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Chapter 10

Feeding biofuels co-products to pigs

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ABSTRACT

Dried distillers grains with solubles (DDGS) and other co-products from the fuel ethanol industry may be included in diets fed to pigs in all phases of production. The concentration of digestible energy (DE) and metabolizable energy (ME) in DDGS and maize germ is similar to maize, but high-protein dried distillers grain (HPDDG) contains more energy than maize. In contrast, if the oil is removed from DDGS, the co-product will have a lower energy concentration than maize or conventional DDGS. Glycerin is a co-product from the biodiesel industry and also contains more energy than maize. Phosphorus in DDGS and HPDDG is highly digestible to pigs, and apparent total tract digestibility (ATTD) values of approximately 60 percent have been reported for these ingredients. In contrast, the digestibility of phosphorus in maize germ is much lower and similar to maize. The concentration of starch in DDGS is low (between 3 and 11 percent on an as-fed basis), but the concentration of fat in DDGS is approximately 10 percent and the concentration of acid-detergent fibre (ADF), neutral-detergent fibre (NDF), and total dietary fibre in DDGS is approximately three times greater than in maize (9.9, 25.3 and 42.1 percent, respectively). The ATTD of dietary fibre is less than 50 percent, which results in low digestibility values for dry matter (DM) and energy in DDGS. The concentration of most amino acids in DDGS is approximately three times greater than in maize, but the standardized ileal digestibility (SID) of most amino acids average approximately 10 percentage units less than in maize. The same is the case for maize germ and HPDDG. Nursery pigs, beginning at two to three weeks post-weaning, and growing-finishing pigs may be fed diets containing up to 30 percent DDGS without any negative impact on pig growth performance, if they are formulated on a SID amino acid basis using crystalline amino acids to ensure that all digestible amino acid requirements are met.

However, carcass fat in pigs fed DDGS-containing diets has a higher iodine value (unsaturated to saturated fatty acid ratio) than in pigs fed no DDGS. As a result, it may be necessary to withdraw DDGS from the diet of finishing pigs during the final three to four weeks prior to harvest to achieve desired pork fat quality. High-protein DDGS may be used in diets fed to growing-finishing pigs in quantities sufficient to replace all of the soybean meal, and at least 10 percent of maize germ. Up to 30 percent de-oiled DDGS can be included in diets fed to weanling pigs, but results from one experiment indicate that adding de-oiled DDGS at any level to growing-finishing pig diets results in reduced growth rate and feed conversion. Due to limited research on this co-product, it is unclear if this is a valid and repeatable finding. Crude glycerin can be included in diets fed to weanling and growing-finishing pigs in quantities of up to 6 and 15 percent, respectively, and lactating sows fed diets containing up to 9 percent crude glycerol perform similarly to sows fed a standard maize-soybean meal diet. Lactating sows can be fed diets containing up to 30 percent DDGS, and DDGS can replace all of the soybean meal in diets fed to gestating sows without negatively impacting sow or litter performance. Inclusion of DDGS in diets fed to pigs may improve intestinal health and the immune system activation, but more research is needed to elucidate the mechanism responsible for these effects. Manure volume will increase if DDGS is included in the diet because of the reduced dry matter digestibility. Nitrogen excretion may also increase, but this can be prevented by the use of crystalline amino acids in diets containing DDGS. In contrast, P excretion can be reduced in diets containing DDGS if the total dietary concentration of P is reduced to compensate for the greater digestibility of P in DDGS.

INTRODUCTION

Distillers co-products have been used in swine diets for more than 50 years, but the rapid growth of the United States fuel ethanol industry in the past decade has dramatically increased the total quantities of distillers co-products available to the livestock and poultry industries. Distillers

MAIN MESSAGES

- **Maize DDGS is the predominant ethanol industry co-product available for use in swine diets, and can be added at levels up to 30% of diets in all phases of production, and up to 50% in gestating sow diets, to achieve acceptable performance.**
- **Maize DDGS is primarily an energy source but also contributes significant amounts of digestible amino acids and available phosphorus to swine diets.**
- **Limited quantities and information is available on the nutritional value, optimal dietary inclusion rates and benefits and limitations of feeding other maize co-products from the ethanol industry.**
- **Glycerin is a co-product of the biodiesel industry, has an energy value greater than maize for swine and can be added at levels of up to 6% for weanling pigs, 9% for lactating sows and 15% for growing-finishing pigs to achieve acceptable performance.**
- **Significant opportunities exist to use particle size reduction, hydrothermal processing and enzymes to enhance energy and nutrient digestibility of distillers co-products, but the application and potential benefits of these technologies are not well understood.**
- **Special consideration should be given to the methanol content of crude glycerin, as well as to the possible presence of mycotoxins in DDGS when using them in swine diets.**
- **Feeding diets containing increasing levels of DDGS to growing-finishing pigs reduces pork fat firmness, but reducing feeding levels, withdrawing it from the diet for a period of time before harvest and adding conjugated linoleic acid to the diet 3 to 4 weeks before harvest can minimize the negative effects of DDGS diets on pork fat quality.**

grain production increased from 2.7 million tonne in 2000 to 32.5 million tonne in 2010. In 2011, there were over 200 ethanol plants in the United States producing distillers co-products. The two main types of ethanol production processes are dry-grind ethanol plants (Figure 1) and wet mills (Figure 2). Both process maize and mix it with yeast to convert starch into ethanol and carbon dioxide. After distillation of ethanol, the residual co-products are centrifuged to remove water, and are often dried to produce co-products for the feed industry. The type of milling and further processing determines the nutritional value and composition of distillers co-products. Wet mills use maize to produce ethanol, maize gluten feed, maize gluten meal, steep water, maize germ meal, and crude maize oil. The majority of ethanol produced today is from dry-grind ethanol plants, and the maize co-products they produce include wet distillers grain, condensed distillers solubles (CDS), modified wet distillers grain, dried distillers grain (DDG), and dried distillers grain with solubles (DDGS). For swine diets, DDGS is the predominant form used.

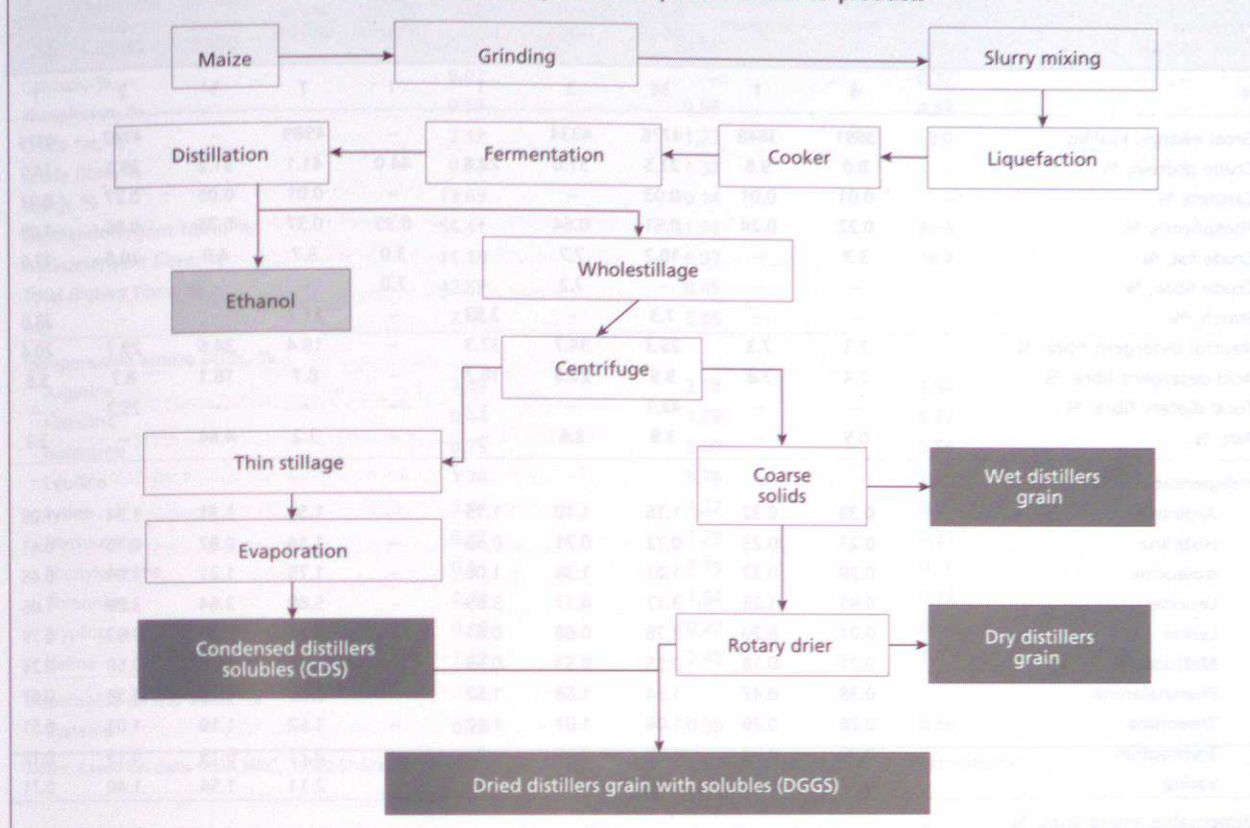
New ethanol and co-product production technologies are being implemented and include "back-end" oil extraction, and, to a much lesser extent, "front-end" fractionation, which are creating an increasing number of nutritionally diverse maize co-products, including high-protein DDGS (from fractionation), de-oiled or de-fatted DDGS (from oil extraction), maize germ meal, maize bran, and crude maize oil. Furthermore, maize, wheat, barley, grain sorghum, or mixtures of these cereal grains, may be used in the production of ethanol, and the co-products produced from each grain source are distinctly different in nutrient composition and value.

The United States biodiesel industry grew from production of 424 million litres of biodiesel in 2005, to 2.616 billion litres in 2008, before declining to 1.192 billion litres produced by 140 biodiesel plants in 2010 (NBB, 2011). The recent decline in United States biodiesel production has been mainly due to excess production capacity, product surpluses, and poor profitability. The principal co-product of biodiesel production is crude glycerin[1] (Ma and Hanna, 1999; van Gerpen, 2005), with 0.3 kg of crude glycerin generated for every gallon of biodiesel produced. Glycerin has thousands of uses, with new uses being continually developed as new technologies are adopted. When United States biodiesel production increased from 2005 to 2008, crude glycerin supplies exceeded demand for industrial uses and more of it became available, at an economical price, for use in animal feeds. Although the quantity of crude glycerin is significantly less than the amount of distillers co-products currently being produced, it does have applications in swine diets as an energy source when adequate supplies are available and economics are favourable for its use.

In order for the swine industry to capture maximum value and dietary use of biofuels co-products, the nutritional value (energy, nutrient content and digestibility), maximum dietary inclusion rates and any limitations affecting their use must be determined for each co-product in each pig production phase.

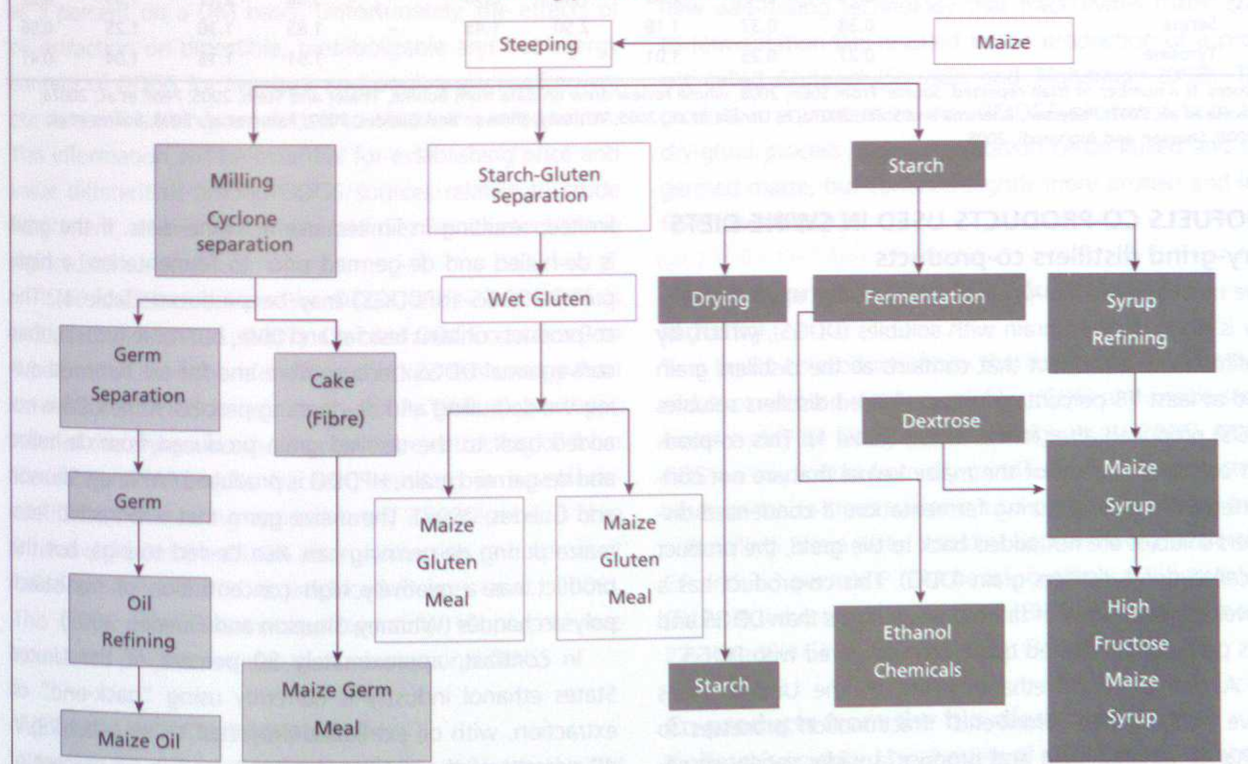
[1] Use of the word "glycerin" refers to the chemical compound or feedstuff while "glycerol" refers to glycerin on a biochemical basis relative to its function in living organisms. In addition, because glycerin is marketed on a liquid basis, all data are presented on an "as is" basis.

FIGURE 1
Dry-grind ethanol production processes and co-products



Source: Erickson et al., 2005

FIGURE 2
Wet-milling processes and co-products



Source: Erickson et al., 2005

TABLE 1
Chemical composition of maize, sorghum and distillers co-products produced from maize and sorghum (as-fed basis)

Parameter	Maize	Sorghum	Maize DDGS	Sorghum DDGS	Maize DDG	Maize HPDDGS	Maize HPDDG	De-oiled maize DDGS	Enhanced maize DDGS	Maize germ
N	4	1	34	3	1	1	1	1	2	1
Gross energy, kcal/kg	3891	3848	4776	4334	–	–	4989	–	4742	4919
Crude protein, %	8.0	9.8	27.5	31.0	28.8	44.0	41.1	31.2	29.1	14.0
Calcium, %	0.01	0.01	0.03	–	–	–	0.01	0.05	0.27	0.03
Phosphorus, %	0.22	0.24	0.61	0.64	–	0.35	0.37	0.76	0.86	1.09
Crude fat, %	3.3	–	10.2	7.7	–	3.0	3.7	4.0	10.8	17.6
Crude fibre, %	–	–	–	7.2	–	7.0	–	–	–	-
Starch, %	–	–	7.3	–	3.83	–	11.2	–	–	23.6
Neutral-detergent fibre, %	7.3	7.3	25.3	34.7	37.3	–	16.4	34.6	29.7	20.4
Acid-detergent fibre, %	2.4	3.8	9.9	25.3	18.2	–	8.7	16.1	8.7	5.6
Total dietary fibre, %	–	–	42.1	–	–	–	–	–	25.2	-
Ash, %	0.9	–	3.8	3.6	–	–	3.2	4.64	–	3.3
Indispensable amino acids, %										
Arginine	0.39	0.32	1.16	1.10	1.15	–	1.54	1.31	1.34	1.08
Histidine	0.23	0.23	0.72	0.71	0.68	–	1.14	0.82	0.75	0.41
Isoleucine	0.28	0.37	1.01	1.36	1.08	–	1.75	1.21	1.04	0.45
Leucine	0.95	1.25	3.17	4.17	3.69	–	5.89	3.64	3.26	1.06
Lysine	0.24	0.20	0.78	0.68	0.81	1.03	1.23	0.87	0.93	0.79
Methionine	0.21	0.18	0.55	0.53	0.56	–	0.83	0.58	0.58	0.25
Phenylalanine	0.38	0.47	1.34	1.68	1.52	–	2.29	1.69	1.38	0.57
Threonine	0.26	0.29	1.06	1.07	1.10	–	1.52	1.10	1.03	0.51
Tryptophan	0.09	0.07	0.21	0.35	0.22	–	0.21	0.19	0.19	0.12
Valine	0.38	0.48	1.35	1.65	1.39	–	2.11	1.54	1.40	0.71
Dispensable amino acids, %										
Alanine	0.58	0.86	1.94	2.90	2.16	–	3.17	2.13	1.99	0.91
Aspartic acid	0.55	0.60	1.83	2.17	1.86	–	2.54	1.84	1.80	1.05
Cysteine	0.16	0.18	0.53	0.49	0.54	–	0.78	0.54	0.52	0.29
Glutamic acid	1.48	1.92	4.37	6.31	5.06	–	7.11	4.26	4.06	1.83
Glycine	0.31	0.29	1.02	1.03	1.00	–	1.38	1.18	1.11	0.76
Proline	0.70	0.77	2.09	1.40	2.50	–	3.68	2.11	1.99	0.92
Serine	0.38	0.37	1.18	2.50	1.45	–	1.85	1.30	1.25	0.56
Tyrosine	0.27	0.25	1.01	–	–	–	1.91	1.13	1.04	0.41

Notes: N = number of trials reported. *Source*: From Stein, 2008, whose review drew on data from Bohlke, Thaler and Stein, 2005; Feoli *et al.*, 2007a; Jacela *et al.*, 2007; Pedersen, Boersma and Stein, 2007a, b; Urriola *et al.*, 2009; Whitney, Shurson and Guedes, 2007; Pahm *et al.*, 2008; Soares *et al.*, 2008; Shurson and Alghamdi, 2008.

BIOFUELS CO-PRODUCTS USED IN SWINE DIETS

Dry-grind distillers co-products

The most common co-product from the fuel ethanol industry is dried distillers grain with solubles (DDGS), which, by definition, is a product that contains all the distillers grain and at least 75 percent of the condensed distillers solubles (CDS) produced after fermentation (Table 1). This co-product contains all parts of the maize kernel that are not converted into ethanol during fermentation. If condensed distillers solubles are not added back to the grain, the product is called dried distillers grain (DDG). This co-product has a lower concentration of fat and phosphorus than DDGS and it is produced in limited quantities compared with DDGS.

A few dry-grind ethanol plants in the United States have implemented "front-end" fractionation processes to enhance ethanol yield and produce a wider variety of co-products. However, the quantities of these co-products are limited, resulting in limited use in swine diets. If the grain is de-hulled and de-germed prior to fermentation, a high-protein DDGS (HPDDGS) may be produced (Table 1). This co-product contains less fat and fibre, but more protein, than conventional DDGS because fibre and fat are removed during the de-hulling and de-germing process. If the CDS is not added back to the distilled grain produced from de-hulled and de-germed grain, HPDDG is produced (Whitney, Shurson and Guedes, 2007). The maize germ that is extracted from maize during de-germing can also be fed to pigs, but this product has a relatively high concentration of non-starch polysaccharides (Whitney, Shurson and Guedes, 2007).

In contrast, approximately 30 percent of the United States ethanol industry is currently using "back-end" oil extraction, with oil extraction projected to be occurring in 40 percent of the industry by 2012, and in 55 percent of the industry by 2013. Currently, the range in crude fat content of DDGS sources is increasing (6 to 14 percent on a DM basis) compared with the typical range in crude fat content in DDGS only a few years ago (9 to 13 percent on a DM basis). However, depending upon the extraction equipment and methodology, crude fat levels in DDGS can be as low as 5 percent on a DM basis. Unfortunately, the effects of oil extraction on digestible, metabolizable and net energy content of DDGS for livestock and poultry are not known, but research is being conducted to obtain this information. This information will be essential for establishing price and value differentials among DDGS sources relative to crude fat content, as well as for accurate diet formulations using reduced-oil co-products.

TABLE 2
Composition of co-products from the maize wet-milling industry (as-fed basis)

Parameter	Maize germ meal	Maize gluten meal	Maize gluten feed	Glutenol
Crude protein, %	21.07	60.66	21.5	45.0
Calcium, %	0.03	–	0.22	–
Phosphorus, %	0.58	0.58	0.83	–
Crude fat, %	2.12	1.23	3.0	3.3
Crude fibre, %	9.53	1.32	–	3.8
Starch, %	13.63	10.14	–	1.5
Neutral-detergent fibre, %	54.41	11.21	33.3	–
Acid-detergent fibre, %	11.13	6.93	10.7	–
Total dietary fibre, %	42.57	8.45	–	–
Ash	2.41	3.65	–	4.0
Indispensable amino acids, %				
Arginine	1.49	2.18	1.04	–
Histidine	0.64	1.29	0.67	–
Isoleucine	0.75	2.59	0.66	–
Leucine	1.70	9.76	1.96	–
Lysine	1.04	1.27	0.63	–
Methionine	0.37	1.29	0.35	–
Phenylalanine	0.91	3.79	0.76	–
Threonine	0.78	1.94	0.74	–
Tryptophan	0.18	0.22	0.07	–
Valine	1.22	2.91	1.01	–
Dispensable amino acids, %				
Cysteine	0.33	0.99	0.46	–

Notes: Based on data from NRC, 1998; Shurson and Alghamdi, 2008; and unpublished data from University of Minnesota.

If oil is extracted from the DDGS, a de-oiled DDGS is produced (Jacela *et al.*, 2007). De-oiled DDGS contains 2 to 4 percent oil, and therefore also contains less energy than conventional DDGS (Jacela *et al.*, 2007; Table 1). However, most of the dry-grind ethanol plants are extracting oil from the condensed solubles fraction, resulting in a semi-de-oiled DDGS containing approximately 7 percent oil. If fibre is removed from the DDGS after production, a co-product called enhanced DDGS is produced (Soares *et al.*, 2008). This co-product contains approximately 10 percent less non-starch polysaccharides than conventional DDGS.

WET-MILLING CO-PRODUCTS

Although the majority of ethanol produced in the United States is from dry-grind ethanol plants, some plants use wet-milling technology. The major co-products produced from wet milling include maize germ meal, maize gluten meal and maize gluten feed (Table 2). The majority of these co-products are marketed to the ruminant feed industry, but they are also potential feed ingredients for swine. A new wet-milling technology that fractionates maize prior to fermentation has resulted in the production of a product called Glutenol (Shurson and Alghamdi, 2008). This product is equivalent to the HPDDGS produced from the dry-grind process after fermentation of de-hulled and de-germed maize, but contains slightly more protein and less fibre than HPDDGS.

Liquid co-products from the fuel ethanol industry

Two liquid co-products from the fuel ethanol industry – maize condensed distillers solubles (CDS) and maize steep water – may be fed to pigs (de Lange *et al.*, 2006). Maize CDS is a co-product from dry-grind fuel ethanol production, whereas maize steep water is a co-product produced from wet milling. Steep water contains approximately 50 percent CP and 3.3 percent P (DM basis), but only 0.5 percent oil (Table 3), whereas CDS contains 18.9 percent oil, but only 22.3 percent CP and 1.43 percent P (DM basis).

Co-products from the bio-diesel industry

Biodiesel is produced by a variety of esterification technologies, using new or used vegetable oils and animal fats as

TABLE 3
Composition of maize condensed distillers solubles (CDS) and maize steep water (dry matter basis)

Item	Maize CDS	Maize steep water
N	5	3
Dry matter, %	30.5	45
Crude protein, %	22.3	50
Crude fat, %	18.9	0.5
Ash, %	8.4	18.0
Ca, %	0.04	–
P, %	1.43	3.3
Na, %	0.21	–
K, %	–	5.0
pH	3.7	4.3
Acetic acid, %	0.11	–
Propionic acid, %	0.63	–
Butyric acid, %	0.01	–
Lactic acid, %1	9.8	20.0
Total non-starch polysaccharides, %	6.1	–
Starch, %	9.9	–
Total sugars, %	3.5	–

Notes: N = number of trials reported. *Source*: Based on data from Braun and de Lange, 2004; Niven *et al.*, 2006.

the initial feedstock. In general, oils and fats are filtered and pre-processed to remove water and contaminants, followed by mixing with an alcohol (usually methanol) and a catalyst (sodium or potassium methylate). This causes the oil molecules (triglycerides) to be broken apart into methyl esters and glycerin, which are then separated from each other and purified (NBB, 2011). Biodiesel is the name given to these esters when they are intended for use as fuel. The biodiesel industry can use any fat or oil feedstock, including recycled cooking grease and algae oil, but historically the primary feedstock source has been soybean oil. However, current prices of soybean oil have accelerated the industry's interest in utilization of alternative oil or fat sources for their initial feedstock.

NUTRIENT AND ENERGY COMPOSITION AND DIGESTIBILITY IN DISTILLERS GRAIN CO-PRODUCTS

Concentration and digestibility of carbohydrates

Most cereal grains contain between 60 and 70 percent starch, which is easily digested by pigs and absorbed in the form of glucose. However, production of alcohol from grain requires that the grain is fermented, and most of the starch in the grain is converted to alcohol during this process. All distillers co-products therefore have a low concentration of starch, whereas the concentration of most other nutrients is increased compared with their content in the original grain (Tables 1 and 2). Therefore, the concentrations of carbohydrates in distillers co-products are lower than in cereal grains and most of the carbohydrates are non-starch polysaccharides (fibre). The concentration of the different fibre fractions (neutral-detergent fibre - NDF, acid-detergent fibre - ADF, and total dietary fibre - TDF) is approximately three times greater in DDGS and DDG than in maize, but high-protein dried distillers grain (HPDDG), high-protein dried distillers grain with solubles (HPDDGS) and glutenol contain less fibre than DDG and DDGS because the maize was de-hulled before fermentation. The digestibility of fibre in DDGS and in DDG is less than 20 percent in the small intestine and less than 50 percent over the entire gastro-intestinal tract (Urriola, Shurson and Stein, 2010). Therefore, the fibre fraction contributes relatively little to the energy value of these products (Urriola, Shurson and Stein, 2010). It is expected that the digestibility of fibre in other distillers co-products is equally low, but fibre digestibility has not yet been reported for these co-products.

The low digestibility of fibre in distillers co-products results in increased quantities of manure being excreted from pigs fed these ingredients because the overall DM digestibility of diets containing distillers co-products is lower than in maize-based diets (Pedersen, Boersma and Stein, 2007a). Currently, much effort is directed towards developing feed additives such as enzymes or yeast products that can improve the digestibility of fibre in distillers co-products. If the digestibility of fibre in distillers co-products is improved, the energy value of these products will also improve.

Digestibility of amino acids

The digestibility of most amino acids in maize DDGS (Table 4) is approximately 10 percentage units lower than in maize (Fastinger and Mahan, 2006; Stein *et al.*, 2006; Pahm *et al.*, 2008). The lower digestibility of amino acids in maize DDGS compared with maize, may be a result of the greater concentration of fibre in DDGS than in maize, because dietary fibre reduces amino acid digestibility. Another reason for the variability and reduced digestibility of amino acids among maize DDGS sources compared with maize, is due to differences in production technologies and drying temperatures and duration among plants producing maize DDGS (Pahm *et al.*, 2008). Excessive heating during the drying process has been shown to result in the production of Maillard products, which reduce amino acid digestibility, particularly lysine (Urriola *et al.*, 2009). However, variability in digestibility of amino acids does not appear to be related to the region within the United States where the DDGS is produced (Pahm *et al.*, 2008).

The variability in the concentration and digestibility of lysine in maize DDGS is greater than the variability in digestibility of most other amino acids. Urriola *et al.* (2009) determined amino acid digestibility of 8 maize DDGS sources and showed that lysine standardized ileal digestibility (SID) ranged from 55.7 to 68.7 percent, and tryptophan digestibility ranged from 56.2 to 72.0 percent,

TABLE 4
Standardized ileal digestibility of amino acids in maize, sorghum, and distillers co-products produced from maize and sorghum

Item	Maize	Sorghum	Maize DDGS	Sorghum DDGS	Maize DDG	Maize HPDDG	Maize germ	De-oiled maize DDGS	Maize gluten meal	Maize gluten feed
n	2	1	34	1	1	1	1	1	1	1
Indispensable amino acids, %										
Arginine	87	70	81	78	83	83	83	83	89	87
Histidine	83	65	78	71	84	81	69	75	80	78
Isoleucine	81	66	75	73	83	81	57	75	84	80
Leucine	87	70	84	76	86	91	68	84	88	85
Lysine	72	57	62	62	78	64	58	50	80	66
Methionine	85	69	82	75	89	88	68	80	90	83
Phenylalanine	84	68	81	76	87	87	64	81	85	87
Threonine	74	64	71	68	78	77	53	66	84	71
Tryptophan	70	57	70	70	72	81	67	78	63	64
Valine	79	64	75	72	81	80	62	74	80	77
Dispensable amino acids, %										
Alanine	83	69	78	73	82	86	64	77	–	–
Aspartic acid	80	66	69	68	74	76	60	61	–	–
Cysteine	82	64	73	66	81	82	64	64	82	59
Glutamic acid	80	52	80	76	87	88	72	78	–	–
Glycine	84	71	63	67	66	75	76	53	–	–
Proline	96	50	74	83	55	73	84	73	–	–
Serine	83	72	76	73	82	84	65	73	–	–
Tyrosine	82	67	81	-	-	88	59	81	87	84

Notes: n = number of trials reported; HPDDG = high-protein dried distillers grain. *Source*: Adapted from Stein, 2008, based on data from Bohlke, Thaler and Stein, 2005; Jacela *et al.*, 2007; Pedersen, Boersma and Stein, 2007b; Stein, 2007; Urriola *et al.*, 2009; Whitney, Shurson and Guedes, 2007; Pahm *et al.*, 2008.

but standardized ileal digestibility of other amino acids was less variable among sources. The production of Maillard products results in a reduction in the total concentration of lysine as well as in the digestibility of lysine, but the concentration of crude protein is not changed. In non-heat-damaged maize DDGS, the concentration of lysine as a percentage of crude protein is between 3.1 and 3.3 percent, but in heat-damaged maize DDGS this percentage can be as low as 2.10 percent (Stein, 2007). Therefore, it is recommended that the lysine concentration is measured before maize DDGS is used in swine diets, and only sources that contain at least 2.80 percent lysine, expressed as a percentage of crude protein, be used in diets fed to swine (Stein, 2007). Some of the variability in amino acid digestibility, and lysine digestibility in particular, is caused by the addition of solubles to the distilled grain fraction before drying, because the solubles contain some residual sugars that were not fermented into ethanol. The presence of these sugars will increase the likelihood of Maillard reactions occurring when the mixture of distilled grain and condensed solubles is dried. As a result, the digestibility of amino acids in maize DDG is greater than in maize DDGS, because the solubles are not added to the distilled grain when DDG is produced (Pahm *et al.*, 2008).

The digestibility of amino acids in maize HPDDG is within the range of values measured for maize DDGS, but data for only one source are available (Whitney, Shurson and Guedes, 2007). The digestibility of amino acids in maize germ is less than in maize DDG and maize DDGS. The reason for this observation may be due to the proteins in maize germ having different chemical properties compared with other proteins in the grain kernel (Whitney, Shurson and Guedes, 2007).

Although sorghum has a lower digestibility of amino acids than maize (Pedersen, Boersma and Stein, 2007b), sorghum DDGS has amino acid digestibilities that are within the range of values observed in maize DDGS (Urriola *et al.*, 2009). However, amino acid digestibility data have been reported for only one source of sorghum DDGS. Digestibility of amino acids was measured in one source of de-oiled maize DDGS and all values reported were within the range of values reported for conventional maize DDGS (Jacela *et al.*, 2007).

Digestibility of phosphorus

Fermentation results in release of a portion of the phytate-bound phosphorus in maize, which in turn results in a greater digestibility of P in fermented feed ingredients than in maize (Table 5). Therefore, the ATTD of phosphorus is much greater in maize DDGS and maize HPDDG than in maize, whereas the digestibility of phosphorus in maize germ is similar to maize (Stein, Pedersen and Boersma,

TABLE 5
Concentration and digestibility of phosphorus in maize and distillers co-products produced from maize (as-fed basis)

Parameter	Maize	Maize DDGS	Maize HPDDG	Maize germ
n	2	10	1	1
Total phosphorus (%)	0.22	0.61	0.37	1.09
Total phosphorus (as % of DM)	0.25	0.70	0.40	1.18
ATTD (%)	24.1	59.0	59.6	28.6
Digestible phosphorus (%)	0.05	0.36	0.22	0.31

Notes: n = number of trials reported; ATTD = Apparent total tract digestibility; HPDDG = high-protein dried distillers grain. *Sources*: Stein, 2008, based on data from Bohlke, Thaler and Stein, 2005; Pedersen, Boersma and Stein, 2007a; Whitney, Shurson and Guedes, 2007.

2005; Pedersen, Boersma and Stein, 2007a; Whitney, Shurson and Guedes, 2007). There are no data on the ATTD of phosphorus in other sources of distillers co-products produced from maize or in DDGS produced from sorghum.

Digestibility of lipid

The ATTD of lipid in DDGS has been reported only from one experiment, which showed that the ATTD of oil in DDGS is approximately 70 percent (Stein, Pedersen and Boersma, 2005). However, there is a need for more information on oil and fatty acid digestibility in distillers co-products because of the important contribution of the oil to co-product energy value, as well as the effects on carcass fat quality in pigs.

Digestibility of energy

The ATTD of energy in most distillers co-products is lower than in maize because of the greater concentration of fibre in the co-products than in maize (Table 6). The fibre in maize DDGS has a low digestibility in the small intestine, and the fermentation of fibre in the large intestine is less than 50 percent complete, resulting in low digestibility of energy in distillers co-products. In maize DDGS, the ATTD of energy is 82.9 percent compared with 90.4 percent in maize (Pedersen, Boersma and Stein, 2007a). However, because of the higher oil concentration in maize DDGS compared with maize, the concentration of gross energy (GE) is also greater in maize DDGS than in maize (5434 vs 4496 kcal GE/kg DM). As a result, the concentration of digestible energy (DE) in maize DDGS is similar to maize (4088 vs 4140 kcal DE/kg DM; Stein, Pedersen and Boersma, 2005; Pedersen, Boersma and Stein, 2007a), but varies among DDGS sources (Pedersen, Boersma and Stein, 2007a; Anderson *et al.*, 2012; Mendoza *et al.*, 2010b). The concentration of DE in maize germ (3979 kcal DE/kg DM) is also similar to maize, but maize HPDDG has a greater concentration of DE (4763 kcal DE/kg DM) than maize (Whitney, Shurson and Guedes, 2007). The ME content of DDG containing 7.9 percent crude fat (2959 ±100 kcal/kg DM) was similar to that determined for DDGS containing 8.9 percent crude fat (2964 ±81 kcal/kg DM; Dahlen *et al.*, 2011). In contrast, de-oiled maize DDGS has a lower concentration of DE than maize (3093 kcal DE/kg DM; Jacela *et al.*, 2007). The concentration of DE in sorghum DDGS has been measured in one experiment and it was reported that sorghum DDGS contained approximately 220 kcal/kg (as-is basis) less than maize DDGS (Feoli *et al.*, 2007a), which may be a result of a lower concentration of oil in sorghum DDGS compared with maize DDGS.

IMPROVING NUTRIENT DIGESTIBILITY OF DDGS

Energy digestibility of DDGS is at least 10 percent lower than that of the feedstock grain from which it was produced, indicating that signficant opportunities for improvement exist. The relatively high concentration of fibre in DDGS may be one of the main reasons for reduced nutrient digestibility in DDGS compared with the grain source from which it was derived (Stein and Shurson, 2009). The impact of feed processing and feed additives such as supplemental enzymes on nutrient digestibility of DDGS has not been extensively studied, but knowledge from recent studies will be useful for identifying strategies for improving nutrient digestibility of DDGS in feed processing plants.

Particle size reduction

Grinding grain is common in the feed industry to improve nutrient digestibility and feed processing, and in the ethanol industry to improve fermentation and ethanol production efficiency. Reducing mean particle size from coarse to fine (e.g. from 1000 to 400 μm) will improve nutrient digestibility of ground grain such as maize (e.g. Wondra *et al.*, 1995) and also of protein sources such as soybean meal

TABLE 6
Concentration of energy in maize and in distillers co-products produced from maize and sorghum (DM-basis)

Parameter	Maize	Maize DDGS	Sorghum DDGS	Maize HPDDG	Maize Germ	De-oiled maize DDGS	Maize gluten meal	Maize gluten feed
n	2	10	2	1	1	1		
Gross energy (kcal/kg DM)	4458	5434	4908	5399	5335	4655	–	–
ATTD (%)	90.0	76.8	76.0	88.2	74.6	–	–	–
Digestible energy (kcal/kg DM)	4072	4140	3459	4763	3979	3093	4694	3322
Metabolizable energy (kcal/kg DM)	3981	3897	–	4476	3866	2851	4256	2894

Notes: n = number of trials reported; ATTD = apparent total tract digestibility. *Source*: Stein, 2008, based on data from NRC, 1998; Feoli *et al.*, 2007d; Jacela *et al.*, 2007; Pedersen, Boersma and Stein, 2007a; Whitney, Shurson and Guedes, 2007; Widmer *et al.*, 2007.

(Fastinger and Mahan, 2003). The underlying mechanism is that large feedstuff particles provide less surface area per unit of mass for digestive enzymes to interact with their substrates (Goodband, Tokach and Nelssen, 2002). Nutrient digestibility for larger particles is therefore lower than for smaller particles, because nutrient digestion is limited to a specific time interval due to digesta transit through the gastrointestinal tract.

Opportunities may exist to grind DDGS to increase nutrient digestibility, because the mean particle size of DDGS varies widely among samples. For example, the mean particle size of unground maize DDGS ranged from 434 to 949 μm from dry-grind ethanol plants (Liu, 2008). Mendoza *et al.* (2010c) evaluated DDGS from 15 different sources and observed considerable variability in particle size among sources, but DE and ME content can be improved by grinding to a smaller particle size.

Reducing mean particle size from 517 to 383 μm in DDGS increased the apparent ileal digestibility and ATTD of energy in grower pigs by 2.3 and 1.3 percentage units, respectively (Yáñez *et al.*, 2011). Liu *et al.* (2011b) showed an even greater response for improving ME of DDGS by reducing particle size, where each 25-micron decrease in DDGS particle size (from 818 μm to 308 μm), resulted in a ME contribution from DDGS to the diet of 13.6 kcal/kg DM, but diet flowability was reduced. Combined, grinding of DDGS will have more of a positive impact on nutrient digestibility on the DDGS sources with a mean particle size greater than 660 μm (Liu, 2008), and mean particle size should be measured routinely in feed quality evaluation.

Hydrothermal processing

Unlike grinding, which is common for all dry feed, not all monogastric feed is subjected to hydrothermal processing (Hancock and Behnke, 2001). Steam pelleting of feed is common in some parts of the United States and Western Europe, whereas mash feeding is common in western Canada and Australia. The impact of pelleting on nutrient digestibility of maize co-products is not clear, but it appears to improve nutrient digestibility. Growth performance and nutrient digestibility was improved when nursery pigs were fed diets containing 30 percent maize DDGS (Zhu *et al.*, 2010). Pelleting of diets containing high levels of maize fibre (maize gluten feed) improved N balance, apparently due to the increased availability of tryptophan (Yen *et al.*, 1971).

Extrusion subjects feed to heat and pressure more extensively than steam pelleting, and can open the physical structure of the feedstuff matrix (Hancock and Behnke, 2001). Extrusion processing is common for aquaculture and pet feed, because fish and companion animals have generally much lower nutrient digestibility of plant-based feeds than swine and poultry. Therefore, extrusion is required to achieve suitable feed management characteristics. However, very little is known about the effects of extruding maize and maize co-products on nutritional value for swine (Muley *et al.*, 2007). In broiler chicks, extrusion of DDGS from triticale, wheat and maize improved energy and amino acid digestibility (Oryschak *et al.*, 2010a, b). In contrast, extrusion of DDGS from wheat and maize increased energy digestibility for both in pigs, perhaps, in part, by enhancing nutrient digestibility of residual starch in DDGS, but also by improving amino acid digestibility in maize DDGS (Beltranena *et al.*, 2009). These results indicate that effects of extrusion processing on nutrient digestibility will be specific to source of DDGS and species targeted.

Supplemental enzymes

The addition of exogenous enzymes to animal feeds to improve nutrient digestion is not a new concept, and responses have been reviewed in detail (Chesson, 1987; Bedford, 2000). The majority of commercial enzyme products have been targeted toward poultry (Annison and Choct, 1991; Cowan, 1993) and are typically added to diets containing barley, oats, peas, rye or wheat (Aimonen and Nasi, 1991; Thacker, Campbell and GrootWassink, 1992; Viveros *et al.*, 1994; Hubener, Vahjen and Simon, 2002), with only limited research evaluating enzyme use in maize-soybean meal diets (Saleh *et al.*, 2005).

The introduction of larger quantities of co-products, such as DDGS, into swine diets will increase the dietary content of fibre. The negative effects on energy and nutrient digestibility, and ultimately animal performance, from feeding such diets may be reduced partly by using supplemental enzymes (Zijlstra, Owusu-Asiedu and Simmins, 2010). Detailed chemical characterization of fibre components in DDGS indicates that it contains arabinoxylan constituents, which is one potential substrate for supplemental fibre-degrading enzymes, and that some intact phytate remains as substrate for supplemental phytase (Widyaratne and Zijlstra, 2007; Liu, 2011). However, results from a recent study by Kerr, Weber and Shurson (2011) showed minimal effects on nutrient digestibility, and no improvement in growth performance, from supplementing with ten different commercial enzyme products and additives in nursery or finishing pig diets containing 30 percent DDGS.

Phytase

Plant-based phytate is well known for its ability to bind P and other nutrients and thereby reduce digestibility of these nutrients (Oatway, Vasanthan and Helm, 2001). The phytate contained in the grain is partly transformed during the fermentation process to produce ethanol and co-products. Intact phytate (inositol hexaphosphate) does, unlike nutrients other than starch, not concentrate 2 to 3 fold in the DDGS, but is instead partially hydrolyzed into inositol phosphates, which contain 5 or fewer P molecules

(Widyaratne and Zijlstra, 2007). Digestibility of P is therefore higher in DDGS than in the feedstock grain. Still, sufficient phytate in DDGS remains to hinder P digestibility. Indeed, the addition of 500 FTU (phytase units) of phytase to a maize starch diet containing 44 percent DDGS increased the ATTD of energy of P in the diet by 10.5 percentage units, but did not affect energy and amino acid digestibility (Yáñez *et al.*, 2011). However, data on the impact of phytase, with or without other enzymes, on nutrient (and energy) digestibility in maize co-product diets is lacking and inconsistent. While addition of 500 units phytase improved P digestibility in diets containing 20 percent DDGS in starter or finisher pigs, it did not improve DM digestibility (Xu, Whitney and Shurson, 2006a, b). In contrast, Lindemann *et al.* (2009) reported that pigs fed diets containing 20 percent DDGS supplemented with 250 or 500 U/kg phytase exhibited greater DM, energy, and N digestibility than unsupplemented pigs, but there were no further improvements in faecal DM, energy or N digestibility with additional xylanase supplementation. Therefore, even though DDGS has a higher P digestibility than grain and protein meals, supplemental phytase may provide additional benefits in diets containing DDGS.

Fibre-degrading enzymes

The negative impact of fibre or non-starch polysaccharides has been described for cereal grains, including barley and wheat (Fairbairn *et al.*, 1999; Zijlstra *et al.*, 2009). The positive effects of fibre-degrading enzymes on energy digestibility of wheat have been defined, as long as the supplemental enzyme matches with a substrate that limits nutrient utilization or animal performance (e.g. Mavromichalis *et al.*, 2000; Cadogan, Choct and Campbell, 2003; Barrera *et al.*, 2004). Thus, not surprisingly, diets containing wheat co-products from flour milling (co-products that have been subjected to limited processing during production) have a drastically increased non-starch polysaccharide content and hence arabinoxylan content, and supplemental xylanase improved energy digestibility in swine (Nortey *et al.*, 2007, 2008). Combined, these results indicate that wheat fibre in its native form is a good substrate for supplemental xylanase in swine diets.

Interestingly, the relationship between co-products from ethanol production (maize or wheat DDGS) and the potential benefits from supplemental xylanase is less clear. Studies have shown no improvement in growth performance from adding enzymes to maize DDGS diets for nursery pigs (Jones *et al.*, 2010), while studies by Spencer *et al.* (2007) and Yoon *et al.* (2010) showed improvements from the use of enzymes in nursery and in grower-finisher diets, respectively. Additional studies have also shown improvements in nutrient digestibility when enzymes are added to DDGS diets (Jendza *et al.*, 2009; Yoon *et al.*, 2010; Feoli *et al.*, 2008d), but improvements in nutrient digestibility do not always result in improvements in growth performance (Kerr, Weber and Shurson, 2011). Because DDGS has been subjected to extensive periods in solution, followed by drying, adding supplemental xylanase to DDGS diets does not always seem to improve energy digestibility of wheat DDGS (Widyaratne, Patience and Zijlstra, 2009; Yáñez *et al.*, 2011) or maize DDGS (Mercedes *et al.*, 2010), although positive examples exist (Lindemann *et al.*, 2009). Furthermore, xylanase supplementation did not improve growth performance in nursery pigs fed diets containing 30 percent maize DDGS (Jones *et al.*, 2010), although xylanase improved growth performance and digestibility of diet components in broilers (Liu *et al.*, 2011a). Finally, supplementation of a multi-enzyme complex to diets containing wheat DDGS improved growth performance and nutrient digestibility in finisher pigs (Emiola *et al.*, 2009), although the barley and maize contained in the diets used might have also interacted with the multi-enzyme to provide the positive response, and the multi-enzyme complex may be required to open the fibre matrix.

The more extensive processing used during ethanol production compared with flour milling might thus have caused changes in the feedstuff matrix that may make supplemental enzymes less advantageous for improving nutrient digestibility. These differences in enzyme responses may be due to fibre-degrading enzymes that can be added during the ethanol production process to enhance ethanol yield, making the regular substrate for these supplemental enzymes not the limiting factor for nutrient digestibility. Feedstuffs and enzyme selection require proper characterization to ensure that the substrates and enzymes match, and that the substrate is indeed the critical factor that hinders nutrient digestibility.

IN VITRO ENERGY DIGESTIBILTY IN DDGS

Nutritional value of DDGS is known to vary substantially among sources (Nuez Ortín and Yu, 2009; Stein and Shurson, 2009; Zijlstra and Beltranena, 2009). Specifically, the ATTD of energy ranged from 74 to 83 percent for maize DDGS (Pedersen, Boersma and Stein, 2007a) and from 56 to 76 percent for wheat DDGS (Cozannet *et al.*, 2010). Prediction of quality of DDGS prior to feed processing is thus an important component of reducing the risk of less predictable animal performance when using DDGS in animal feeds. *In vitro* energy digestibility techniques can be used to screen ranges in energy digestibility among feedstuff samples and thereby support the development of feedstuff databases and rapid feed quality evaluation systems such as near-infrared reflectance spectroscopy (Zijlstra, Owusu-Asiedu and Simmins, 2010).

In vitro digestibility techniques using enzymes and incubation periods that mimic *in vivo* digestion can predict with reasonable accuracy the ATTD of energy among feedstuffs in swine (Boisen and Fernández, 1997). However, variation within feedstuffs such as DDGS is a greater concern for processing complete feed with an accurate DE content, and should be explored thoroughly for individual feedstuffs or feedstuff combinations.

Using *in vitro* digestibility techniques, the ATTD among samples of the same cereal grain can be predicted accurately for barley (Regmi, Sauer and Zijlstra, 2008) and wheat (Regmi, Ferguson and Zijlstra, 2009a). However, similar efforts were not successful in predicting the ATTD for protein feedstuffs with a more complex fibre and protein matrix, such as DDGS (Regmi *et al.*, 2009; Wang *et al.*, 2010).

In vitro fermentation has been used recently as a tool in feedstuff characterization, based on the hypothesis that gas produced and fermentation kinetics reflect the same kinetics as *in vivo* fermentation of fibre in the large intestine of swine. Although *in vitro* fermentation characteristics have been measured in an array of feedstuffs, only recently has *in vitro* fermentation of maize DDGS been compared with other feedstuffs, and its fermentation rate is similar to wheat bran and lower than field pea and sugar beet pulp (Jha *et al.*, 2011).

ENERGY PREDICTION EQUATIONS FOR DDGS

Because of variability in DE and ME values among DDGS sources, several prediction equations have been developed to estimate ME content using various chemical analysis measures (Mendoza *et al.*, 2010b; Anderson, Shurson and Kerr, 2009; Pedersen, Boersma and Stein, 2007a). However, there are several challenges in accurately predicting ME content of DDGS sources:

- Accuracy has not been validated.
- May not represent the wide range in nutrient variability among sources.
- Some analytes required by equations (e.g. GE, TDF) are not routinely measured or are expensive to analyse.
- Analytical variability among labs and procedures affects accuracy (e.g. NDF).
- Adjustments for fat and fibre in some equations seem counterintuitive.

NUTRIENT AND ENERGY COMPOSITION AND DIGESTIBILITY IN MAIZE CO-PRODUCTS FROM WET-MILLING

The majority of the research with energy and nutrient digestibility has been conducted with products from the dry-grind fuel ethanol industry, and only limited data are available on the digestibility of nutrients and energy in co-products from the wet-milling process for swine. For maize germ meal and glutenol, no data on energy and nutrient digestibility have been published, and for maize gluten meal and maize gluten feed, only data for amino acid digestibility have been published (Table 4). Both maize gluten meal and maize gluten feed have amino acid digestibility values that are greater than in maize DDGS, and for most amino acids the digestibility in maize gluten meal is similar to the values measured in maize (Table 4), whereas the values in maize gluten feed generally are intermediate compared with those measured in maize and maize DDGS. Values for DE and ME in maize gluten meal are greater than in maize and maize DDGS, and similar to values reported for maize HPDDG, but DE and ME in maize gluten feed are lower than in maize and similar to values measured for de-oiled DDGS (Table 6).

CRUDE GLYCERIN

Energy composition and digestibility

During digestion in non-ruminants, intestinal absorption of glycerin has been shown to range from 70 to 90 percent in rats (Lin, 1977), to more than 97 percent in pigs and laying hens (Bartlet and Schneider, 2002). Glycerin is water soluble and can be absorbed by the stomach, but at a rate that is slower than that of the intestine (Lin, 1977). Absorption rates are high, which is probably due to glycerin's small molecular weight and passive absorption, rather than going through the process of becoming part of a micelle that is required for absorption of medium- and long-chain fatty acids (Guyton, 1991). Once absorbed, glycerol can be converted to glucose via gluconeogenesis or oxidized for energy production via glycolysis and the citric acid cycle, with the shuttling of protons and electrons between the cytosol and mitochondria (Robergs and Griffin, 1998). Glycerol metabolism largely occurs in the liver and kidney, where the amount of glucose carbon arising from glycerol depends upon metabolic state and level of glycerol consumption (Lin, 1977; Hetenyi, Perez and Vranic, 1983; Baba, Zhang and Wolfe, 1995). With gluconeogenesis from glycerol being limited by the availability of glycerol (Cryer and Bartley, 1973; Tao *et al.*, 1983), crude glycerin has the potential of being a valuable dietary energy source for monogastric animals.

Pure glycerin is a colourless, odourless and sweet-tasting viscous liquid, containing approximately 4.3 Mcal GE/kg on an as-is basis (Kerr *et al.*, 2009). However, crude glycerin can range from 3 to 6 Mcal GE/kg, depending upon its composition (Brambilla and Hill, 1966; Lammers *et al.*, 2008a; Kerr *et al.*, 2009). The difference in GE between crude glycerin and pure glycerin is not surprising, given that crude glycerin typically contains about 85 percent glycerin, 10 percent water, 3 percent ash (typically Na or K chloride), and a trace amount of free fatty acids. As expected, high amounts of water negatively influence GE levels, while high levels of free fatty acids elevate the GE concentration. The ME of glycerin has been assumed to be approximately 95%

of its GE (Brambilla and Hill, 1966; Lin, Romsos and Leveille, 1976; Rosebrough *et al.*, 1980; Cerrate *et al.*, 2006), but there have been no empirical determinations of the ME of crude glycerin in swine until recently.

Bartlet and Schneider (2002) reported ME values of refined glycerin in 35-kg pigs and determined that the ME value of glycerin decreased as the level of dietary glycerin increased (4189, 3349 and 2256 kcal/kg at 5, 10 and 15 percent inclusion levels, respectively) with an average value of 3292 kcal/kg on an as-is basis. Because pre-caecal digestibility of glycerin was determined to be approximately 97 percent (Bartlet and Schneider, 2002), the observed decrease in ME value may be a result of increased blood glycerol levels following glycerin supplementation (Kijora *et al.*, 1995; Kijora and Kupsch, 2006; Simon, Bergner and Schwabe, 1996), suggesting that complete renal reabsorption is prevented and glycerol excretion in the urine is increased (Kijora *et al.*, 1995; Robergs and Griffin, 1998).

In nursery and finishing pigs, Lammers *et al.* (2008a) determined that the ME content of a crude glycerin co-product containing 87 percent glycerin was 3207 kcal/kg, and did not differ between pigs weighing 10 or 100 kg (Table 7). Based strictly on its glycerin content, this equates to 3688 kcal ME/kg on a 100 percent glycerin basis (3207 kcal ME/kg/87 percent glycerin), which is slightly lower than the 3810 kcal ME/kg (average of the 5 and 10 percent inclusion levels) reported by Bartlet and Schneider (2002), but similar to the 3656 kcal ME/kg as reported by Mendoza *et al.* (2010a) using a 30 percent inclusion level of glycerin.

Similar to data reported by Bartlet and Schneider (2002), increasing crude glycerin from 5 to 10 to 20 percent in 10-kg pigs (Lammers *et al.*, 2008a) quadratically reduced ME content (3601, 3239 and 2579 kcal ME/kg, respectively), suggesting that high dietary concentrations of crude glycerin may not be fully utilized by 10-kg pigs. In contrast, dietary concentrations of crude glycerin had no effect on ME determination in 100-kg pigs (Lammers *et al.*, 2008a). The ratio of DE:GE is an indicator of how well a crude glycerin source is digested, and for the crude glycerin source evaluated by Lammers *et al.* (2008a), it equalled 92 percent, suggesting that crude glycerin is well digested, being only slightly lower that the 97 percent of glycerin digested before the caecum, as reported by Bartlet and Schneider (2002). In addition, the ratio of ME:DE indicates how well energy is utilized once digested and absorbed. For the crude glycerin source evaluated by Lammers et al. (2008a), the ratio was 96 percent, which is identical to the ME:DE ratio for soybean oil, and is comparable to the ratio of ME:DE (97%) for maize grain (NRC, 1998), all of which support the assertion that crude glycerol is well utilized by the pig as a source of energy.

TABLE 7
Digestible and metabolizable energy of crude glycerin fed to pigs, as-is basis

Trial	Pigs	Initial BW (kg)	DE (kcal/kg)	SEM	ME (kcal/kg)	SEM
1	18	11.0	4,401	282	3,463	480
2	23	109.6	3,772	108	3,088	118
3	19	8.4	3,634	218	3,177	251
4	20	11.3	4,040	222	3,544	237
5	22	99.9	3,553	172	3,352	192

Notes: All experiments represent data from 5-day energy balance experiments following a 10-day adaptation period (Lammers *et al.*, 2008a); BW = body weight; DE = digestible energy, ME = metabolizable energy; SEM = Standard Error of the Mean. Trial 1 included pigs fed diets containing 0, 5 and 10% crude glycerin. Trial 2 included pigs fed diets containing 0, 5, 10 and 20% crude glycerin. Trials 3, 4 and 5 included pigs fed diets containing 0% and 10% glycerin.

Chemical composition variability

Similar to other co-products used to feed livestock, the chemical composition of crude glycerin can vary widely (Thompson and He, 2006; Kijora and Kupsch, 2006; Hansen *et al.*, 2009; Kerr *et al.*, 2009). The consequences of this variable chemical composition in crude glycerin relative to its energy value for animals have not been well described. Recently, 10 sources of crude glycerin from various biodiesel production facilities in the United States were evaluated for energy utilization in growing pigs (Table 8). The crude glycerin sources originating from biodiesel plants using soybean oil averaged 84 percent glycerin, with minimal variability noted among 6 of the sources obtained. Conversely, crude glycerin sources obtained from biodiesel plants using tallow, yellow grease or poultry oil as initial lipid feedstock ranged from 52 to 94 percent glycerin. The crude glycerin co-products derived from either non-acidulated yellow grease or poultry fat had the lowest glycerin content, but also had the highest free fatty acid concentrations. The high fatty acid content of the non-acidulated yellow grease product was expected because the acidulation process results in greater separation of methyl esters, which subsequently results in a purer form of crude glycerin containing less free fatty acids (Ma and Hanna, 1999; Van Gerpen, 2005; Thompson and He, 2006). In contrast, the relatively high free fatty acid content in the crude glycerin obtained from the biodiesel plant utilizing poultry fat as a feedstock is difficult to explain because details of the production process were not available. Moreover, these two crude glycerin co-products (derived from non-acidulated yellow grease and poultry fat) had higher methanol concentrations than

TABLE 8
Chemical analysis of crude glycerin, percentage as-is basis

Sample ID	Glycerin	Moisture	Methanol	pH	NaCl	Ash	Fatty acids
USP	99.62	0.35	ND	5.99	0.01	0.01	0.02
Soybean oil	83.88	10.16	0.0059	6.30	6.00	5.83	0.12
Soybean oil(1)	83.49	13.40	0.1137	5.53	2.84	2.93	0.07
Soybean oil	85.76	8.35	0.0260	6.34	6.07	5.87	ND
Soybean oil	83.96	9.36	0.0072	5.82	6.35	6.45	0.22
Soybean oil	84.59	9.20	0.0309	5.73	6.00	5.90	0.28
Soybean oil	81.34	11.41	0.1209	6.59	6.58	7.12	0.01
Tallow	73.65	24.37	0.0290	3.99	0.07	1.91	0.04
Yellow grease	93.81	4.07	0.0406	6.10	0.16	1.93	0.15
Yellow grease(2)	52.79	4.16	3.4938	8.56	1.98	4.72	34.84
Poultry fat	51.54	4.99	14.9875	9.28	0.01	4.20	24.28

Notes: Samples analysed as described in Lammers *et al.* (2008a), courtesy of Ag Processing Inc., Omaha, NE 68154, USA. Glycerin content determined by difference as: 100 -% methanol -% total fatty acid -% moisture -% ash. Data obtained from Kerr *et al.*, 2009. ND = not determined. USP = United States Pharmacopeial Convention grade glycerin or initial feedstock lipid source. (1) Soybean oil from extruded soybeans. All other soybean oil was obtained by hexane extraction of soybeans. (2) Crude glycerin that was not acidulated.

the other glycerin sources. Recovery of methanol is also indicative of production efficiency because it is typically re-used during the production process (Ma and Hanna, 1999; Van Gerpen, 2005; Thompson and He, 2006). The high amount of methanol content in crude glycerin from non-acidulated yellow grease was expected because this co-product had not been fully processed at the production facility. The reason crude glycerin obtained from the plant utilizing poultry fat contained relatively high methanol is unclear because no processing information was available from the plant. However, this higher level of methanol may be due to lower overall efficiency of the production process at this plant (Ma and Hanna, 1999; Van Gerpen, 2005; Thompson and He, 2006).

The average ME of the 11 sources of glycerin described in Table 9 was 3486 kcal/kg (Kerr *et al.*, 2009), with little difference among the sources, with the exception of the two sources with high levels of free fatty acids (co-products obtained from non-acidulated yellow grease and poultry fat). These sources high in free fatty acid content had higher ME values than the other crude glycerin co-products, which was not surprising given that these two co-products also had a higher GE concentration than the other co-product sources. The ME:GE ratio among all glycerin co-products was similar, averaging 85 percent, which is similar to ratios reported by others (88%, Lammers *et al.*, 2008a; 88%, Bartlet and Schneider, 2002; 85%, Mendoza *et al.*, 2010a). Because the GE of the crude glycerin can vary widely among co-product sources, comparison of ME as a percentage of GE provides valuable information on the caloric value of crude glycerin for swine. A high ME:GE ratio indicates that a crude glycerin source is well digested and utilized.

Because more than one chemical component can influence energy content of feed ingredients, stepwise regression was used to predict GE and ME values, and to predict ME as a percentage of GE among glycerin sources.

TABLE 9
Energy values of crude glycerin co-products in swine, on an as-is basis

Sample	GE (kcal/kg)	ME (kcal/kg)	% of GE
USP	4325	3682	85.2
Soybean oil	3627	3389	93.4
Soybean oil(1)	3601	2535	70.5
Soybean oil	3676	3299	89.9
Soybean oil	3670	3024	82.5
Soybean oil	3751	3274	87.3
Soybean oil	3489	3259	93.5
Tallow	3173	2794	88.0
Yellow grease	4153	3440	92.9
Yellow grease(2)	6021	5206	86.6
Poultry fat	5581	4446	79.7

Notes: USP = United States Pharmacopeial Convention (USP) grade glycerin or initial feedstock lipid source. (1) Soybean oil from extruded soybeans. All other soybean oil was obtained by hexane extraction of soybeans. (2) Crude glycerin that was not acidulated. *Source*: Kerr *et al.*, 2009.

If the GE of a crude glycerin source is unknown, it can be predicted by using the following equation: GE kcal/kg = -236 + (46.08 × % of glycerin) + (61.78 × % of methanol) + (103.62 × % of fatty acids), (R^2 = 0.99). Metabolizable energy content can subsequently be predicted by multiplying GE by 84.5% with no adjustment for composition (Kerr *et al.*, 2009). Additional research is needed to refine and validate these equations relative to glycerin, methanol, ash and total fatty acid concentrations for all body weights.

SPECIAL CONSIDERATIONS FOR CO-PRODUCTS FROM THE ETHANOL INDUSTRY

Mycotoxins

Like all feed ingredients, maize co-products may contain mycotoxins that can negatively affect animal performance, or might be stored under conditions that cause co-product deterioration. Mycotoxins can be present in maize co-products if the grain delivered to the ethanol plant is contaminated with them. Mycotoxins are not destroyed during the ethanol production process, nor are they destroyed during the drying process to produce distiller co-products. In fact, if they are present in maize used to produce ethanol, their concentration will be increased by a factor of approximately three in DDGS. However, the risk of mycotoxin contamination in United States distillers grain by-products is very low because it is uncommon for most of the major maize growing regions in the United States to have climatic and weather conditions that lead to mycotoxin production in maize on a regular basis. Furthermore, most ethanol plants monitor grain quality and reject sources that exceed acceptable (very low) levels of mycotoxins.

Recently, Zhang *et al.* (2009) conducted surveys to assess the prevalence and levels of aflatoxins, deoxynivalenol, fumonisins, T-2 toxin and zearalenone in 235 DDGS samples. The samples were collected between 2006 and 2008 from 20 ethanol plants in the mid-western United States and from 23 export shipping containers, and analysed using state-of-the-art analytical methodologies. Their results indicated that (1) none of the samples contained aflatoxins or deoxynivalenol levels higher than the U.S. Food and Drug Administration (FDA) guidelines for use in animal feed; (2) no more than 10 percent of the samples contained levels of fumonisins higher than the recommendation for feeding equids and rabbits, and the remaining bulk of the samples contained fumonisins lower than FDA guidelines for use in animal feed; (3) no samples contained detectable levels of T-2 toxins; 4) most samples contained no detectable zearalenone; and 5) the containers used for export shipping of DDGS did not contribute to mycotoxin production.

The prevalence and levels of deoxynivalenol (vomitoxin) in the 2009 United States maize crop were unusually high, resulting in production of deoxynivalenol-contaminated DDGS in 2010. As a result, researchers (Fruge *et al.*, 2011a, b; Barnes *et al.*, 2011) evaluated the effectiveness of commercial products for mitigating the negative effects of feeding diets containing DDGS contaminated with deoxynivlenol, and some benefits were observed.

Sulphur

Sulphur levels can be highly variable among DDGS sources and can range from 0.31 to 1.93 percent (average 0.69 percent) on a DM basis (University of Minnesota data; www.ddgs.umn.edu). Sulphuric acid is commonly added during the dry-grind ethanol production process to keep pH at desired levels for optimal yeast propagation and fermentation in order to maximize the conversion of starch to ethanol, and is less costly compared with other acids. According to AAFCO (2010), sulphuric acid is generally recognized as safe according to U.S. Code of Federal Regulation (21 CFR 582) and is listed as an approved food additive (21 CFR 573). In addition, maize naturally contains about 0.12 percent sulphur, and is concentrated by approximately three-fold, like other nutrients, when maize is used to produce ethanol and DDGS. Yeast also contains about 3.9 g/kg sulphur and naturally creates sulphites during fermentation.

Sulphur is an essential mineral for animals and serves many important biological functions in the animal body. However, when excess sulphur (greater than 0.40 percent of diet DM) is present in ruminant diets, neurological problems resulting from polioencephalomalacia (PEM) can occur. In contrast, sulphur content of DDGS does not appear to be a concern in swine diets. Kim, Zhang and Stein (2010) conducted four experiments to determine the effects of dietary sulphur level on feed palatability and growth performance of weanling and growing-finishing barrows. Their results showed that inclusion of 20 to 30 percent of DDGS in diets fed to weanling and grow-finishing pigs reduced palatability of the diets and negatively affected growth performance. However, the concentration of sulphur in the DDGS-containing diets had no impact on feed palatability or growth performance.

Lipid oxidation

Some sources of DDGS may contain high levels of oxidized lipids due to the high drying temperatures used in some ethanol plants. Song, Saari Csallany and Shurson (2011) reported that the thiobarbituric acid reactive substances (TBARS; a measure indicative of lipid oxidation) level can vary considerably (1.0 to 5.2 malondialdehyde (MDA) equivalent ng/mg oil) among 31 DDGS sources. The highest TBARS level measured in one DDGS source was 26 times higher than that of maize (0.2 MDA equivalent ng/mg oil). As a result, the use of supplemental dietary antioxidants may be warranted in order to minimize metabolic oxidation. Harrell *et al.* (2010) and Harrell, Zhao and Reznik (2011) reported that the dietary addition of an commercial antioxidant can improve growth performance of pigs fed diets containing oxidized maize oil or 20 to 30 percent DDGS, and in a subsequent study showed that supplementing nursery pig diets with another commercially available antioxidant improved growth performance of pigs when fed diets containing 60 percent DDGS. However, no research has been conducted to determine the efficacy of these synthetic antioxidants relative to common forms of vitamin E.

SPECIAL CONSIDERATIONS FOR CRUDE GLYCERIN

Because glycerin varies in energy content, salt content and methanol concentration, modifications in diet formulation may be required. Depending on the salt level in the crude glycerin, supplemental levels of dietary salt may need to be limited, depending upon the animal species and stage of production where it is fed. It is generally well accepted that feeding diets containing up to 3 percent dietary NaCl will have no adverse effects on pig performance as long as adequate water is freely available (adapted from NRC, 1980). However, the impact of increased water intake on increased manure volume and changes in composition (Sutton *et al.*, 1976) needs to be considered.

Adding 10 to 20 percent crude glycerin to swine mash diets may also affect the ability of feed to flow in bulk bins and automatic feeding systems, as indicated by Cerrate *et al.* (2006), Hansen *et al.* (2009), Lammers *et al.* (2008a) and Kerr *et al.*, (2009), especially in feeds containing dried whey. Because no quantitative measurements to assess feed flowability were taken in any of these experiments, the potential interactions among levels of glycerin supplementation, diet type and feed handling system affecting feed flowability are yet to be characterized.

Methanol levels in crude glycerin warrant special consideration. Methanol is a potentially toxic compound and has been reviewed in detail by others (Roe, 1982; Medinsky and Dorman, 1995; Skrzydlewska, 2003). Methanol can be introduced orally, by respiration or through the skin, and is distributed by the blood to all organs and tissues in proportion to their water content (Liesivuori and Savolainen, 1991). Metabolic elimination of methanol is much slower than that of ethanol. Small amounts of methanol are excreted in the kidney and lung, but the majority is metabolized by the liver and released as CO_2. Acute methanol intoxication is manifested initially by signs of narcosis followed by a latent period in which formic acid accumulates causing metabolic acidosis (reduced blood pH, depletion of blood bicarbonate and visual degeneration, with abdominal, leg and back pain). Chronic exposure to methanol causes headache, insomnia, gastrointestinal problems and blindness. Animals differ widely in their ability to metabolize methanol, depending upon enzyme activity and hepatic folate levels (Roe, 1982; Black *et al.*, 1985; Medinsky and Dorman, 1995; Skrzydlewska, 2003). Little research on methanol metabolism or toxicity has been conducted in pigs. Makar *et al.* (1990) reported that pigs, compared with all other species studied, have extremely low levels of folates and very low levels of a key enzyme (10-formyl H_4folate dehydrogenase) in the folate pathway, suggesting the ability of the pig to dispose of formate is limited, and slower than that observed in rats or monkeys. However, Dorman *et al.* (1993) indicated that methanol- and formate-dosed minipigs did not develop optic nerve lesions, toxicologically significant formate accumulation or metabolic acidosis, indicating that minipigs do not appear to be overtly sensitive to methanol toxicity.

When considering the potential for methanol and formate toxicity, it is interesting to note that in some countries, formaldehyde, a methanol metabolite, can be used as a silage preservative, and formic acid can be used in finished feeds to reduce bacterial loads. Formic acid or formate salts have also been used safely in diets for swine (Overland *et al.*, 2000; Canibe *et al.*, 2005) and formaldehyde in diets for laying hens (Khan, Hussain and Khan, 2006). It is also interesting to note that calcium formate has been used as a dietary calcium supplement for humans (Hanzlik, Fowler and Eells, 2005).

As a general-purpose feed ingredient, glycerin is regulated in the United States under 21CFR583.1320, requiring that levels of methanol in methyl esters of higher fatty acids should not exceed 0.015 percent. Recently, however, crude glycerin has been defined by the Association of American Feed Control Officials (AAFCO, 2010) and can be fed to non-ruminants up to 10 percent of the complete feed as long as it contains not less than 80 percent glycerin, not more than 15 percent water, not more than 0.15 percent methanol, up to 8 percent salt, up to 0.1 percent sulphur, and not more than 5 ppm heavy metals. German regulations (Normenkommission fur Einzelfuttermittel im Zentralausschuss der Deutschen Landwirtschaf, 2006) allow 0.5 percent (5000 ppm) methanol in crude glycerin.

FEEDING DISTILLERS CO-PRODUCTS TO SWINE

Sows

Maize DDGS is the only maize co-product that has been evaluated for use in sow diets and for which published reports are available. Feeding diets containing 50 percent maize DDGS to gestating sows resulted in no negative effects on lactation feed intake, litter weight gain, and weaning to oestrus interval (Wilson *et al.*, 2003). In fact, sows fed maize DDGS in gestation (50 percent) and lactation (20 percent) for two consecutive parities had increased litter size in the second parity compared with those fed a maize-soybean meal diet. The reason for this observation is unknown, but it may be a consequence of the increased fibre concentration in diets containing maize DDGS because litter size is sometimes improved if sows are fed high-fibre diets during gestation (Ewan *et al.*, 1996; Grieshop, Reese and Fahey, 2001). More research needs to be conducted to verify if the increase in litter size is a common response to including maize DDGS in diets fed to gestating sows.

Results of four experiments in which maize DDGS was fed to lactating sows have been reported, and dietary inclusion rates in these experiments were: up to 15 percent (Hill *et al.*, 2008b); 20 percent (Wilson *et al.*, 2003) or 30 percent (Song *et al.*, 2010; Greiner *et al.*, 2008) of the diet. No negative performance effects were reported in any of these experiments, and milk composition, apparent nitrogen digestibility or nitrogen retention were not affected by feeding DDGS diets. However, sows fed diets containing 20 or 30 percent maize DDGS had lower values for blood urea nitrogen than sows fed a maize-soybean meal diet (Song *et al.*, 2010), which indicates that these sows were fed diets with a better amino acid balance compared with sows fed the control diet. Greiner *et al.* (2008) observed that sows fed a 30 percent maize DDGS diet had improved weight gain in lactation and reduced wean to oestrus intervals, but these effects were not reported in the other experiments. There is, however, no information on the performance of pigs farrowed by sows fed maize DDGS, but there are no indications that the growth performance of these pigs would be affected.

Therefore, maize DDGS can be included in sow diets at levels up to 50 percent in gestation and up to 30 percent in lactation if diets are formulated on a ME, digestible amino acid and available phosphorus basis. It is possible that the inclusion rate of DDGS in diets fed to gestating sows can be greater than 50 percent, and for lactating sows, greater than 30 percent, but no research has been reported concerning this hypothesis.

Weanling pigs

Growth performance responses (Table 10) from inclusion of maize DDGS at levels up to 30 percent in weanling pig diets have been reported from 10 experiments (Whitney and Shurson, 2004; Linneen *et al.*, 2008; Gaines *et al.*, 2006; Spencer *et al.*, 2007; Barbosa *et al.*, 2008; Burkey *et al.*, 2008). Growth rate was not affected in any of these experiments by feeding DDGS diets, beginning as early as 4 days post-weaning (Whitney *et al.*, 2004). Average daily feed intake was reduced in two experiments when DDGS was included in the diet (Gaines *et al.*, 2006; Barbosa *et al.*, 2008), but the Gain:Feed (G:F) ratio was improved when DDGS was added to the diet in 5 of the 10 experiments (Gaines *et al.*, 2006; Spencer *et al.*, 2007; Barbosa *et al.*, 2008). Nursery pig mortality was reported in only two experiments, and no negative effects were observed from feeding DDGS diets.

Palatability, feed preference and growth performance of nursery pigs have been evaluated when various levels and qualities of distillers co-products were added to the diet (Hastad *et al.*, 2005; Seabolt *et al.*, 2008). Nursery pigs prefer diets without DDGS or HPDDGS, but colour differences among sources appear unrelated to feed preference.

TABLE 10
Effects of including maize dried distillers grain with solubles (DDGS) in diets fed to weanling pigs

Item	n	Response to dietary maize DDGS		
		Increased	Reduced	Unchanged
ADG	10	0	0	10
ADFI	10	0	2	8
G:F	10	5	0	5
Mortality	2	0	0	2

Notes: n = number of trials reported; ADG = Average daily gain; ADFI = Average daily feed intake; G:F = Gain:Feed ratio.
Source: Stein and Shurson, 2009, derived from data calculated from experiments by Whitney and Shurson, 2004; Gaines *et al.*, 2006; Linneen *et al.*, 2006; Spencer *et al.*, 2007; Barbosa *et al.*, 2008; and Burkey *et al.*, 2008.

Effects of introducing DDGS-containing diets to weanling pigs at different times post-weaning was investigated (Spencer *et al.*, 2007) by offering pigs a 4-phase nursery programme in which DDGS was introduced either in phase 1 (7.5 percent), phase 2 (15 percent) or phases 3 and 4 (15 percent). There were no differences in growth performance among treatments, which indicated that DDGS may be introduced immediately after weaning without compromising pig growth performance. However, this result was not observed by Burkey *et al.* (2008), who reported that inclusion of DDGS in diets fed to pigs before day 21 post-weaning resulted in a reduction in growth performance.

Inclusion of sorghum DDGS in diets fed to weanling pigs at levels up to 60 percent of the diets has been investigated in three experiments (Senne *et al.*, 1995, 1996; Feoli *et al.*, 2008d). No differences in average daily gain (ADG), average daily feed intake (ADFI) or G:F ratio were observed when feeding diets containing levels up to 20 percent of sorghum DDGS (Senne *et al.*, 1995), but the inclusion of 30 percent sorghum DDGS in diets reduced growth performance compared with pigs fed diets containing no DDGS (Feoli *et al.*, 2008d). When weanling pigs were fed diets containing 0, 15, 30, 45 or 60 percent sorghum DDGS from day 7 to day 29 post-weaning (Senne *et al.*, 1996), quadratic reductions in ADG and G:F were observed, with growth performance of pigs fed up to 30 percent DDGS being similar to that of pigs fed control diets, but inclusion of 45 or 60 percent DDGS reduced ADG and G:F. It is possible that differences in DDGS quality or diet formulation methods may have contributed to these different responses.

De-oiled maize DDGS can be included in diets fed to weanling pigs in concentrations of up to 30 percent, with no changes in ADG, ADFI or G:F (Jacela *et al.*, 2008a). No experiments have been conducted to investigate the effects of including distillers co-products other than DDGS and de-oiled DDGS in diets fed to weanling pigs. As a result, it is unknown if any of the other maize co-products can be used effectively in weanling pig diets.

Growing-finishing pigs – growth performance

In the last decade, results from at least 25 experiments have been reported on growth performance of growing-finishing pigs fed diets containing up to 30 percent maize DDGS (Table 11). In 23 of these experiments, DDGS was included in maize- and soybean-meal-based diets, and wheat-field pea-based diets were used in two experiments. There are also reports from eight experiments in which sorghum DDGS was included in diets, with two experiments using wheat DDGS in growing-finishing pig diets.

Results from early research showed that adding up to 20 percent maize DDGS to growing-finishing pig diets would be acceptable for maintaining growth performance, but performance was reduced if 40 percent was used (Cromwell *et al.*, 1983). Average daily gain was improved in one experiment, reduced in six experiments, and not affected by DDGS level in 18 experiments when up to 20 percent maize DDGS was added to diets adequately fortified with amino acids (McEwen, 2006, 2008; Augspurger *et al.*, 2008; Drescher *et al.*, 2008; Duttlinger *et al.*, 2008b; Widmer *et al.*, 2008) and studies where up to 30 percent maize DDGS was added (Cook, Paton and Gibson, 2005; DeDecker *et al.*, 2005). In contrast, data from other experiments in which 10, 20 or 30 percent maize DDGS was included in diets fed to growing-finishing pigs showed a linear reduction in ADG (Fu *et al.*, 2004; Whitney *et al.*, 2006; Linneen *et al.*, 2008; Weimer *et al.*, 2008). A linear reduction in ADFI was also observed in two of these experiments (Fu *et al.*, 2004; Linneen *et al.*, 2008). Xu *et al.* (2010b) showed that ADG was not affected, but ADFI was reduced and G:F was linearly improved in pigs fed diets containing 0, 10, 20 or 30 percent DDGS. Results from two additional experiments in which performance of finishing pigs fed diets containing 0 or 30 percent DDGS were compared showed no differences in ADG and ADFI, but G:F was reduced in pigs fed the DDGS-containing diets (Gaines *et al.*, 2007a, b). The reduction in G:F in the latter experiments and the increase in G:F in the experiment by Xu *et al.* (2010b) suggests that the energy concentration may have varied among the sources of DDGS used in these experiments.

TABLE 11
Effects of including maize dried distillers grain with solubles (DDGS) in diets fed to growing-finishing pigs

Parameter	n	Response to dietary maize DDGS		
		Increased	Reduced	Unchanged
Average Daily Gain	25	1	6	18
ADFI	23	2	6	15
Gain:Feed (G:F)	25	4	5	16
Dressing percentage	18	0	8	10
Backfat (mm)	15	0	1	14
Lean meat (%)	14	0	1	13
Loin depth (cm)	14	0	2	12
Belly thickness (cm)	4	0	2	2
Belly firmness	3	0	3	0
Iodine value	8	7	0	1

Notes: ADFI = Average daily feed intake. Based on experiments (n is number of trials involved) published after 2000 and where a maximum of 30% DDGS was included in the diets. The primary source was Stein and Shurson, 2009, whose data derived from experiments by Gralapp *et al.*, 2002; Fu *et al.*, 2004; Cook, Paton and Gibson, 2005; DeDecker *et al.*, 2005; Whitney *et al.*, 2006; McEwen, 2006, 2008; Gaines *et al.*, 2007a, b; Gowans *et al.*,2007; Hinson *et al.*, 2007; Jenkin *et al.*, 2007; White *et al.*, 2007; Widyaratne and Zijlstra, 2007; Xu *et al.*, 2010a, b; Augspurger *et al.*, 2008; Drescher *et al.*, 2008; Duttlinger *et al.*, 2008b; Hill *et al.*, 2008a; Linneen *et al.*, 2008; Stender and Honeyman, 2008; Weimer *et al.*, 2008; and Widmer *et al.*, 2008.

A linear increase in ADG and G:F was also observed when a barley-wheat-field pea-based diet was fortified with 0, 5, 10, 15, 20 or 25 percent maize DDGS and fed to growing-finishing pigs (Gowans *et al.*, 2007). However, inclusion of 25 percent DDGS in a wheat-field pea-based diet reduced ADG and ADFI compared with results obtained for pigs fed a diet containing no DDGS (Widyaratne and Zijlstra, 2007).

Data for ADFI were reported only in 23 experiments: increasing in two experiments, decreasing in six experiments, and unaffected by dietary DDGS inclusion in 15 experiments. G:F was improved in 4 experiments, reduced in 5 experiments and unaffected by dietary treatments in 16 experiments.

Based on the data provided from these 25 experiments, it is not possible to determine the reasons why pig performance was maintained in most, but not in all, experiments in which DDGS was included in the diets. It is possible that the maize DDGS used in the experiments in which performance was reduced may have been of a poorer quality (lower nutrient digestibility) than expected. In some of the experiments in which performance was reduced by feeding increasing levels of maize DDGS, dietary CP levels were also increased. In such diets, DDGS inclusion rate is confounded by CP level and it is not possible to determine if the reduced performance is caused by the increase in maize DDGS concentration or by the increase in CP concentration. However, in most of the experiments in which ADG was reduced, a reduction in ADFI was also observed. It is therefore possible that the poorer performance was due to reduced palatability of the maize DDGS used in those diets. It has been demonstrated that, if given a choice, pigs prefer to consume diets containing no maize DDGS (Hastad *et al.*, 2005; Seabolt *et al.*, 2008).

Results from the eight experiments in which sorghum DDGS was included in diets fed to growing-finishing pigs demonstrated that if sorghum DDGS is used at concentrations of 30 percent or less, no differences in pig performance are observed (Senne *et al.*, 1995, 1996). However, if greater dietary inclusion rates are used, ADG will be reduced (Senne *et al.*, 1996; 1998; Feoli *et al.*, 2007b, c; 2008a, b, c). Likewise, G:F is not affected if the inclusion of sorghum DDGS is limited to 30 percent (Senne *et al.*, 1995; 1996), but G:F may be reduced if 40 percent is used (Senne *et al.*, 1998; Feoli *et al.*, 2008a), although this is not always the case (Feoli *et al.*, 2007c, 2008b, c). Average daily feed intake is not affected by sorghum DDGS if 30 percent or less is included in the diet (Senne *et al.*, 1995), but ADFI may be reduced at greater inclusion levels (Senne *et al.*, 1996; Feoli *et al.*, 2007c, 2008b).

Inclusion of 25 percent wheat DDGS in a wheat-field pea-based diet fed to growing-finishing pigs did not affect ADG or G:F (Widyaratne and Zijlstra, 2007), but adding up to 25 percent wheat DDGS in wheat-soybean meal-based diets for growing pigs linearly reduced ADG and ADFI, whereas G:F was unaffected (Thacker, 2006). However, when the dietary inclusion of DDGS was reduced to 0, 3, 6, 9, 12 or 15 percent during the finishing phase in this experiment, no differences in growth performance were observed during this period (Thacker, 2006). The diet used by Widyaratne and Zijlstra (2007) was formulated based on concentrations of digestible amino acids measured in the batch of DDGS that was fed to the pigs, whereas the diets used by Thacker (2006) were formulated based on a total amino acid basis. This may explain why different responses were obtained in these experiments because it has been shown that wheat DDGS sometimes has a very low lysine digestibility (Nyachoti *et al.*, 2005; Lan, Opapeju and Nyachoti, 2008).

The addition of up to 40 percent high-protein maize DDG to diets fed to growing-finishing pigs was evaluated by Widmer *et al.* (2008), where maize HPDDG replaced all of the soybean meal in the maize-based diets. Overall growth performance was not different for pigs fed the maize HPDDG diets compared with pigs fed the maize-soybean meal control diets, but ADFI and ADG were reduced during the growing phase when 40 percent maize HPDDG was fed (Widmer *et al.*, 2008). These results indicate that maize HPDDG may be included in maize-based diets fed to growing-finishing pigs at levels needed to replace all the soybean meal, but it is necessary to include relatively large concentrations of crystalline amino acids in HPDDG diets to compensate for the low concentrations of lysine and tryptophan in this ingredient, and diets should always be formulated on the basis of standardized ileal digestible amino acids.

Widmer *et al.* (2008) also determined the effects of adding 5 or 10 percent maize germ to maize-soybean meal diets for growing-finishing pigs and observed a linear increase in the final weight of the pigs as the level of maize germ increased in the diets, and a tendency for increased average daily gain. Therefore, feeding diets containing 10 percent maize germ improves growth performance compared with typical maize-soybean meal diets, and it is possible that higher dietary inclusion rates can be used, but research to investigate this possibility is needed.

De-oiled DDGS was evaluated in diets fed to growing-finishing pigs in one experiment (Jacela *et al.*, 2008b). Results from this experiment showed that inclusion of 5, 10, 20 or 30 percent de-oiled maize DDGS linearly reduced ADG and ADFI. Based on the data from this experiment, it is concluded that de-oiled DDGS should not be included in diets fed to growing-finishing pigs. However, more research is needed to verify if the results from this experiment are repeatable or if it is possible to change diet formulations in such a way that de-oiled DDGS can successfully be included in diets fed to growing-finishing pigs.

Growing-finishing pigs – carcass composition and quality

The effects of feeding maize DDGS diets on carcass dressing percentage have been reported from 18 experiments (Table 11). In ten of these experiments, no difference in dressing percentage was observed (Fu *et al.*, 2004; McEwen, 2006, 2008; Xu *et al.*, 2007; Augspurger *et al.*, 2008; Drescher *et al.*, 2008; Duttlinger *et al.*, 2008b; Hill *et al.*, 2008a; Stender and Honeyman, 2008; Widmer *et al.*, 2008), whereas reduced dressing percentage of DDGS-fed pigs was observed in eight experiments (Cook, Paton and Gibson, 2005; Whitney *et al.*, 2006; Gaines *et al.*, 2007a, b; Hinson *et al.*, 2007; Xu *et al.*, 2010b; Linneen *et al.*, 2008; Weimer *et al.*, 2008). For pigs fed sorghum DDGS, the dressing percentage increased in one experiment (Senne *et al.*, 1996), was unaffected by dietary DDGS inclusion in one experiment (Senne *et al.*, 1998), and was reduced in five experiments (Feoli *et al.*, 2007b, c, 2008a, b, c). For pigs fed wheat DDGS, dressing percentage also was reduced (Thacker, 2006) and this was also the case for pigs fed de-oiled maize DDGS (Jacela *et al.*, 2008b). It has been suggested that the inclusion of fibre-rich ingredients in diets fed to pigs may reduce the dressing percentage of pigs because of increased gut fill and increased intestinal mass (Kass, van Soest and Pond, 1980). This may explain the reduced dressing percentage observed in DDGS-fed pigs in some experiments, but it is unknown why this effect has not been observed in other experiments.

Backfat thickness of pigs fed maize DDGS was reduced in one experiment (Weimer et al., 2008), but in 14 other experiments no difference in backfat thickness was observed (Table 11). Loin depth was not affected by the dietary inclusion of maize DDGS in 12 experiments, but in two experiments loin depth was reduced (Whitney *et al.*, 2006; Gaines *et al.*, 2007b). A reduction in loin depth was also reported when wheat DDGS was included in the diet (Thacker, 2006). The reduced loin depth may be a result of pigs fed DDGS having lower ADG in these experiments and therefore being marketed at a lighter weight. Of the 14 experiments that reported lean percentage of pigs fed diets containing maize DDGS, only one experiment (Gaines *et al.*, 2007b) reported a reduction in lean percentage, whereas no differences were reported in the remaining experiments. Carcass lean percentage was also reported for pigs fed sorghum DDGS (three experiments) and wheat DDGS (one experiment), but no changes due to dietary DDGS inclusion were observed in these experiments.

Belly thickness was reported to be linearly reduced if maize DDGS was included in the diet (Whitney *et al.*, 2006; Weimer *et al.*, 2008), and also if sorghum DDGS was used (Feoli *et al.*, 2008c). However, pigs fed DDGS-containing diets also had reduced ADG in these experiments, and as a result they were marketed at a lighter weight than the control pigs, which may explain the reduction in belly thickness. In the experiments by Widmer *et al.* (2008) and Xu *et al.* (2010a, b), no differences in the final bodyweight of pigs were observed, and in these experiments no differences were observed in belly thickness between pigs fed control or DDGS-containing diets.

The adjusted belly firmness of pigs fed diets containing maize DDGS is reduced compared with pigs fed maize-soybean meal diets with no DDGS (Whitney *et al.*, 2006; Xu *et al.*, 2010a; Widmer *et al.*, 2008). This observation is in agreement with data showing that the iodine value of the belly fat is increased in pigs fed DDGS (Whitney *et al.*, 2006; White *et al.*, 2007; Xu *et al.*, 2010a, b; Hill *et al.*, 2008a; Linneen *et al.*, 2008; Stender and Honeyman, 2008). An increase in iodine value of carcass fat also occurs when pigs are fed sorghum DDGS diets (Feoli *et al.*, 2007c; 2008b, c). The increase in carcass fat iodine values in pigs fed DDGS-containing diets is a result of the relatively large quantities of unsaturated fatty acids, particularly linoleic acid (C18:2), in maize and sorghum DDGS because increases in dietary unsaturated fatty acid concentrations will increase carcass fat iodine values (Madsen *et al.*, 1992).

Carcass fat iodine values are important measures of carcass quality because high iodine values result in soft and potentially less valuable bellies and loins. As a result, several studies have been conducted to evaluate alternative nutritional strategies in an attempt to reduce the negative effects of DDGS on iodine values. The dietary inclusion of up to 5 percent tallow in diets containing 40 percent sorghum DDGS did not reduce the iodine value in jowl fat (Feoli *et al.*, 2007c), even though tallow contains a high proportion of saturated fatty acids. Similarly, the addition of 5 percent tallow to 30 percent DDGS diets did not improve backfat or belly fat iodine values (Pomerenke *et al.*, 2011). In contrast, the addition of one percent conjugated linoleic acid to diets containing 20 or 40 percent maize DDGS for ten days prior to pig harvest reduced fat iodine values and the n6:n3 ratio (White *et al.*, 2007). This observation is consistent with the observation that conjugated linoleic acids may reduce the activity of the delta-9 desaturase enzyme that is responsible for desaturation of de novo synthesized fatty acids (Gatlin *et al.*, 2002). Thus, addition of conjugated linoleic acids to DDGS containing diets fed during the late finishing phase may be used to reduce iodine values in carcass fat. Removal of DDGS from the diet during the final three to four weeks prior to harvest will also reduce the negative impact of DDGS on carcass fat iodine values, and will result in pigs that have acceptable iodine values (Hill *et al.*, 2008a; Xu *et al.*, 2010b). Evans *et al.* (2010) conducted a study to evaluate the effects on pork fat quality of feeding diets containing 0 or 0.6 percent conjugated linoleic acid, 0 or 20 percent DDGS, and 0 or 7.4 ppm ractopamine to finishing pig 27 days prior to harvest. Iodine value increased in belly fat and jowl fat with diets containing DDGS and ractopamine, and decreased when finishing pigs were fed diets containing conjugated linoleic acid. Similarly, Gerlemann *et al.* (2010) evaluated the effects of feeding 0 or 20 percent DDGS, 0 or 7.4 ppm ractopamine, and 0 or 0.6 percent conjugated linoleic acid to finishing pigs 27 days prior to harvest on growth performance and carcass characteristics. Their results indicated that feeding diets containing ractopamine and conjugated linoleic acid improved growth performance and carcass quality, and the responses of DDGS, ractopamine and conjugated linoleic acid are independent of each other. Overall consumer acceptance of bacon and cooked pork loins from pigs fed diets containing up to 30 percent DDGS was evaluated by Xu *et al.* (2010b) and no differences were observed compared with pork from pigs fed maize-soybean meal diets.

There is no information on the effect of feeding diets containing wheat DDGS on belly firmness and iodine values, but wheat DDGS contains less fat than DDGS produced from maize or sorghum. Therefore, it is expected that inclusion of wheat DDGS in diets fed to finishing pigs will have less of an impact on carcass iodine values than if maize or sorghum DDGS is used.

Pigs fed diets containing maize HPDDG or de-oiled maize DDGS may also have softer bellies and increased iodine values compared with pigs fed maize-soybean meal diets (Jacela *et al.*, 2008b; Widmer *et al.*, 2008), but pigs fed diets containing maize germ have firmer bellies and reduced iodine values (Widmer *et al.*, 2008). There are no reports of the effects of other distillers co-products on carcass composition and quality. Overall consumer acceptance of pork from pigs fed maize DDGS, maize HPDDG, and maize germ was not different from that of pigs fed maize-soybean meal diets. It is therefore unlikely that consumers will be able to tell whether or not the pork they are eating was from a pig that was fed distiller's co-products or not.

Only one experiment has been conducted to evaluate the effects of feeding diets containing DDGS to gestating and lactating sows on pork (bratwurst) quality (White *et al.*, 2008). These researchers fed diets containing 30 percent DDGS during gestation and 15 percent DDGS during lactation, with or without an omega-3 feed supplement. Bratwurst from sows fed DDGS and the omega-3 dietary supplement had the highest overall quality score and a lower calculated iodine value compared with sows fed DDGS diets without the supplement, but higher iodine values than bratwurst from sows fed the control diet and the control diet supplemented with omega-3 fatty acids.

Feeding liquid distillers co-products to growing-finishing pigs

Squire *et al.* (2005) fed diets containing 0, 7.5, 15.0 and 22.5 percent CDS to growing pigs and showed that feed

TABLE 12
Growth performance, nutrient digestibility and carcass quality of pigs fed liquid diets containing maize and soybean meal with either non-fermented or fermented maize condensed distillers solubles (CDS) at 15% of DM

Parameter	Diet		
	Control	Non-fermented CDS	Fermented CDS
Initial BW (kg)	23.5	23.3	23.4
Final BW (kg)	50.1 a	47.5 b	48.6 ab
ADG (g)	952 a	858 b	898 ab
ADFI (kg)	1.62 a	1.49 b	1.61 a
Feed:gain	1.70	1.73	1.80
Energy digestibility (%)	81.6 ab	82.5 a	79.9 b
Protein digestibility (%)	72.5 a	73.2 a	69.3 b
Fat digestibility (%)	80.9 b	85.4 a	85.4 a
Final BW (kg)	106.5	107.0	–
Carcass dressing (%)	82.1	82.6	–
Backfat depth (mm)	16.6	17.1	–
Loin depth (mm)	54.3	53.7	–
Carcass lean yield (kg)	61.1	60.9	–
Loin pH	5.74 b	5.80 a	–
Loin drip loss (%)	9.63	8.83	–

Notes: ADG = average daily gain; ADFI = average daily feed intake; BW= body weight; a,b = Means within rows lacking a common letter are different (P <0.05). Data for growth performance are expressed on a diet DM basis. *Source*: Based on data from de Lange *et al.*, 2006.

palatability was reduced when more than 15 percent CDS was included in the diet (Table 12). Feeding the non-fermented CDS diet resulted in reduced growth rate, feed intake and feed conversion compared with pigs fed the maize-soybean meal control diet, while growth performance of pigs fed the fermented CDS diet was not different from pigs fed the control diet (Table 12). Energy and protein digestibility were reduced when feeding the fermented CDS diet compared with pigs fed the non-fermented CDS and the control diet. However, fat digestibility of the non-fermented and fermented CDS diets was greater than when pigs were fed the control diet. In this study, only pigs on the control and non-fermented CDS diets were fed to slaughter weight. Feeding the non-fermented CDS diet resulted in similar carcass dressing percentage, backfat depth, loin depth and carcass lean yield compared with pigs fed the control diet, indicating that acceptable carcass quality can be achieved when feeding liquid non-fermented CDS diets to growing-finishing pigs. Loin pH was greater from pigs fed the CDS diet compared with pigs fed the control diet, which probably resulted in a trend toward reduced loin drip loss. Reduced drip loss is a significant benefit to meat processors.

Niven *et al.* (2006) reported results from a preliminary study that showed that growth rate and feed conversion were numerically improved when pigs were fed liquid diets containing 5 percent maize steep water, but adding 10 percent maize steep water numerically reduced pig performance. In a larger subsequent study, de Lange *et al.*

TABLE 13
Growth performance and carcass characteristics of pigs feds liquid diets containing increasing levels of phytase-treated maize steep water

Parameter	Inclusion of maize steep water (%)			
	0	7.5	15.0	22.5
Initial BW (kg)	69.1	68.8	68.8	69.3
Final BW (kg)	108.3	104.6	107.7	103.1
ADG (g)	1191 a	1080 a	1063 a	899 b
ADFI (kg)	2.76 a	2.49 ab	2.58 ab	2.29 b
Feed:gain	2.33 a	2.30 a	2.42 ab	2.55 b
Carcass weight (kg)	86.3	82.7	83.4	80.5
Loin depth (mm)	58.2	58.9	56.4	58.3
Backfat depth (mm)	18.1	18.7	18.0	17.1
Lean yield (%)	60.3	60.3	60.5	60.1

Notes: ADG = average daily gain; ADFI = average daily feed intake; BW= body weight; a,b = Means within rows lacking a common letter are different (P <0.05). *Source*: Based on data from de Lange *et al.*, 2006.

(2006) showed that ADG, ADFI and F:G were not changed when pigs were fed liquid diets containing 0, 7.5 or 15 percent phytase-treated maize steep water, but adding 22.5 percent maize steep water to the diets resulted in reduced performance (Table 13). No effects were observed for dietary inclusion level of maize steep water for carcass weight, loin depth, backfat depth and lean yield.

In summary, feeding diets containing 15 percent fermented maize CDS results in growth performance comparable to when typical liquid maize-soybean meal diets are fed, but feeding diets containing 15 percent non-fermented maize distillers solubles results in reduced performance due to reduced palatability. However, feeding liquid diets containing 15 percent non-fermented CDS results in similar carcass composition compared with pigs fed liquid maize-soybean meal diets. Similarly, feeding liquid maize-soybean meal diets containing up to 15 percent maize steep water treated with phytase results in acceptable growth performance and carcass composition comparable to feeding a typical liquid maize-soybean meal diets. Maize CDS and steep water can successfully be used in liquid feeding systems for growing-finishing pigs to achieve satisfactory growth performance and carcass quality at a substantial savings in feed cost.

FEEDING CRUDE GLYCERIN TO SWINE

Growth performance and carcass characteristics

In swine, German researchers (Kijora and Kupsch, 2006; Kijora *et al.*, 1995, 1997) have suggested that up to 10 percent crude glycerin can be fed to pigs with little effect on pig performance. Likewise, Mourot *et al.* (1994) indicated that growth performance of pigs from 35 to 102 kg was not affected by the addition of 5 percent glycerin (unknown purity) to the diet. The impact of dietary glycerin on carcass quality in pigs has been variable. Kijora *et al.* (1995) and

Kijora and Kupsch (2006) showed no consistent effect of 5 or 10 percent crude glycerin addition to the diet on carcass composition or meat quality parameters, while in an additional study, pigs fed 10 percent crude glycerin exhibited a slight increase in backfat, 45-minute pH, flesh colour, marbling and leaf fat (Kijora *et al.*, 1997). Although they did not note any significant change in the saturated fatty acid profile of the backfat, there was a slight increase in oleic acid, accompanied by a slight decrease in linoleic and linolenic acid concentrations, resulting in a decline in the polyunsaturated to monounsaturated fatty acid ratio in backfat. Likewise, Mourot *et al.* (1994) reported no consistent change in carcass characteristics due to 5 percent crude glycerin supplementation of the diet, but did note an increase in oleic acid and a reduction in linoleic acid in backfat and *Semimembranosus* muscle tissue. Kijora and Kupsch (2006) found no effect of glycerin supplementation on water loss in retail pork cuts. However, Mourot *et al.* (1994) reported a reduction in 24-hour drip loss (1.75 versus 2.27 percent) and cooking loss was also reduced (25.6 vs 29.4 percent) from the *Longissimus dorsi* and *Semimembranosus* muscles due to dietary supplementation with 5 percent glycerin. Likewise, Airhart *et al.* (2002) reported that oral administration of glycerin (1 g/kg BW) 24 hours and 3 hours before slaughter tended to decrease drip and cooking loss of *Longissimus dorsi* muscle.

Recently, there has been increased interest in utilization of crude glycerin in swine diets due to the high cost of feedstuffs traditionally used in swine production. For newly weaned pigs, it appears that crude glycerin can be utilized as an energy source up to 6 percent of the diet, but crude glycerin does not appear to be a lactose replacement (Hinson, Ma and Allee, 2008). In 9 to 22-kg pigs, Zijlstra *et al.* (2009) reported that adding up to 8 percent crude glycerol to diets as a wheat replacement improved growth rate and feed intake, but had no effect on G:F. In 28 to 119-kg pigs, supplementing up to 15 percent crude glycerol to the diet quadratically increased ADG and linearly increased ADFI, but the net effect on feed efficiency was a linear reduction (Stevens *et al.*, 2008). These authors also reported that crude glycerin supplementation appeared to increase backfat depth and Minolta L* of loin muscle, but decreased loin marbling and the percentage of fat-free lean with increasing dietary glycerin levels. In 78 to 102-kg pigs, increasing crude glycerin from 0 or 2.5 percent to 5 percent reduced ADFI when fat was not added to the diet, but had no effect when 6 percent fat was supplemented (Duttlinger *et al.*, 2008a). This decrease in feed intake resulted in depressed average daily gain, but had no effect on feed efficiency. In contrast, Duttlinger *et al.* (2008b) reported supplementing up to 5 percent crude glycerin to diets had no effect on growth performance or carcass traits of pigs weighing 31 to 124 kg.

Supplementing 3 or 6 percent crude glycerin in pigs from 11 to 25-kg body weight increased average daily gain even though no effect was noted on feed intake, feed efficiency, dry matter, nitrogen or energy digestibility (Groesbeck *et al.*, 2008). Supplementing 5 percent pure glycerin did not affect pig performance from 43 to 160 kg, but pigs fed 10 percent glycerin had reduced growth rate and feed efficiency compared with pigs fed the control or 5 percent glycerin supplemented diets (Casa *et al.*, 2008). In addition, diet did not affect meat or fat quality, or meat sensory attributes. In 51 to 105-kg pigs, including up to 16 percent crude glycerin did not affect pig growth performance or meat quality parameters (Hansen *et al.*, 2009). Lammers *et al.* (2008b) fed pigs (8 to 133-kg body weight) diets containing 0, 5 or 10 percent crude glycerin and reported no effect of dietary treatment on growth performance, backfat depth, loin eye area, percentage fat-free lean, meat quality or sensory characteristics of the *Longissimus dorsi* muscle. In addition, dietary treatment did not affect blood metabolites or frequency of histological lesions in the eye, liver or kidney, and only a few minor differences were noted in the fatty acid profile of loin adipose tissue. Likewise, Mendoza *et al.* (2010a) fed heavy pigs (93 to 120 kg) up to 15 percent refined glycerin and reported no effect on growth performance, carcass characteristics or meat quality. Schieck *et al.* (2010b) fed pigs either a control diet (16 weeks, 31 to 128 kg), 8 percent crude glycerin during the last 8 weeks (45 to 128 kg) or 8 percent crude glycerin for the entire 16 week period (31 to 128 kg), and reported that feeding crude glycerin during the last 8 weeks before slaughter supported similar growth performance, with little effect on carcass composition or pork quality, except for improvement in belly firmness, compared with pigs fed the maize-soybean meal control diet. Longer-term feeding (16 weeks) resulted in a slight improvement in growth rate, but a small depression in feed efficiency. Some minor differences in carcass composition were noted, but there was no impact on pork quality. When considering the results from all of these studies (Table 14), there appears to be no consistent (positive or negative) effect of feeding up to 15 percent crude glycerin on growth performance, carcass composition or pork quality in growing-finishing pigs compared with typical cereal grain-soybean meal-based diets.

Sows

Only one study has been reported relative to feeding crude glycerin to lactating sows. In that study, lactating sows fed diets containing up to 9 percent crude glycerin performed similar to sows fed a standard maize-soybean-meal diet (Schieck *et al.*, 2010a).

EFFECTS OF DDGS ON PIG HEALTH

Distiller's by-products contain residual yeast cells and yeast cell components and approximately 3.9 percent of the

TABLE 14
Relative performance of pigs fed supplemental glycerin(1)

Glycerin equivalency(2)	ADG	ADFI	G:F ratio	Base feed	Pig size	Source
4.0(3)	105	109	98	Wheat-soybean meal-fish meal-lactose	9–22 kg	Ziljstra *et al.*, 2009
8.0(3)	108	105	104			
5.0	98	100	99	Maize- soybean meal	10–22 kg	Hinson, Ma and Allee, 2008
2.7	107	103	103	Maize- soybean meal	11–25 kg	Groesbeck *et al.*, 2008
5.4	108	104	103			
4.8	105	108	97	Barley- soybean meal	31–82 kg	Kijora *et al.*, 1995
9.7	112	112	100			
19.4	96	103	94			
29.4	82	105	78			
2.9	103	108	97	Barley- soybean meal	24–95 kg	Kijora and Kupsch, 2006
4.9	102	106	97			
7.6	102	101	101			
8.3	102	107	97			
10.0	103	104	100			
10.0	106	110	96	Barley- soybean meal	27–100 kg	Kijora *et al.*, 1997
4.6	114	110	103	Barley- soybean meal	32–96 kg	Kijora *et al.*, 1995
9.7	119	113	106			
5.0	97	101	96	Wheat- soybean meal	35–102 kg	Mourot *et al.*, 1994
4.2	101	102	97	Maize- soybean meal (whey in Phase 1)	8–133 kg	Lammers *et al.*, 2008b
8.5	100	103	97			
4.2	103	103	100	Maize- soybean meal	28–119 kg	Stevens *et al.*, 2008
8.4	103	104	99			
12.6	100	108	92			
2.5	99	99	99	Maize- soybean meal	31–124 kg	Duttlinger *et al.*, 2008b
5.0	99	101	98			
3.0	98	104	93	Wheat-barley-lupin, soybean meal -blood meal-meat meal	51–105 kg	Hansen *et al.*, 2009
6.1	87	93	95			
9.1	96	102	94			
12.2	91	98	93			
6.6	104	105	98	Maize-soybean meal	31–127 kg	Schieck *et al.*, 2010b
2.5	97	99	98	Maize-soybean meal	78–102 kg	Duttlinger *et al.*, 2008a
5.0	95	97	98			
5.0	101	100	101	Maize-barley-wheat bran- soybean meal	43–159 kg	Casa *et al.*, 2008
10.0	96	100	95			
5.0	106	105	101	Maize- soybean meal	93–120 kg	Mendoza *et al.*, 2010a
10.0	100	101	98			
15.0	95	100	95			

Notes: ADG = average daily gain; ADFI = average daily feed intake; BW= body weight. (1) Percentage relative to pigs fed the diet containing no supplemental glycerin. Percentage difference does not necessarily mean there was a significant difference from pigs fed the diet containing no supplemental glycerin. Main dietary ingredients and weight range of pigs tested are also provided with each citation. (2) Represents a 100% glycerin basis. In studies utilizing crude glycerin, values adjusted for purity of glycerin utilized. (3) Unknown purity, but product contained 6.8% ash and 15.6% ether extract.

dry weight of DDGS is contributed by yeast cell biomass (Ingledew, 1999). Beta-glucans, mannan-oligosaccharides, chitin and proteins are biologically important fractions of yeast cell walls and many of these compounds are capable of stimulating phagocytosis (Stone, 1998). Yeast cells also contain nucleotides, glutamate and other amino acids, vitamins and trace minerals, which may also affect the activity of the immune system when fed to pigs (Stone, 1998).

Whitney, Shurson and Guedes (2006a, b) conducted two experiments to investigate if adding 10 or 20 percent DDGS to the diet of young growing pigs was effective in reducing the prevalence, length or severity of intestinal lesions produced by porcine proliferative enteropathy (ileitis) after pigs were challenged with *Lawsonia intracellularis*. These results indicated that dietary inclusion of DDGS may aid in resisting a moderate ileitis challenge similar to an approved antimicrobial regimen, but under more severe challenges, DDGS may not be effective.

Knott *et al.* (2005) studied the effects on weaned pigs of feeding spray-dried CDS, a spray-dried, high lipid fraction of CDS and a residual solubles fraction of CDS after the lipid was removed. Pigs fed diets containing either dried condensed distillers soluble or the residual soluble fraction had growth performance that was similar to that of pigs fed diets containing carbadox, but lower ADG and ADFI than pigs fed diets containing spray-dried porcine plasma. Feeding the diet containing residual solubles and the positive control diet containing spray-dried porcine plasma resulted in greater villi height and villi height:crypt depth ratio compared with pigs fed diets containing carbadox.

More recently, Perez and Pettigrew (2010) showed that feeding diets containing up to 20 percent DDGS does not prevent pigs from bearing an *E. coli* infection or showing clinical signs of the disease. However, feeding DDGS diets appears to delay the shift from commensal to β-haemolytic coliforms in faeces, speed the excretion of β-haemolytic bacteria and recovery, as well as promote more stable and uniform gut microbiota.

In conclusion, results from one study indicate that feeding a diet containing DDGS may be effective in reducing the incidence, severity, and length of lesions caused by a moderate *Lawsonia intracellularis* infection. The mode of action of this response is unknown, but it seems that there are compounds in a fraction of CDS that may improve villi height:crypt depth ratio in the proximal portion of the small intestine. It is also appears that feeding DDGS diets has beneficial effects in modulating the gut microbiota when weaned pigs are challenged with β-haemolytic coliforms.

EFFECTS OF DDGS ON NUTRIENT CONCENTRATION AND GAS AND ODOUR EMISSIONS OF SWINE MANURE

Odour and gas characteristics of swine manure, and energy, N and P balance were measured in pigs fed a maize-soybean meal diet or a diet containing DDGS (Spiehs *et al.*, 2000). Dietary treatment had no effect on H_2S, NH_3 or odour detection levels over the 10-week experimental period. Pigs fed the DDGS-containing diets had greater N intake, but ADFI and percentage N retention were not different between treatments. Feeding DDGS-containing diets tended to increase N excretion, but P retention did not differ between dietary treatments. Gralapp *et al.* (2002) fed diets containing 0, 10 or 20 percent DDGS to finishing pigs to determine the effects on growth performance, manure characteristics and odour emissions. There were no differences in total solids, volatile solids, chemical oxygen demand or total N or P concentration of manure among dietary DDGS levels. However, there was a trend for increasing odour concentration with increasing dietary levels of DDGS. More recently, Li, Powers and Hill (2010) compared the effects of feeding three diets (maize-soybean meal-based control diet, diet containing 20 percent DDGS with inorganic trace mineral sources, and a diet containing 20 percent DDGS with organic trace mineral sources) on ammonia, hydrogen sulphide, nitrous oxide, methane and non-methane total hydrocarbon emissions from growing-finishing pigs. Emissions of hydrogen sulphide, methane and non-methane total hydrocarbon emissions increased when pigs were fed DDGS diets, but adding organic sources of trace minerals to diets alleviated the adverse effects of DDGS on hydrogen sulphide emissions.

Inclusion of DDGS in diets fed to lactating sows also reduced the concentration of P in the faeces (Hill *et al.*, 2008b), but it is unknown if total P excretion was reduced, because DM digestibility of the diets was not determined. Feeding diets containing 40 percent DDGS to gestating sows reduced apparent DM digestibility of the diet and increased faecal output, but did not affect the total volume of slurry produced or N, P or K output in slurry (Li, Powers and Hill, 2010; Li *et al.*, 2011).

The effects of extrusion and inclusion of DDGS on nitrogen retention in growing pigs has also been determined by Dietz *et al.* (2008). As DDGS increased in the diet, faecal N concentration increased but the concentration of N in the urine decreased. Extrusion and inclusion of DDGS in the diet reduced the amount of N digested per day, but N digestibility as a percentage of N intake decreased when DDGS was included in the diet but was not affected by extrusion. Nitrogen retention also tended to be reduced by dietary inclusion of DDGS and was reduced by extrusion, resulting in a trend for reduced net protein utilization from extrusion. These results suggest that extrusion of diets containing DDGS may reduce N retention in growing pigs.

Four experiments were conducted to evaluate effects of diet formulation method, dietary level of DDGS and the use of microbial phytase on nutrient balance in nursery and grower-finisher pigs (Xu *et al.*, 2006a, b; Xu, Whitney and Shurson, 2006a, b). Nursery pigs were fed a maize-soybean meal control diet or a diet containing 10 or 20 percent DDGS and formulated on a total P basis or on a relative bio-available P basis, using a relative P bio-availability estimate of 90 percent for DDGS (Xu, Whitney and Shurson, 2006a). Phosphorus digestibility, retention and faecal and urinary excretion were similar for pigs fed the control diet and pigs fed the DDGS containing diets. Within dietary DDGS levels, pigs fed diets formulated on a total P basis had greater P retention and urinary P excretion than pigs fed diets formulated on a relative bio-available P basis. No differences were observed among treatments in the concentration of soluble or insoluble P in the manure. It was also shown that pigs fed a DDGS-containing diet without or with phytase had lower DM digestibility compared with pigs fed a maize-soybean meal diets without or with phytase, which resulted in the excretion of greater manure volume (Xu *et al.*, 2006b). However, N digestibility and excretion were not affected by dietary treatment, but phytase improved P digestibility and reduced P excretion.

Diets without DDGS or with 20 percent DDGS and phytase were formulated to contain Ca:available P ratios of 2.0:1, 2.5:1 and 3.0:1 to determine the optimal Ca:available P ratio in nursery diets (Xu *et al.*, 2006a).

Dietary DDGS and phytase resulted in greater P digestibility and reduced P excretion compared with maize-soybean meal diets containing no DDGS or phytase. Nitrogen and Zn digestibility were not affected by dietary treatments, but Ca digestibility was greater for maize-soybean meal diets than for DDGS diets. There were no interactions between dietary DDGS and phytase and the Ca:available P ratio, suggesting that the range of Ca:available P ratios (2:1 to 3:1) established by NRC (1998) are acceptable when 20 percent DDGS and phytase are added to nursery diets to minimize P excretion in the manure.

The effects of feeding maize-soybean meal diets containing 20 percent DDGS and phytase on DM, N and P digestibility in growing-finishing pigs have also been measured (Xu, Whitney and Shurson, 2006b). Unlike for nursery-age pigs, feeding diets containing DDGS without or with phytase resulted in no change in DM digestibility and DM excretion. Although N digestibility was not affected by dietary treatment, there was a trend for reduced N excretion when phytase was added to the diets.

KNOWLEDGE GAPS AND FUTURE RESEARCH NEEDS

Much has been learned over the past decade about the nutritional value, optimal dietary inclusion rates, benefits and limitations of using DDGS in swine diets. However, current record high feed prices, as well as the abundant supply and cost competitiveness of DDGS, requires more evaluation of diet formulation approaches to further increase its use in swine diets without the risk of reduced performance. As high dietary inclusion rates of DDGS continue to be used, new feed formulation strategies and the use of additives effective in reducing the negative effects of DDGS on pork fat quality need to be developed. Nutritional tools need to be developed to provide accurate assessments of value differences among DDGS sources and provide accurate estimates of nutrient loading values (energy and digestible amino acids) for use in more accurate diet formulation as a means to manage variability in nutrient content and digestibility among sources. Further research is also needed to evaluate feed processing technologies and exogenous enzyme applications that can enhance energy and nutrient digestibility by focusing on the fibre component on distillers co-products. There appear to be potential health and immune system benefits from feeding distillers co-products to swine, which need to be further explored and understood. Finally, nutritional value and feeding applications for new distillers co-products need to be defined if they are to be used successfully in swine diets.

CONCLUSIONS

Dried distillers grain with solubles is the predominant maize distillers co-product used in swine diets. Although nutrient content and digestibility varies among DDGS sources, it is considered to be primarily an energy source (approximately equal to that of maize), but also contributes significant amounts of digestible amino acids and available phosphorus to swine diets in all phases of production. Energy digestibility of DDGS can be improved by grinding to reduce particle size, but other feed processing technologies need to be further evaluated for their potential benefits in improving nutrient digestibility, with particular focus on the insoluble fibre fraction. The use of exogenous enzymes and other additives have potential for also improving the nutritional value of DDGS, but their responses have been inconsistent. Mycotoxin levels in United States maize DDGS are typically low and reflect the prevalence in the grain used to produce ethanol and DDGS. Although sulphur levels in DDGS are variable, and some sources may contain levels exceeding one percent, there is no evidence that sulphur levels in DDGS are detrimental to pig health and performance. Research is underway to determine the impact, if any, of lipid oxidation in DDGS on pig health and performance, although initial evidence indicates that supplemental dietary antioxidants may be warranted to achieve optimal growth performance.

If high quality maize DDGS is used, approximately 30 percent can be included in diets fed to lactating sows, weanling pigs, and growing-finishing pigs, whereas 50 percent can be included in diets fed to gestating sows. Dietary inclusion of sorghum DDGS should be limited to 20 percent in weanling pig diets, but 30 percent may be included in diets fed to growing-finishing pigs. Maize HPDDG may be included in diets fed to growing-finishing pigs in quantities sufficient to substitute all soybean meal, but there are no data on the inclusion of maize HPDDG in diets fed to sows or weanling pigs. Maize germ can be included in diets fed to growing-finishing pigs in concentrations of at least 10 percent.

Carcass composition and eating characteristics of pork products are not influenced by the inclusion of DDGS, HPDDG or maize germ in diets fed to growing-finishing pigs. However, belly firmness is reduced and fat iodine values are increased by the inclusion of DDGS and HPDDG in these diets. It may therefore be necessary to reduce the dietary inclusion levels of these co-products in the diets fed during the final 3 to 4 weeks prior to slaughter, or to supplement diets with conjugated linoleic acid to minimize negative effects on pork fat quality.

There is some evidence that feeding DDGS diets may enhance gut health of growing pigs, but more research is needed to determine if this response is repeatable. Formulating DDGS-containing diets on a digestible P basis reduces manure P concentration, but, due to lower DM digestibility, manure volume is increased in pigs fed diets containing DDGS. Adding DDGS to swine diets seems to

have minimal, if any impact on gas and odour emissions from manure, and with the exception of the concentration of P, the chemical composition of manure is not changed if pigs are fed DDGS containing diets. The use of crystalline amino acids to balance the amino acid profile in DDGS diets is essential not only for achieving optimal performance but also for minimizing excess nitrogen excretion.

Crude glycerin is a co-product from the biodiesel industry and contains more energy than maize for swine. When available and economical, glycerin may be included in diets for sows by up to 9 percent, in weanling pig diets by at least 6 percent, and in diets for growing-finishing pigs by up to 15 percent. At these inclusion levels, no change in pig performance or carcass composition will be observed, but feed flowability may be reduced. However, it is important to measure sodium and methanol content of the sources to be fed to swine in order to adjust dietary inclusion rates if necessary.

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