) and metabolizable energy (ME) systems overestimate the energy contribution of co-products high in fiber or protein to support maintenance and growth, while the net energy (NE) system offers a more accurate ranking of feedstuffs. Values have been reported widely for an array of feedstuffs in tables (Sauvant et al., 2004; CVB, 2007). The feed industry in the Netherlands has been reliant on the NE system since 1970 (CVB, 1993), partly to manage the risk of a wide ingredient matrix due to a greater array of available co-products (Zijlstra and Payne, 2007). The recent NRC committee has also
diets with equal planned nutrient density, resulting in a predictable growth performance.

**Feed processing**

Co-products tend to be high in NSP, although exceptions exist, and the negative impact of fiber or NSP on energy utilization has long been recognized. Supplemental enzymes may increase energy digestibility, as long as the supplemental enzyme matches with a substrate that limits nutrient utilization (Zijlstra et al., 2010a). Thus, not surprisingly, diets containing wheat co-products from flour milling have a drastically increased NSP and arabinoxylan content, and supplemental xylanase increased energy digestibility in swine (Nortey et al., 2008). Interestingly, the relationship between co-products from ethanol production such as corn or wheat DDGS and supplemental xylanase is less clear. The DDGS has been subjected to extensive periods in solution followed by drying, and supplemental xylanase does not always seem to improve energy digestibility of DDGS (Yáñez et al., 2011), even though phytase does increase phosphorus digestibility. On the other hand, fine grinding increases nutrient digestibility of DDGS indicating that increased digestibility can be achieved (Yáñez et al., 2011). Regardless, further technologies such as extrusion (Oryschak et al., 2010) should be explored to enhance nutrient digestibility of co-products.

**Mycotoxins**

In crops, mycotoxins may occur naturally and, therefore, also in their co-products. Some mycotoxins are resistant to processes such as fermentation and drying and are 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 with 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 in pigs (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 cereals and oilseed 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., 2009). Similarly, inclusion of off-grade canola with variable toxin loads in expelled canola press cake may affect growth performance beyond what is expected pressing uncontaminated canola seed.

**Residues**

A final risk associated with co-products is residues, especially for batches of unknown or less reputable sources. A worst-case scenario was the introduction of polychlorinated biphenyls (PCB)/dioxin via contaminated feedstuff into the feed (Covaci et al., 2008). Residues such as PCB can accumulate in pork (Hoogenboom et al., 2004), and thereby pose a significant risk for the consumer. 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 in pigs (Kerr et al., 2007). Such challenges 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.

**Carcass and pork quality**

Some co-products from cereal grains such as DDGS and oilseeds such as expeller-pressed canola meal contain 10 to 20% residual oil and larger quantities of fiber than the parent feedstock. Thus, for example, feeding increasing dietary inclusions of DDGS will increase dietary fiber and polyunsaturated fatty acid (PUFA) content that consequently will decrease dressing percentage and reduce fat hardness, respectively (Xu et al., 2009a). Dietary fiber increases gut weight (Jørgensen et al., 1996) and dietary PUFA are directly deposited into carcass fat depots. Therefore, co-products from flaxseed that are rich in omega-3 PUFA may also increase value-attributes of pork for the consumer (Eastwood et al., 2009; Jha et al., 2010). To reduce the negative impact of feeding DDGS on dressing percentage, a three-week withdrawal of DDGS before slaughter can be implemented (Xu et al., 2009b; Beltranena and Zijlstra, 2010). For corn DDGS, some ethanol plants have started removing part of the residual oil resulting in DDGS with one-half of the original fat content. Nonetheless, the length and effectiveness of co-product feeding and withdrawal periods to manage effects of PUFA on pork fat hardness and PUFA profile require further evaluation.

Preference tests are one of the methods to evaluate co-products. Here pigs are choosing between two feeds that each contain a specific co-product (photo credit: Jose Landero).
Societal pressure

Occasionally, animal production systems are criticized for their use of human-edible food as feedstuffs (Nonhebel, 2004), their use of non-edible food residues, and their carbon footprint. The human-edible protein balance index was 1.02 for 2005 to 2007 for some countries that rely heavily on the feeding of co-products to livestock (the Netherlands) whereas it is 0.53 for countries that rely heavily on the feeding of feed grains (U.S.), indicating that increased feeding of co-products may improve this index and therefore sustainability from a societal perspective (FAO, 2011). Indeed, while non-edible food residues contain nutrients (Westendorf et al., 1998), they may also contain viruses (Xiao et al., 2012) and bacteria, and their use in swine feeding should thus be tightly controlled or avoided to ensure food safety (Myer and Brendemuhl, 2001). With the feeding of co-products, increased fiber enters the gastrointestinal tract and is partially fermented into methane. Furthermore, the production of co-products also produces carbon emissions, and if these carbon emissions are partly attributed to the co-product instead of all to the main product, increased co-product utilization of dried co-products may increase carbon emissions by pigs (Meul et al., 2012). Finally, feeding increasing dietary inclusion of co-products will generally increase nutrient excretion because their nutrient digestibility is less than for cereal grains (Jarret et al., 2011). However, high fiber fermentability may reduce ammonia emissions (Jarret et al., 2011), and partial phytate degradation during processing may actually increase phosphorus digestibility of DDGS (Widyaratne and Zijlstra, 2007). Nonetheless, the conversion of non-edible residues from the food, bio-fuel, and bio-processing industries into high quality animal protein food mitigates the impact of these industries on the environment. We feel that the swine industry should receive credit for these efforts. Combined, these challenges indicate that co-products feeding should be used with care. However, solutions exist to handle these challenges, resulting in production systems that are more sustainable both economically and environmentally.

Conclusion

For the long-term sustainability of swine production, economics, societal acceptance, and the environment are key components. Dietary inclusion of co-products and less reliance on cereal grains are important. As an omnivorous species, the pig is suited to efficiently convert co-products to pork products, but feeding co-products also provide challenges and opportunities. First, co-products add variability in macronutrient profile in the feedstuff matrix beyond the variability intrinsic to the crops. Therefore, feed quality evaluation for energy, amino acids, and phosphorus content and their availability or digestibility is crucial, 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 greater fiber content of co-products reduces dressing percentage. The increased residual oil content of some co-products provides unsaturated fatty acids that soften pork fat. In conclusion, feeding alternative feedstuffs may reduce feed costs per unit of pork produced, but also provides challenges to achieve cost-effective, predictable growth performance, animal health, environmental footprint, carcass characteristics, and pork quality.


Nonhebel, S. 2004. On resource use in food production systems: The value of live-
xylanase supplementation on digestibility and digestible content of energy,
amino acids, phosphorus, and calcium in wheat by-products from dry milling in
ington, DC.
Oryschak, M., D. Korver, M. Zuidhof, X. Meng, and E. Beltranena. 2010. Compar-
ative feeding value of extruded and nonextruded wheat and corn distillers
Oryschak, M., D. Korver, M. Zuidhof, X. Meng, and E. Beltranena. 2010. Compara-
Nonhebel, S. 2004. On resource use in food production systems: The value of live-
xylanase supplementation on digestibility and digestible content of energy,
amino acids, phosphorus, and calcium in wheat by-products from dry milling in
ington, DC.
Oryschak, M., D. Korver, M. Zuidhof, X. Meng, and E. Beltranena. 2010. Compar-
ative feeding value of extruded and nonextruded wheat and corn distillers
Oryschak, M., D. Korver, M. Zuidhof, X. Meng, and E. Beltranena. 2010. Compara-
Nonhebel, S. 2004. On resource use in food production systems: The value of live-
xylanase supplementation on digestibility and digestible content of energy,
amino acids, phosphorus, and calcium in wheat by-products from dry milling in
ington, DC.
Oryschak, M., D. Korver, M. Zuidhof, X. Meng, and E. Beltranena. 2010. Compar-
ative feeding value of extruded and nonextruded wheat and corn distillers
Oryschak, M., D. Korver, M. Zuidhof, X. Meng, and E. Beltranena. 2010. Compara-
Nonhebel, S. 2004. On resource use in food production systems: The value of live-
xylanase supplementation on digestibility and digestible content of energy,
amino acids, phosphorus, and calcium in wheat by-products from dry milling in
ington, DC.
Oryschak, M., D. Korver, M. Zuidhof, X. Meng, and E. Beltranena. 2010. Compar-
ative feeding value of extruded and nonextruded wheat and corn distillers
Oryschak, M., D. Korver, M. Zuidhof, X. Meng, and E. Beltranena. 2010. Compara-
Nonhebel, S. 2004. On resource use in food production systems: The value of live-