Chapter 9

Nutritional value and utilization of wheat dried distillers grain with solubles in pigs and poultry

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ABSTRACT

Dried distillers grain with solubles (DDGS) are a co-product of ethanol production from starch cereals (mainly maize in North America and wheat in Europe), which contains approximately the non-starch or non-fermentable fractions of the grain. As more becomes available with increasing bio-ethanol production, DDGS is being included not only in diets for ruminants but also in pig and poultry diets. This review paper considers the introduction possibilities of wheat DDGS in poultry and pig diets. Nutrients content in wheat DDGS and digestibility vary among ethanol plants, reflecting the starch extraction process and drying of the residues after starch extraction. Most of the variability concerns amino acid (AA) contents and their standardized ileal digestibility (SID), affected by the occurrence of Maillard reactions, reflected in the lightness score (L) of wheat DDGS. Samples with low L values (<50) are dark and have the lowest nutritional value, both in pigs and in poultry. Lysine is the most affected AA, with contents ranging between 0.9 (dark) and 3.0 percent of crude protein (CP; N×6.25) for wheat DDGS. In parallel, lysine SID is also variable, with the lowest values observed in DDGS with low lysine level in CP. For the darkest products, lysine SID is close to zero. Energy digestibility varies in parallel with changes in lysine content and L values, but is more related to other nutrients such as dietary fibre, fat and residual starch contents. In addition, wheat DDGS can supply significant amounts of available phosphorus. DDGS from wheat can be used in diets for poultry and pigs; however, in relation with nutritional value variability, practical use should take into account correct energy values or lysine SID content in order to prevent any performance deterioration. Finally, only the light-coloured products are recommended for non-ruminants, and their introduction at high inclusion rates will contribute to reducing the energy value of the diet.

INTRODUCTION

In recent years, ethanol production, as a partial substitute for petrol, has rapidly increased (Windhorst 2007; ePURE, 2010; RFA, no date). Ethanol is produced via enzymatic breakdown of starch and yeast-controlled fermentation of glucose into ethanol. Second-generation ethanol production, based on cellulose, is still in a development phase. The first generation production is mainly based on sugar cane in Brazil and maize in the United States, whereas in Canada and Europe wheat, triticale or barley are used in ethanol plants. Dried distillers grain with solubles (DDGS) is the primary co-product of this production when based on cereals. Mainly used initially in ruminant feeds, this co-product has become more available for non-ruminants, reflecting the increased supplies and also better nutritional information about this co-product. However, knowledge of its characteristics, its nutritional value and its acceptability and practical utilization in feeds for monogastric animals is rather recent, especially for wheat DDGS. More abundant literature is available for maize DDGS, both for pigs (Stein and Shurson, 2009) or poultry (Batal and Dale, 2006). Thus, the objective of this review is to summarize recent results on wheat DDGS in poultry and pigs. It is partly based on the previous reviews of Cozannet *et al.* (2009, 2010d) and the results of a research project conducted in France on European wheat DDGS (Cozannet *et al.*, 2010a, b, c, 2011).

COMPOSITION AND CHEMICAL CHARACTERISTICS OF WHEAT DDGS

Ethanol production from wheat consists of extracting, hydrolysing and fermenting the starch fraction of the grain. It can then be assumed that the residue of that extraction that corresponds to the so-called wheat DDGS is more or less equivalent to the non-starch fractions of the grain. As for maize DDGS (Stein and Shurson, 2009), the wheat DDGS composition is then first dependent on the nutrient

MAIN MESSAGES

- **Wheat DDGS, a co-product of the wheat ethanol industry, contains high levels of crude protein (ca 30 percent), but with a low and variable content of lysine. This variability in lysine level is dependent on the ethanol production process and the heat damage occurring during the DDGS drying process.**
- **In both pigs and poultry, the ileal digestibility of lysine in DDGS is lower than in wheat, and is also quite variable, with the lowest values in heat-damaged products.**
- **Overall, heat-damaged DDGS should not be fed to non ruminants; the dark colour of such products is an indicator of their poorer nutritional value.**
- **The energy value of wheat DDGS for pigs or poultry is lower than for wheat and is dependent mainly on their dietary fibre content.**
- **Standard or high quality wheat DDGS can be included at high levels in poultry or pig diets (up to 30 percent) without marked detrimental effects on performance, as far as they are included in diets meeting the animals' overall nutrient requirements.**
- **Overall, wheat DDGS represents a valuable source of energy and protein for non-ruminant animals, but attention should be paid to the variable composition and nutritional value of DDGS when formulating diets.**
- **Wheat (and maize) DDGS will evolve over the near future, with more fractionation of the nutrients other than starch; an increased use of enzymes; improvements and diversification of ethanol production technologies—all these contributing new opportunities for feeding pigs and poultry.**

TABLE 1
Composition of wheat dried distillers grain with solubles (DDGS) and its comparison with wheat and maize dried distillers grain with solubles

	Wheat[1]	Wheat DDGS[2]		Maize DDGS[3]
		Mean	Min. – Max.	
Dry matter (DM)	86.8	92.7	89.3 – 94.4	88.9
Composition (as % of DM)				
Ash	1.8	5.0	4.6 – 5.7	5.8
Crude protein (N×6.25)	12.1	36.6	32.7 – 39.2	30.0
Crude fat	1.7	4.4	3.4 – 5.1	10.7
Crude fibre	2.5	7.6	6.1 – 9.0	8.6
Neutral detergent fibre (NDF)	14.3	30.1	25.4 – 35.3	41.5
Acid detergent fibre (ADF)	3.6	10.7	8.1 – 13.1	16.1
Acid detergent lignin (ADL)	1.2	3.2	2.1 – 4.5	
Starch	69.7	5.1	2.5 – 10.1	8.2
Sugars	2.8	4.0	2.4 – 7.2	
Gross energy (MJ/kg)[4]	16.20	18.67	18.24 – 19.10	20.21

Notes: (1) Sauvant, Perez and Tran, 2004. (2) n = 7; products with luminance >50; Cozannet *et al.,* 2010a. (3) n=12, for dry matter, ash, protein, crude fat, crude fibre, NDF, ADF – Spiehs, Whitney and Shurson, 2002; n = 10, for gross energy and starch – Pedersen, Boersma and Stein, 2007. (4) Gross energy is standardized for a 89% DM content.

composition of the grain. Consequently, the nutrients, except starch, would be expected to be approximately three fold higher in wheat DDGS than those in the original grain (Table 1).

However, in practice, the chemical composition of wheat DDGS is much more variable than in the original cereals, with large differences among ethanol plants according to the method of grain preparation, namely with or without previous dehulling; the fermentation process; the amount of soluble fractions blended with distillers grain; the duration and temperature of drying; and possible further fractionation of the non-starch fractions (separation of proteins, etc.) (Belyea, Rausch and Tumbleson, 2004). There are two main technologies in use, resulting in co-products with different starch content (Cozannet *et al.,* 2010a). The first involves entire grain grinding and fermentation, leaving a low-starch-content DDGS (<7%); whereas in the other process wheat bran is removed, leaving a higher-starch-content DDGS (>7%). In addition, reflecting the technical aspects among and within processes, the colour of DDGS can vary from light yellow to dark brown (Photo 1).

Measured with a Minolta colorimeter, luminance (L) values of 10 European wheat DDGS ranged from 43 (black products) to 63 (yellow products) in the study of Cozannet *et al.* (2010a). From their results it can be inferred that wheat DDGS with L values <50 have been overheated, with a high incidence of Maillard reactions. This agrees with previous recommendations for maize DDGS (Cromwell,

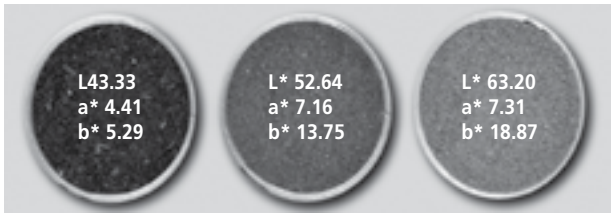


Photo 1
Range in colour of wheat DDGS; L, a* and b* correspond to lightness, red index and yellow index, respectively*

TABLE 2
Concentration of crude protein (CP) and amino acids (AA) in wheat and wheat dried distillers grain with soluble (DDGS)

	Wheat[1]	Wheat DDGS[2]	
		Mean	Min – Max
Crude protein (as % of DM)	12.1	36.6	32.7 – 39.2
Essential AA (% CP)			
Arg	5.1	4.3	3.7 – 4.6
His	2.3	2.1	1.9 – 2.2
Lys	2.9	2.3	1.7 – 3.0
Phe	4.7	4.5	4.3 – 4.6
Leu	6.8	6.5	6.2 – 6.8
Ile	3.6	3.5	3.4 – 3.5
Val	4.4	4.3	4.2 – 4.4
Met	1.6	1.5	1.4 – 1.5
Thr	3.1	3.0	2.9 – 3.1
Trp	1.2	1.1	1.0 – 1.2
Total	35.7	33.0	31.2 – 34.4
Non-essential AA	61.9	56.3	53.9 – 57.7

Notes: (1) Sauvant, Perez and Tran, 2004. (2) n = 7; products with luminance > 50 – Cozannet *et al*., 2010b.

Herckelman and Stahly, 1993; Pahm *et al.,* 2008a, b) defining an L value of 30 as the limit between overheated and standard products. In addition, only light-coloured DDGS have a sweet and fermented smell. Finally, the fermentation products correspond to 93 percent ethanol, 3 percent yeast and 4 percent glycerol (Hazzledine*,* 2008). Most of the non-ethanol components will be recovered in the DDGS residue and affect its composition.

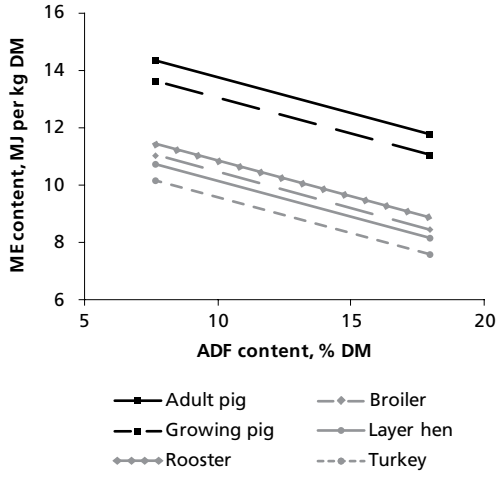
Average protein and essential amino acids (AA) contents for seven samples of European wheat DDGS are summarized in Table 2; these results agree with the data of Bandegan *et al.* (2009) obtained for Canadian wheat DDGS. According to the process, AA profiles (% N×6.25) should be in close agreement with those of the initial cereal. Nevertheless, yeasts used for starch fermentation represent an additional protein source, equivalent to about 5 percent of the total DDGS protein content (Ingledew, 1993). In addition, the level of soluble fractions added into distillers grain may be variable and influence the protein content and the AA profile. Despite these potential sources of variability, the AA profile is quite comparable in wheat and wheat DDGS, except for lysine and arginine, which are lower in DDGS (Table 2). In addition, even though crude protein (CP) contents are rather constant between wheat DDGS samples, the lysine and arginine levels in CP are highly variable, even in light products: 1.7 to 3.0 percent and 3.7 to 4.6 percent, respectively (Cozannet *et al.*, 2010b). Consequently, unlike wheat or its milling co-products, poor correlations exist between lysine or arginine contents (as percentage of dry matter (DM)) and CP content. In other words, CP content cannot be used as a single indicator of lysine or arginine levels in wheat DDGS. These assumptions are more obvious when dark DDGS samples are included in the relationship, with lysine level being as low as 1 percent of CP (Table 5).

The sum of crude fat, CP, neutral detergent fibre (NDF) (or total dietary fibre – TDF; Prosky *et al.*, 1985), sugars, starch and ash is usually about 100 percent on a DM basis, especially for the grain. In the case of wheat DDGS, it is only 85 to 90 percent, and even less in low-L-value samples (Table 1). No clear interpretation of this situation is available: the presence of Maillard reaction components not included in the above chemical analyses may (partly) explain the difference. Some sources also indicate a sum higher than 100 percent, probably due to analytical mistakes and an overestimation of the dietary fibre fractions that can contain proteins (Stein *et al.,* 2006; Table 5). Sodium sulphite may be used in order to prevent this difficulty and to achieve lower NDF values (Kleinschmit *et al.*, 2006). This phenomenon is most important in the darkest samples with high rates of Maillard reactions, and nitrogen in NDF or acid detergent fibre (ADF) may then vary considerably between light and dark products (Table 5). For the same reasons, the analysis of lysine may be complicated and the interpretation of analytical results quite complex in connection with the blockage of a variable fraction of the lysine (Pahm *et al.*, 2008a, b; Cozannet *et al.*, 2011). Again, these difficulties are most important for low-L-value wheat DDGS. Overall, analytical difficulties are quite frequent for wheat and maize DDGS, and the interpretation of the results may be difficult. This also means that the DDGS chemical parameters measured cannot always be used for predicting accurately nutritional values such as net energy (NE) content of this co-product.

ENERGY VALUE OF WHEAT DDGS

Gross energy content is higher in wheat DDGS than in wheat (18.7 vs 16.2 MJ/kg; Sauvant, Perez and Tran, 2004; Table 1) due to the higher fat and CP contents. But, as for maize DDGS, and due to their variation in nutrient content and their high dietary fibre (DF) content, the metabolizability of energy in cockerels or the digestibility coefficient of energy in young or adult pigs are markedly lower for wheat DDGS than for wheat (minus 20 points) with digestible (DE) or metabolizable (ME) values lower for wheat DDGS than for wheat (minus 3 to 4 MJ ME/kg). The average energy values with European DDGS for pigs and poultry are reported in Tables 3 and 4. In addition, the energy values

FIGURE 1
Effect of ADF content of wheat DDGS on ME value (corrected for zero N balance) in pigs and poultry



Source: Adapted from Cozannet *et al.*, 2010a, c; R^2 = 0.91; RSD = 0.57.

of wheat DDGS are variable according to species and physiological stage, with most of the variation related to the DF content. In the case of ADF used as predictor of the DF content, Figure 1 indicates that the ME values are reduced by 0.24 MJ for each 1 percent increase in ADF; the coefficient does not differ significantly between the different groups of animals. This figure also illustrates that the ME values differ between animal species and physiological stages, with higher values in pigs than in poultry and also lower energy values in the growing animal (i.e. broilers or growing pigs) than in adults (i.e. cockerels or sows).

Overall, it can be concluded that the high DF content of DDGS penalizes their energy value, with a subsequent preferential use of these co-products in low-energy diets or in animals with greater ability to use the high DF feeds efficiently (adult pigs, for instance). These comparisons between species and physiological stages also illustrate that the relative energy values of ingredients are variable, with fibre-rich ones being better used in animals able to efficiently degrade the DF fractions of the feed or to tolerate higher DF levels in the feed (pigs vs poultry; adult vs young).

The DE or ME concepts have been used above for estimating the energy values of DDGS in order to compare the energy values on a common basis. There is no NE system available for poultry, while it is widely used in pigs with, as for any ingredient, a calculation of the NE value from DE value and crude fat, starch, CP and CF measurements (equation no. 4 in Noblet *et al.*, 1994; see also EvaPig, 2008). In connection with its high DF and CP contents, the NE/ME ratio in wheat DDGS is rather low (61 percent vs 78 percent for wheat; EvaPig, 2008) with a subsequent energy value expressed as a percentage of the energy value of wheat that is markedly lower in NE than in the DE or ME systems (Table 4). In practice, this means that for ingredients like DDGS, the NE system should be preferred, at least for pigs.

TABLE 4
Energy digestibility and energy values of wheat dried distillers grain with solubles (DDGS) in growing and adult pigs

	Growing pig	Adult pig
Energy digestibility (%)	69.5	74.4
Energy values (MJ/kg)		
DE	12.96	13.86
ME	12.17	12.93
NE	7.89	8.77

Notes: DM content is standardized at 89%; n = 7; products with luminance > 50; DE = Digestible energy; ME = metabolizable energy; NE = net energy. *Source*: Cozannet *et al.,* 2010a. For comparison, the ME values of wheat average 13.7 and 13.9 MJ per kg (89% DM) in growing and adult pigs, respectively.

PROTEIN VALUE OF WHEAT DDGS

The protein value of ingredients for monogastric animals is usually estimated as the ileal digestibility of N and AA at the end of the small intestine, and the values are standardized to take into account the "basal" endogenous N and AA losses not related to the quantities of protein and AA included in the ingredients (Stein *et al.*, 2007). The so-called standardized ileal digestibilities (SID) of essential AA of wheat DDGS measured with caecectomized roosters and ileo-rectal anastomized pigs are presented in Table 5. Results indicate that most AA in wheat DDGS have a SID that is approximately 5 to 10 percentage units less than for wheat; that is mainly a consequence of the greater concentration of dietary fibre in DDGS than in cereals. But the difference is more accentuated for lysine (minus 20 points), reflecting presumably a loss in digestibility due to the drying of DDGS. In addition, the SID of

TABLE 3
Apparent metabolizable energy corrected for zero nitrogen deposition (AMEn) and AMEn/gross energy ratio in wheat dried distillers grain with solubles (DDGS) fed to cockerels, layers, broilers or turkeys

	Rooster		Layer		Broiler		Turkey	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range
AMEn/GE,%	51.3	47.3–55.1	48.1	46.4–49.8	48.2	41.9–56.5	45.5	42.0–49.7
AMEn, MJ per kg	9.55	8.76–10.08	8.94	8.64–9.33	8.96	7.78–10.35	8.49	7.99–9.11

Notes: DM content is standardized at 89%; n=7; products with luminance > 50. *Source*: Cozannet *et al.,* 2010c. For comparison, the AMEn value of wheat in cockerels averages 12.8 MJ/kg at 89% DM; Sauvant, Perez and Tran, 2004).

TABLE 5
Standardized ileal digestibility of crude protein and amino acids (AA) of wheat dried distillers grain with solubles (DDGS) in caecectomized cockerels and ileo-rectal anastomized pigs

	Cockerel	Pig
Crude protein	82	82
Essential AA		
Arginine	78	88
Histidine	78	84
Lysine	61	69
Phenylalanine	88	89
Leucine	83	85
Isoleucine	79	76
Valine	81	79
Methionine	81	79
Threonine	73	80
Tryptophan	75	82
Total	78	82
Non-essential AA	84	84

Notes: n=7; products with luminance > 50. *Sources*: Cozannet *et al.*, 2010b, 2011.

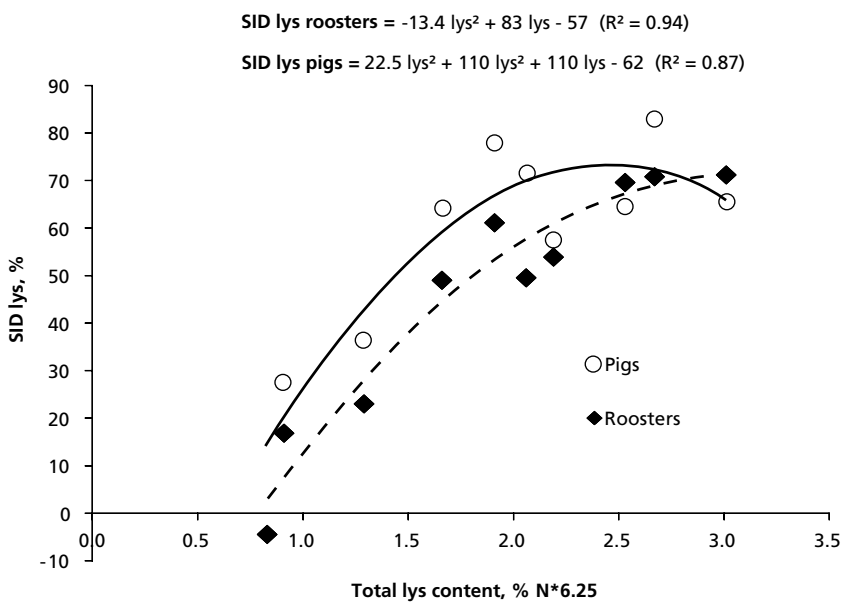
lysine appears highly variable (Figure 2), since it ranged from 0 to 71 percent in roosters (Cozannet *et al.*, 2011) and from 9 to 83 percent in pigs (Cozannet *et al.*, 2010b) for 10 samples of wheat DDGS; the lowest values were observed in dark products with the probable occurrence of Maillard reactions (Table 6). These results suggest that colour determination might be a quick and reliable method for estimating the lysine digestibility of DDGS or, at least, identifying DDGS sources with a poor AA digestibility. Nevertheless, Cozannet *et al.* (2010b; 2011) obtained a poor relationship between lysine digestibility and colour score for 10 samples of wheat DDGS, either in pigs or in roosters.

A better prediction was obtained with lysine content in CP according to a quadratic regression model (Figure 3) or a linear-plateau regression model with breakpoints of 1.9 percent lysine in CP either in roosters or in pigs, corresponding with 63 percent and 68 percent plateau SID values, respectively. The relationship between L values and lysine content of CP indicates that this breakpoint lysine percentage corresponds to an L value of 50. Overall, these data suggest that dark products with L values <50 have low and variable lysine content in CP and low and variable lysine SID values in both pigs and poultry. Consequently, they should not be used in feeds for non-ruminants. For light-coloured products, the situation is less critical, but attention should still be paid to lysine, which is less digestible than most other AAs, and to the lysine content of CP, which remains rather low in comparison with the requirements of growing birds or pigs.

MINERALS AND PHOSPHORUS VALUE OF WHEAT DDGS

As for the other nutrients, minerals are three times more concentrated in wheat DDGS than in wheat grain (Table 7). This is particularly true for potassium, calcium and phosphorus. However, the sodium content is greater than what could be expected from the inherent mineral content in

FIGURE 2
Relationship between lysine content in wheat DDGS (as % of crude protein) and lysine digestibility in pig and in poultry (SID lys)



Source: Adapted from Cozannet *et al.*, 2010c, 2011.

TABLE 6
Digestive utilization of nutrients of wheat dried distillers grain with solubles (DDGS) in poultry and pigs: impact of colour

	Dark (1)	Light (1)
Lightness (L value)	46.2	57.4
Dietary fibre (as % of DM)		
NDF	33.6	30.1
ADF	18.4	10.7
Crude protein in ADF (as% of DM)	6.8	1.1
Lysine content (% of N×6.25)	1.01	2.29
Amino acid digestibility in rooster (%)		
Crude protein	59.8	81.8
Non-essential AA	64.1	83.9
Essential AA	51.0	78.0
Lysine	12	61
Amino acid digestibility in pig (%)		
Crude protein	66.7	81.9
Lysine	24	69
AMEn value in poultry (MJ/kg) (2)		
Rooster	8.38	9.55
Layer	7.62	8.94
Broiler	8.31	8.96
Turkey	7.25	8.49
DE value in pigs (MJ/kg) (2)		
Growing pig	11.18	12.96
Adult pig	11.99	13.86

Notes: AA = amino acid; ADF = acid-detergent fibre; NDF = neutral-detergent fibre; AMEn = apparent metabolizable energy corrected for zero nitrogen deposition. (1) 3 dark products and 7 light products. (2) DM content is standardized at 89% for AMEn and DE values.
Sources: Cozannet *et al.,* 2010a, b, c, 2011.

wheat grain. This extra source of sodium derives from sodium hydroxide (NaOH) used in the industrial ethanol process. For sulphur, even if no published data is available for wheat DDGS, those published for maize DDGS (Waldroup *et al.*, 2007) show that extra sulphur is related to the addition of sulphuric acid (H_2SO_4) in the process. It would be similar in some plants producing wheat DDGS. For poultry, a sodium imbalance could lead to lower feed intake (low-sodium diet) or greater water consumption (high-sodium diet), which may increase the incidence of wet litter or dirty eggs. These values should also be taken into account when calculating the electrolytic balance of the diets.

Phosphorus is mainly present in the form of phytic phosphorus in wheat (Table 7; 65 percent) which is not digestible in pigs or poultry (no digestive phytase activity). As reported by several authors (Waldroup *et al.*, 2007), there could be a heat destruction of phytate during drying, but mainly a phytate hydrolysis by *Saccharomyces cerevisiae* during the fermentation stage (Martinez-Amezcua, Parsons and Noll, 2004.). Thus, Widyaratne and Zijlstra (2007) demonstrated a partial hydrolysis of inositol phosphate 6 (IP6) of wheat used for ethanol production into lower inositol phosphates (IP5, IP4, etc.) in wheat DDGS. The same result has been confirmed in 7 wheat DDGS samples (Table 7; P. Cozannet, unpublished data). Thus, wheat DDGS phosphorus digestibilities ranging from 50 to 62 percent were measured in pigs (Nyachoti *et al.*, 2005; Widyaratne and Zijlstra, 2007; Yañez *et al.*, 2011); these values are in agreement with those of Pedersen, Boersma and Stein (2007) for maize DDGS. However, there is a lack of data for poultry, even if we can hypothesize, in parallel with pig data, that wheat DDGS phosphorus availability should be at least 60 percent. When considering these data, one should be aware that several factors could affect phosphorus content and digestibility. Thus, in the case of maize DDGS, the extent of addition of solubles to the wet grain prior to drying affects the phosphorus

TABLE 7
Mineral composition and phosphorus digestibility of wheat dried distillers grain with solubles (DDGS) and comparison with wheat and maize dried distillers grain with solubles

Mineral content (as% of DM)	Wheat(1)	Wheat DDGS(2)		Maize DDGS(3)
		Mean	Range	
Sodium	0.01	0.36	0.24 – 0.63	0.22
Sulphur	0.17	0.65	–	0.84
Potassium	0.46	1.07	0.94 – 1.13	0.96
Calcium	0.08	0.22	0.14 – 0.39	0.08
Magnesium	0.12	0.29	0.26 – 0.31	–
Zinc	0.31	–	–	–
Copper	0.06	–	–	–
Total Phosphorus	0.37	0.86	0.80 – 0.97	0.70
Phytic Phosphorus	0.24	0.23	0.07 – 0.45	–
Phytic P/Total P (%)	65	27	8 – 54	–
Pig P digestibility(4) (%)	30		50 – 62	59
Poultry P availability (%)	58	–	–	62

Notes: (1) Data from Sauvant, Perez and Tran, 2004. (2) Unpublished data from Cozannet and co-workers; n = 7; products with luminance > 50; completed with average values for magnesium and sulphur from Sauvant, Perez and Tran, 2004, and Piron *et al.,* 2008. (3) Data from Waldroup *et al.,* 2007, based on a literature review. (4) Wheat P digestibility values 30% and 45% without and with endogenous wheat phytase – Sauvant, Perez and Tran, 2004; wheat DDGS values from Nyachoti *et al.,* 2005, Widyaratne and Zijlstra, 2007, 2008, and Yañez *et al.,* 2011; maize DDGS value from Pedersen, Boersma and Stein, 2007. n = 10.

content because the solubles contain three times more phosphorus than wet grain (Martinez-Amezcua *et al.*, 2007). The drying temperature can also improve maize DDGS phosphorus bio-availability. For instance, Martinez-Amezcua and Parsons (2007) showed an increase from 69 percent in the control DDGS to as much as 91 percent in the highest-heat treated DDGS sample. But, with these highest drying temperatures, lysine digestibility was markedly depressed. Finally, in the case of wheat DDGS, phytic phosphorus is mainly concentrated in the aleurone layer (Pointillart, 1994), which is one of the outer membranes of the grain, while phytic phosphorus is located mainly in the germ in maize. Some ethanol plants remove the bran from the wheat grain at the beginning and re-introduce it at the end of the process, thus leading to less hydrolysis of phytate phosphorus (52 and 54 percent Phytic P/Total P ratio for this type of process; P. Cozannet and co-workers, unpublished data, Table 7). We can then hypothesize that such wheat DDGS would have a lower phosphorus digestibility, probably close to the values for wheat or wheat gluten (30 and 28 percent P digestibility in pigs, respectively; Sauvant, Perez and Tran, 2004).

PERFORMANCE IN POULTRY AND PIGS FED WHEAT DDGS

Most results on performance of poultry and swine fed DDGS concern maize DDGS, and due to the relative similarity between wheat and maize DDGS, the expected performance and recommendations for wheat DDGS should be close to those for maize DDGS. However, it should be noted that the energy value for maize DDGS is higher than for wheat DDGS due to differences in fat content. For the same reason, the impact of feeding wheat DDGS on fat quality (i.e. hardness or fatty acids composition of fat) should be less than with maize DDGS. In a first series of experiments in which diet formulation did not take into account the actual nutritional values for digestible lysine content or for ME content, results in broilers or turkeys indicated an increase in feed conversion ratio (FCR) with increased levels of maize or wheat DDGS (Lumpkins, Batal and Dale, 2004; Métayer *et al.*, 2009). In addition, these effects were more pronounced in younger than in older birds (Robertson, 2003). One limitation in feeding such diets might be the reduced feed intake due to the high DF presence in the diets, with greater detrimental effects in young birds (Friesen *et al.*, 1991), but more probably a limitation might be the AA shortage or deficiency due to the low and variable availability of amino acids in DDGS associated with lower energy intake (Widyaratne and Zijlstra, 2007), all of which limit protein and body-weight gain. In contrast, a second series of trials indicated that rather high levels of DDGS can be included if the actual AA and energy values of DDGS are considered in the formulation of diets with appropriate supplementations (of AA and/or energy) in order to meet animal requirements (Waldroup *et al.*, 1981). Based upon such results, Lumpkins, Batal and Dale (2004) suggested that a safe inclusion level of maize DDGS was 6 percent in the starter period and 12 to 15 percent in the grower and finisher periods for broilers, whereas Thacker and Widyaratne (2007) suggested that wheat DDGS could be incorporated safely up to 15 percent. Finally, more accurate lysine content estimates would allow higher incorporation levels. For instance, Wang *et al*. (2007) did not show any detrimental effect of maize DDGS inclusion levels up to 25 percent in broilers, in the grower and finisher periods, with low density diets formulated on levels of digestible amino acids. Similarly, for turkey hens, Robertson (2003) demonstrated that 10 percent maize DDGS can be fed in the growing-finishing phases with no detrimental effects on growth performance as long as the actual energy value or lysine levels are considered.

Corresponding data have been reported for swine (Avelar *et al*., 2010). In the review of Stein and Shurson (2009), the inclusion of 10, 22.5 or 30 percent maize DDGS did not affect average daily gain (ADG) in 10 experiments conducted on piglets. Nevertheless, in 10 trials, the average daily feed intake (ADFI) was reduced in two trials and FCR reduced 5 trials. The analysis of data from 25 experiments with grower-finisher pigs fed diets containing maize DDGS suggests that performance is maintained up to 20 percent DDGS in the diet (Cromwell *et al.*, 1983; Stender and Honeyman, 2008). Similarly, the inclusion of 25 percent wheat DDGS (characterized for its energy and protein values) in a wheat and pea-based diet fed to pigs from 52 to 85 kg did not affect ADFI, ADG or FCR (Widyaratne and Zijlstra, 2007). In contrast, inclusion of 0, 5, 10, 15, 20 or 25 percent wheat DDGS in wheat-soybean meal-based diets fed to grower pigs (20 to 51 kg) linearly reduced ADG and ADFI, whereas FCR was not affected (Thacker, 2006). The low quality of wheat DDGS used in the Thacker (2006) study and the BW range of pigs might partly explain these results. Finally, it has been reported in young pigs that the inclusion of 10 percent of maize DDGS can positively affect gut health by reducing the prevalence and severity of lesions due to *Lawsonia intracellularlis* challenge (Whitney *et al.*, 2002). Up to now, no similar effects have been demonstrated with wheat DDGS.

In summary, the performance achieved with wheat DDGS is usually maintained at rather high inclusion rates of DDGS, in either poultry or pigs, if the nutritional value of the diet is maintained. However, the performance of young animals may deteriorate due to primary effects on feed intake, with possible accentuation of the effects due to low availability of amino acids (particularly lysine).

TABLE 8
Digestibility of dried distillers grain with solubles (DDGS) and performance improvement of animals by exogenous enzyme addition

Source	Species	DDGS type	Parameter	Change	Enzyme activities
Yáñez *et al.,* 2011	pig	Wheat/Maize DDGS	Amino acids, energy and phosphorus digestibility	Phosphorus digestibility +13%	Phytase + xylanase
Jones *et al.*, 2010	pig	Maize DDGS	Performance	Average daily gain (ADG) -2.4%; Average daily feed intake (ADFI) -5.6%	α-Galactosidase + galactomannanase + β–glucanase + xylanase
				ADG -7.2%; ADFI -9.1%	Galactomannanase + xylanase
				ADG +1.8%; ADFI +2.2%	Xylanase
Emiola *et al.*, 2009	pig	Wheat DDGS	Nitrogen energy digestibility	Nitrogen digestibility +6.5%; Energy digestibility +12.3%	Xylanase + glucanase + cellulase
				Nitrogen digestibility +9.6%; Energy digestibility +12.6%	Xylanase + glucanase + cellulase (dose 2X)
			Performance	ADG +6.6%; ADFI -1.3%	Xylanase + glucanase + cellulase
				ADG +14.4%; ADFI -1.6%	Xylanase + glucanase + cellulase (dose 2X)
Wang *et al*., 2009	pig	Maize DDGS	Nitrogen and energy digestibility	DM digestibility +7.9%	Mannanase
				DM, N and GE digestibilities +2.0%, +6.1% and +6.7% respectively	Mannanase + galactosidase + mannosidase
			Performance (8 weeks)	ADG +9.5%; FCR -14.3%	Mannanase
				ADG +8.4%; FCR -16.4%	Mannanase + galactosidase + mannosidase
Widyaratne, Patience and Zijlstra, 2009.	pig	Wheat DDGS	Performance	No change	Xylanase
Péron and Plumstead, 2009.	pig	Maize DDGS	Ileal nitrogen and amino acids digestibility, faecal energy digestibility	Nitrogen and amino acids digestibilities from +4 to +8% and Energy digestibility +6%	Xylanase + phytase
Adeola *et al.*, 2010.	broiler	Maize DDGS	Energy digestibility	Energy digestibility +6.0%	Xylanase + amylase
Olukosi, Cowieson and Adeola, 2010.	broiler	Maize DDGS	Performance	ADG +4.6%	Phytase
			Energy and nitrogen digestibility	Nitrogen digestibility +11.7%	Phytase + xylanase
Oryschak *et al.,* 2010a.	broiler	Rice DDGS	Amino acids digestibility	No change	Xylanase + glucanase + amylase + protease + invertase
Péron, Plumstead and Moran, 2009.	broiler	Maize DDGS	Performance (low-energy diet)	ADG +12.0%	Xylanase + amylase + protease + phytase
			Performance (high-energy diet)	ADG +5.0%	
Pérez Vendrell *et al.*, 2009.	broiler	Wheat or Maize DDGS	Energy digestibility	Energy digestibility +7.0% Apparent metabolizable energy	Xylanase + phytase
			Performance (high-energy diet)	ADG +4.0%	
Ghazalah, Abd-Elsamee and Moustafa, 2011.	layer	Maize DDGS	Performance	Egg production 2.4%; Egg mass 3.0%; FCR -2.8%	Glucanase + xylanase + amylase + polygalacturonase + protease

FEED ADDITIVES POTENTIAL FOR WHEAT DDGS

The foregoing sections indicate that the high DF content in DDGS represents a limiting factor in DGGS utilization by non-ruminants, with consequent low DE or apparent metabolizable energy (AME) values and lowered amino acid SID values. It would then be logical to attenuate this effect by supplementing diets with enzymes (Adeola and Cowieson, 2011). Numerous trials have studied the effect of carbohydrases on digestibility and performance in pigs and poultry. The most important results are summarized in Table 8. Numerous different enzymes have been tested in these studies, coupled with DDGS variable in quality and nutritional values. Overall, inconsistent results were observed among studies. For digestibility trials, no significant effect has been reported by Yáñez *et al.* (2010) regarding maize or wheat DDGS amino acids and energy digestibility in piglets. Only phosphorus digestibility has been improved by phytase addition. In contrast, studies by Wang *et al*. (2009) and Adeola *et al.* (2010) suggest a global improvement (+6 percent) of DE (pigs) or AME content (broilers) of maize DDGS supplemented with an exogenous enzyme mixture. Comparable improvements were also suggested in other trials (Perez Vendrell *et al.,* 2009; Olukosi, Cowieson and Adeola, 2010.). Supplementation of a multi-enzyme complex to diets containing wheat DDGS improved the digestibility of nutrients for finisher pigs (Emiola *et al.,*

2009), although the barley and maize contained in the diets might have also interacted with the multi-enzyme complex to contribute to the positive response. These results agree with the positive effects of xylanase on nutrient digestibility of wheat (Barrera *et al.,* 2004) and wheat co-products from flour milling (Yin *et al*., 2000; Nortey *et al.*, 2007, 2008).

For performance, enzyme effects depend on numerous parameters (Adeola and Cowieson, 2011). The study of Emiola *et al*. (2009) suggests a global improvement of performance in animals fed wheat DDGS diets. This positive effect of enzymes supplementation is consistent with the results of Wang *et al. (*2009), Jones *et al.* (2010) or Péron, Plumstead and Moran (2009) with pig diets and Olukosi, Cowieson and Adeola (2010) in poultry diets. In contrast, a meta-analysis carried out by Jacela *et al.* (2009) involving 4506 pigs (4 trials) and different enzyme types suggests no beneficial effect of enzymes in maize-soybean meal diets containing up to 60 percent maize DDGS. These latter results are corroborated by Widyaratne, Patience and Zijlstra (2009).

KNOWLEDGE GAPS AND FUTURE RESEARCH NEEDS

Wheat and maize DDGS are produced after a series of operations, the last being drying the product for its conservation, transportation and inclusion in dry compound feeds. In these stages of the process, and especially during the last stage, proteins and carbohydrates interact with the production of Amadori compounds generated by Maillard reactions. A major impact concerns the lysine fraction of the proteins, which can be destroyed or, at least, blocked and become unavailable for digestion. A major area of research would consist in producing methods for characterizing these compounds, studying their impact on the physical and nutritional parameters of wheat (and maize) DDGS, and proposing methods for a rapid and simple prediction of the nutritional value of DDGS, in addition to the classical prediction methods based on crude nutrients. This would also help the ethanol plants to optimize and standardize their procedures, not only for ethanol yield but also according to the nutritional value of their co-products (Oryschak *et al.,* 2010b). The important effects of drying on product physical properties and nutritional value also suggest the potential of infrared technologies as a quick and reliable tool for DDGS evaluation. This work has been started and is promising, but it still requires additional data for its complete achievement. In addition, the full potential of this raw material should be evaluated according to its proper nutritional values under a least-cost formulation constraint for diets fed to different animal species and stages of production. Environmental impact of biofuels production requires further work, as anticipated by Jarret *et al.* (2011) and Jarret, Martinez and Dourmad (2011) in terms of slurry properties, methane production and carbon footprint of DDGS used as animal feed. Further research would also be required for phosphorus evaluation (Widyaratne and Zijlstra, 2009), which review also pointed out a lack of references in the field of micronutrient and vitamin contents in wheat DDGS. The impact of wheat DDGS on the gut health of pigs and poultry should also be investigated in order to have a full overview of wheat DDGS potential in pig and poultry production. Finally, the production of ethanol from cereals will probably change in the near future due to fractionation of residues in order to produce protein-, fat-, DF- or micro-constituents-rich fractions, with consequent major changes in the composition of DDGS. This implies that DDGS characteristics for pigs and poultry nutrition will need to be defined precisely.

CONCLUSIONS

This review shows that wheat DDGS are a potential source of energy, protein and phosphorus for poultry and pig diets. However, nutritionists using DDGS in diets for monogastric species should be aware of the current variability in nutrient content and digestibility. Colour score appears to be a promising method for a rapid and reliable estimation of both energy and amino acids digestibility, or, at least, a rapid classification method of DDGS usable for non-ruminant animals. In practice, a better knowledge of product quality might prevent any detrimental effect in animals fed DDGS and allow higher inclusion levels. Our review also suggests that the processing of DDGS should be adapted and optimized in order to obtain a high quality co-product. Finally, quality and uniformity improvement might be expected for DDGS in the future, but there will also be diversification of the co-products with the production of more specific co-products (with or without hulls; protein concentrations; germ separation; etc.).

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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.

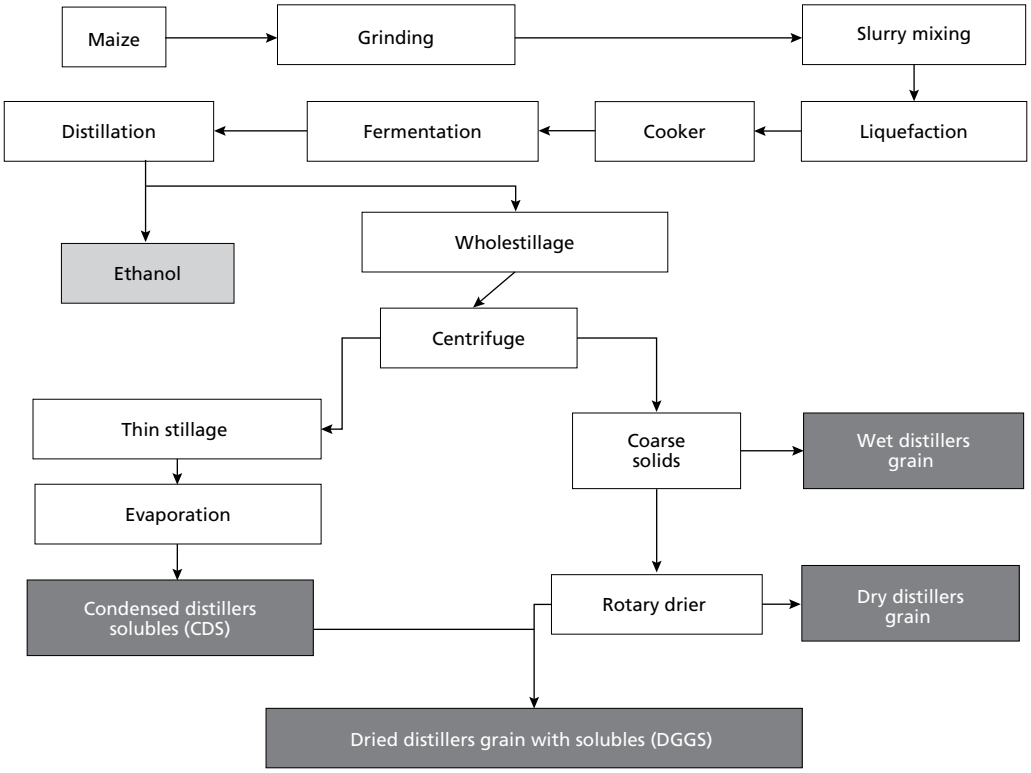
New ethanol and co-product production technologies are being implemented and include "back-end" oil extraction, and, to a much lesser extent, "front-end" fractionation, which are creating an increasing number of nutritionally diverse maize co-products, including high-protein DDGS (from fractionation), 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 producing 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.

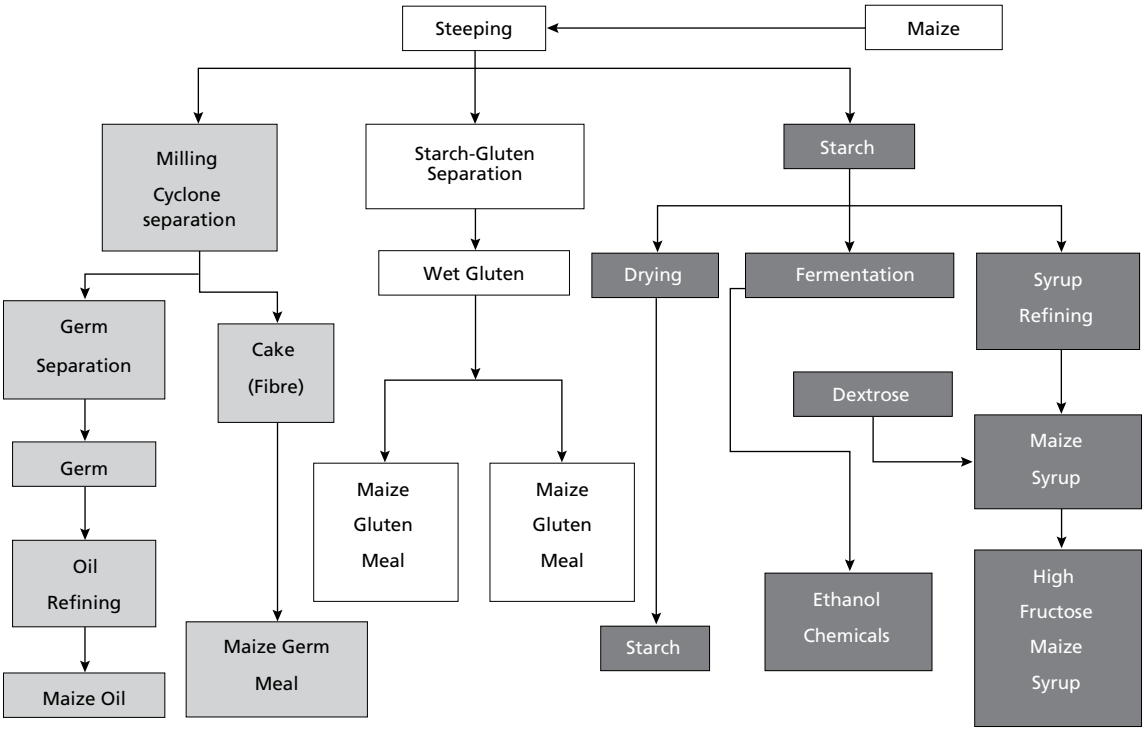
[1] Use of the word "glycerin" refers to the chemical compound or feedstuff while "glycerol" refers to glycerin on a biochemical basis relative to its function in living organisms. In addition, because glycerin is marketed on a liquid basis, all data are presented on an "as is" basis.

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 con-

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.

tent 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.

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.

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 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.

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 threefold, 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.

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.

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.

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

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.

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.

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.* (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.

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.

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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Chapter 11

Co-products from biofuel production for farm animals – an EU perspective

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ABSTRACT

The first part of this chapter presents a brief history of co-products from bio-ethanol production. Co-products, such as distillers grain, are well known for their beneficial nutrient composition and have been used in animal nutrition since the early 1900s. Recent animal trials have shown that wheat-based dried distillers grain with solubles (DDGS) can replace protein supplements like soybean or rapeseed meals in dairy cow diets up to about 200 g/kg dry matter (DM). In contrast to maize-based DDGS in North America, which is higher in fat, European wheat-based DDGS has not influenced milk fat content negatively. Moreover, trials with fattening bulls showed that DDGS as a main protein source is able to sustain high productive performance. Trials with grower-finisher pigs suggested that DDGS up to 200 g/kg diet did not influence growth performance, fattening and slaughtering variables. Similarly, laying intensity of hens as well as egg quality and health were not affected by inclusion levels ranging from 150 g/kg to 300 g/kg diet. Trials with broilers suggest that diets that contain more than 100 g/kg DDGS may reduce performance. Hence, it is recommended to add non-starch polysaccharide (NSP)-degrading enzymes (e.g. xylanase or xylanase mixed with other enzymes) to poultry diets rich in DDGS.

In the second part, a brief review and summary of data is presented on the use of glycerol for farm animals, with emphasis on ruminants, which will cover quality criteria for glycerol, rumen events and effects on feed intake and performance of dairy cows. As a fail-safe usage for glycerol in diets of all farm animals, methanol should be removed from the glycerol as far as technically possible. Glycerol at different purities may help to stabilize the hygienic quality of pelleted compound feeds without compromising pellet physical quality. Glycerol is a versatile feedingstuff, in particular for ruminants. Data on ruminal turnover of glycerol would suggest that it could replace rapidly fermentable carbohydrates and thus is not a direct competitor of propylene glycol. Previous studies have shown that glycerine may help to prevent ketoacidosis in high yielding dairy cows by increasing glucose precursors. Mature cattle can consume considerable quantities of glycerol (1 kg/day). However, greater dry matter intakes by cows supplemented with glycerine often did not result in increased milk or milk component yields. Further effort is thus required to fully explore the potential of glycerol in dairy cow diets, but type of diet and route of glycerol administration seem to play important roles.

In the third part, again putting an emphasis on ruminants, the feeding value of rapeseed products such as rapeseed meal (solvent-extracted) and rapeseed cake (mechanically extracted) is reviewed. Rapeseed meal compares well with soybean meal for dairy cows if fed on an isonitrogenous basis. Milk and milk component yields were similar for diets containing soybean meal or rapeseed meal. The value of rapeseed cake would benefit from standardization of the composition, because varying crude fat and crude protein concentrations makes the feeding value difficult to predict and could also affect storage stability of the cake. Even though the amino acid composition in rapeseed products is quite well balanced and favourable to non-ruminant animals, the sensitive reaction of pigs and poultry to glucosinolates in rapeseed meal and cake are still of concern. Therefore, it is recommended to add iodine, since glucosinolates act as antagonists. However, if glucosinolates are present in high concentrations, the negative effects may not be compensated, even if iodine is supplemented at high levels. Concluding, it is evident that a more widespread use of rapeseed meal and rapeseed cake in diets for pigs and poultry requires further reduction of glucosinolate levels.

Finally, energy utilization efficiency and sustainability of co-products from biofuel are addressed. To date, no definite regulations exist in order to assign emissions either to the main product or the co-product(s). Applying a causation principle, the producer or the responsible party should be accountable for all emissions. However, drying of DGS is only of interest if the products will be utilized as feedstuffs for animals, and thus emissions associated with processing of co-products are not of interest or necessity for biofuel producing companies.

MAIN MESSAGES

- **Efficient utilization of biofuel co-products is a key tool towards more sustainable biofuel production.**
- **Future research should quantify all activities in the processing of biofuel co-products in order to be able to evaluate carbon footprints.**
- **DDGS is a valuable protein supplement for ruminants and non-ruminants.**
- **Glycerine is a valuable energy supplement for ruminants and non-ruminants.**
- **Rapeseed meal and cake are valuable protein supplements for ruminants and non-ruminants.**

INTRODUCTION

Road transport fuels are considered to contribute about 18 percent of greenhouse gas (GHG) emissions in the EU (EEA, 2008; The Royal Society, 2008; Pinkney, 2009), with a consistent increase of about 1.6 percent per year (IEA, 2008a). Apart from more efficient vehicles and new transportation technologies, politics considered the use of biofuels as an essential element to reduce the emissions from fossil fuel and to decarbonize transport fuels. Some expert groups assessed the GHG reduction potential of biofuel as being at least 50 percent of fossil fuel emissions (e.g. CONCAWE, EUCAR and JRC, 2007; RFA, 2011). Estimations by IEA (2008a) expect an increase in world biofuel consumption from 24.4 million tonne oil equivalent (Mtoe) in 2006 to 94 Mtoe in 2020; 125 Mtoe in 2030; and approximately 210 Mtoe in 2050 (about 6 percent of the global need; IEA, 2008a). In 2020, about 55 Mtoe of biofuel will be consumed in the United States and the EU.

Fischer (2009) analysed the relationships among emerging biofuel development, food security and climate change, concluding that the additional non-food use of crops will have a significant impact on the world food system. Therefore, higher plant yields and the continuous development of the second generation of biofuels, produced from woody or herbaceous non-food plant materials, will receive increasing interest in the future (IEA 2008b).

The CO_2-saving effect or the carbon footprints (CF) of biofuel of the first generation depends on many factors, such as proper manufacturing, using the most appropriate feedstock, efficiency of feed production for fermentation, processing of co-products (e.g. drying), and further use of co-products. The utilization of co-products from biofuel production of the first generation, such as glycerine, oilseed cakes, meals and distillers grain with solubles in wet (DGS) or dried (DDGS) form is an important and controversial issue (see Windhorst, 2008; Fischer, 2009; Pinkney, 2009) that encompasses:

- contribution to the reduction of GHG emissions;
- pressure on land use; and
- competition between feed, food and fuel for crop yields.

Co-products may contribute to mitigate this conflict. They contain less fat and starch than oilseeds and cereal grains, respectively, but more fibre, proteins and minerals. The crude protein (CP) concentration of the co-products varies between 300 and 400 g/kg dry matter (DM) and is similar to some traditional feed protein sources. All environmental and nutritional aspects and calculations (e.g. CF) should consider the whole processing chain and all final products. Crutzen *et al.* (2008) estimated the N_2O release from agro-biofuel production without considering co-products and their utilization. They concluded that use of cereal grains and rapeseed for biofuel production is very ineffective and environmentally unfriendly. However, in a more recent publication on this subject the same authors performed a life-cycle analysis and came to a similar conclusion, namely that biofuel production may trigger a net increase in global warming (Mosier *et al.*, 2009).

The objective of this chapter is to analyse and summarize results of studies dealing with co-products from biofuel production in farm animal nutrition under European conditions.

CO-PRODUCTS FROM BIO-ETHANOL PRODUCTION

History

Distillers grain with solubles in wet and dry forms are the most important co-products of alcohol production from cereal grains. The starch of the raw material is mainly fermented to alcohol. The co-product comprises all the other components of the original substrate, such as CP, ether extract, fibre and ash as well as the CP from yeast used for fermentation. Traditionally, DGS at DM concentrations of 40–90 g/kg has been fed to ruminants, horses and pigs in close proximity to the distilleries.

At the end of the nineteenth century considerable data were available on the composition and the feed value of distillers grain (e.g. Schulze and Maerker, 1872, and Behrend and Morgan, 1880, both noted in Kellner, 1905). Already at that time it was known that the raw materials had the ability to influence the composition of DGS, with Maercker (1908) describing that the fermentation of cereal grains resulted in co-products (i.e. DGS) with the highest concentration of nutrients, while molasses fermentation gave the lowest nutritive value. On the basis of the composition of the original substrate and the alcohol output,

TABLE 1
Composition (g/kg dry matter unless stated) of distillery co-products (fresh and dried) of various origins

Source of co-product	Water (g/kg)	Crude protein	Crude fat (Ether extract)	Crude fibre	N-free extractives	Ash
Cereal grains, unspecified, dried	75	235	75	134	415	66
Maize grain, fresh	913	20	9	8	45	5
Dried	86	285	107	102	401	22
Molasses, fresh	922	19	–	–	40	19
Rye grain, fresh	922	17	4	7	46	4
Dried	100	165	82	162	478	13
Potatoes, fresh	943	12	1	6	31	7
Dried	100	243	37	95	408	117

Source: Kellner, 1905.

TABLE 2
Mean digestibility coefficients (ranges in parentheses) of distillery co-products for ruminants and pigs

Source of co-product	Organic matter	Crude protein	Crude fat (Ether extract)	N-free extract	Crude fibre
Ruminants					
Cereals grains, general	0.710 (0.600–0.810)	0.640 (0.490–0.800)	0.940 (0.920–0.940)	0.800 (0.540–0.850)	0.610 (0.410–0.920)
Maize grain	0.690 (0.660–0.720)	0.640 (0.610–0.670)	0.930 (0.910–0.950)	0.700 (0.700–0.710)	0.670 (0.640–0.700)
Rye grain	0.570 (0.450–0.680)	0.590 (0.520–0.650)	0.620 (0.600–0.640)	0.490 (0.440–0.540)	0.500 (0.370–0.620)
Pigs					
Cereal grains, general	0.580	0.780	0.560	0.510	0.360

Source: Kellner, 1905.

the same author calculated the composition of DGS. In his famous textbook *The Nutrition of Domestic Animals*, Kellner (1905) summarized the composition (Table 1), digestibility (Table 2) and starch units for different co-products of ethanol production.

Developments in distilling technology with consequences for composition and nutritive value of DGS during the last century were reported in several scientific publications (e.g. Naesi, 1985; Askbrant and Thomke, 1986), in animal feeding (e.g. Jensen, Falen and Chang, 1974; Firkins, Berger and Fahey, 1985), as substrate for ensiling (e.g. Abrams *et al.*, 1983, Flachowsky *et al.*, 1990) and were summarized in various textbooks in Germany (e.g. Kling, 1928; Nehring, 1949; Becker and Nehring, 1967; Kling and Wöhlbier, 1983; Menke and Huss, 1987; Jeroch, Flachowsky and Weißbach, 1993).

Due to the high demand for liquid fuels throughout Europe and the decreasing availability of fuels from fossil sources, the production of biofuel, including bio-ethanol, has gained more importance. The increased production capacity and the increasing number of large biofuel plants has resulted in large amounts of DGS. It is unrealistic to distribute large quantities of DGS beyond the immediate vicinity of a biofuel plant. Due to the short shelf life of DGS, a large proportion is dried and used as dried distillers grain with solubles (DDGS). The nutritional quality of DGS and DDGS varies considerably, reflecting the variability of the feedstocks, the diversity of the production processes and the proportion of solubles that are included in the final product (Belyea, Rausch and Tumbleson, 2004; Losand *et al.*, 2009; Zijlstra and Beltranena, 2009). Intensive research on the use of distillers grain—mostly maize-based—in livestock has been conducted in North America over the past years (reviewed i.a. by Klopfenstein, Erickson and Bremer, 2008; Schingoethe *et al.*, 2009). However, experiments that examine the nutritional value of DDGS common in Europe, based on wheat, barley or rye, or mixtures of these grains, are rare (Franke, Meyer and Flachowsky, 2009; Aldai *et al.*, 2010; Meyer *et al.*, 2010; Noblet *et al.*, this volume).

Nutritive value and feeding to ruminants

The chemical composition and energy concentration of DGS and DDGS from different grains are presented in Table 3. Distillers grain with solubles is high in CP, with considerable variation between the different types of grain used in the production process. The highest average CP content, 370 g/kg DM, was reported for DDGS produced from a mix of 90 percent wheat and 10 percent barley (Franke, Meyer and Flachowsky, 2009; Losand *et al.*, 2009; Meyer *et al.*, 2010). Mustafa, McKinnon and Christensen (2000) reported that the ruminal escape of CP was lower for wheat- than barley-based DGS (490 versus 415 g/kg CP). Generally, distillers grain has a relatively high fibre concentration, with highest cell-wall (neutral-detergent fibre –

TABLE 3
Chemical composition and net energy (NE) concentration (g/kg of dry matter unless stated) of distillers grain with solubles in wet (DGS) or dried (DDGS) form, as reported by various sources

	Grain source and form					
	Barley, wheat and rye-triticale DGS[1]	Wheat unspecified[2]	Wheat and barley DDGS[3]	Wheat and barley DDGS[4]	Rye DGS[5]	Wheat and barley DDGS[6]
Dry matter (DM) (g/kg)	289	n.a.[2]	923	934	n.a.	923
Crude protein	154	362	367	370	153	367
Ether extract	60	67	62	50	67	64
Ash	42	54	58	54	28	58
NDF	743	414	496	305	n.a.	490
ADF	311	173	159	155	n.a.	162
Starch	110	n.a.	n.a.	n.a.	54	n.a.
Sugar	n.a.	n.a.	n.a.	n.a.	45	n.a.
Calcium	n.a.	3.0	n.a.	n.a.	n.a.	n.a.
Phosphorus	n.a.	10.5	n.a.	n.a.	n.a.	n.a.
Sodium	n.a.	2.3	n.a.	n.a.	n.a.	n.a.
Magnesium	n.a.	6.0	n.a.	n.a.	n.a.	n.a.
Sulphur	n.a.	5.7	n.a.	n.a.	n.a.	n.a.
NE maintenance (MJ/kg)	n.a.	9.13	n.a.	n.a.	n.a.	n.a.
NE gain (MJ/kg)	n.a.	6.28	n.a.	n.a.	n.a.	n.a.
NE lactation (MJ/kg)	n.a.	8.46	n.a.	n.a.	n.a.	n.a.
NE lactation (MJ/kg DM)	n.a.	n.a.	n.a.	7.3	n.a.	n.a.

Notes: n.a. = not analysed; NDF = neutral-detergent fibre; ADF = acid-detergent fibre. *Sources*: (1) Mustafa, McKinnon and Christensen, 2000; (2) Schingoethe *et al.,* 2009; (3) Franke, Meyer and Flachowsky, 2009; (4) Losand *et al.,* 2009; (5) Engelhard, 2011; (6) Meyer *et al.,* 2010.

TABLE 4
Digestibility coefficients of nutrients measured in sheep according to GfE (1991) and estimated concentrations of metabolizable energy (ME) of distillers grain with solubles in wet (DGS) or dried (DDGS) form from rye, wheat or wheat+barley

Grain source + supplement	Rye + DGS	Wheat or wheat+barley, + DDGS[1]	Wheat+barley, +DDGS[2]
n	6	15	4
Organic matter	0.568 (±0.038)	0.758 (±0.048)	0.780 (±0.021)
Ether extract	0.598 (±0.302)	0.839 (±0.107)	0.914 (±0.010)
Crude fibre	0.515 (±0.100)	0.517 (±0.259)	
n		4	
NDF		0.650 (±0.131)	
ADF		0.544 (±0.110)	
ME (MJ/kg DM)	9.1	12.1	12.6

Notes: n = number of sheep in trial; NDF = neutral-detergent fibre; ADF = acid-detergent fibre. (1) Means with standard deviation in parenthesis.
(2) Least squares means with standard error in parenthesis.
Sources: Alert, Losand and Priebe, 2007; Losand *et al.,* 2009; Meyer *et al.,* 2010.

NDF) values found for barley-based distillers grain, probably due to a greater hull proportion in grain DM.

Nutrient digestibility coefficients can be used to calculate metabolizable energy (ME) for ruminating animals (GfE, 1995). Therefore a number of experiments were carried out with adult wethers in order to evaluate the nutrient digestibility of rye DGS as well as wheat- or wheat+barley-based DDGS. The experimental diets consisted of grass hay, grass silage or straw supplemented with DDGS ranging from 15 to 75 percent of diet DM. The apparent total tract digestibility of organic matter, ether extract, crude fibre, NDF and acid-detergent fibre (ADF) is shown in Table 4

The digestibility of ether extract and fibre fractions showed the most variation. When compared with rapeseed meal, wheat- and barley-based DDGS had similar organic matter and ether extract digestibilities (Meyer *et al.,* 2010). Organic matter digestibility of the rye-based DGS was notably lower and ranged from 0.531 to 0.619 (Alert, Losand and Priebe, 2007). This is reflected in a lower concentration of ME for rye DGS, for which no obvious explanation exists. The ME concentrations of wheat- and barley-based DDGS compared well with ME of rapeseed meal (RSM; Meyer *et al.,* 2010).

Table 5 shows results of experiments with lactating dairy cows conducted in Germany and Austria that compared DDGS or DGS (mainly based on wheat) with other protein supplements, like RSM or soybean meal (SBM). The aim of these studies was to investigate whether the different kinds of distillers grain can adequately replace RSM or SBM in diets of high-yielding cows. Most of the rations comprised a con-

TABLE 5
Comparison of four trials with distillers grain with solubles in wet (DGS) or dried (DDGS) form, mainly from wheat fermentation, in diets for lactating dairy cows

Parameter	Trial 1		Trial 2		Trial 3		Trial 4		
Duration (days)	147		50		n.s.	n.s.	60		
Cows (n)	16		36		126	123	3		
Basal diet	MS, GS		MS, GS		MS, GS		MS, GS, Hay		
Protein supplement	Wheat DDGS	RSM	Rye DWG	BG	Wheat DDGS	SBM, RSM	Maize DDGS	Wheat DDGS	SBM, RSC
(kg DM/day)	3.5	3.6	ca. 3.8	ca. 1.9	ca. 1.8	ca. 1.5	ca. 1.1	ca. 1.0	ca. 1.2
DM intake (kg/day)	20.8	21.9	ca. 24.0	ca. 23.6	n.s.	n.s.	20.8	20.9	20.9
Milk (kg/day)	34.9	34.0	42.1	42.5	35.8	37.0	26.4	25.9	26.2
Fat (g/kg milk)	32.6	35.3	38.9	39.7	41.0	42.0	44.6	44.8	44.3
Protein (g/kg milk)	31.1	32.9	32.3	32.4	35.1	35.3	33.3	33.4	33.9

Notes: MS = maize silage; GS = grass silage; RSM = rapeseed meal; BG = brewers grain; SBM = soybean meal; RSC = rapeseed cake. *Sources:* Trial 1 – Franke, Meyer and Flachowsky, 2009, working at Institute of Animal Nutrition, Friedrich-Loeffler-Institut (FLI), Federal Institute for Animal Health, Braunschweig, Germany. Trial 2 – Engelhard, 2011, working at Centre for Livestock Husbandry and Equipment, Regional Institute for Agriculture, Forestry and Horticulture Saxony-Anhalt (LLFG), Iden, Germany. Trial 3 – Dunkel, 2011, working at Agricultural Research Centre of Thuringia (TLL), Jena, Germany. Trial 4 – Urdl *et al.*, 2006, working at Institute of Livestock Research, Agricultural Education and Research Centre Raumberg-Gumpenstein (LFZ), Irdning, Austria.

TABLE 6
Comparison of dried distillers grain with solubles (DDGS) in diets for bulls during the whole fattening period and growing male calves before the beginning of the fattening period

	Trial 1			Trial 2				Trial 3			
Animals (n)	44		42	15		14	15	21			
Final live weight (kg)	710	712	720	556	560	557	558	162	164	153	157
Basal diet	MS			MS				MS + Hay			
Protein supplement	DDGS	SBM	RSM	DDGS	SBM	RSM	RSM + DDGS	DDGS	RSM	DDGS	RSM
Supplement intake (kg DM/day)	ca. 1.3	ca. 1.0	ca. 1.4	1.44	0.96	1.30	0.72 +0.74	0.42	0.44	0.59	0.58
DM intake (kg/day)	9.37	9.37	9.51	7.66	7.54	7.59	7.97	2.4	2.4	2.9	3.0
Crude protein intake (kg/day)	1.110	1.116	1.102	1.118	1.103	1.078	1.155	0.412	0.423	0.469	0.476
Energy intake (MJ ME/day)	108.3	109.3	111.0	86.2	84.9	84.7	89.3	31.0	30.3	35.5	36.2
Live weight gain (kg/day)	1.493 b	1.602 a	1.549 ab	1.310 b	1.390 ab	1.440 ab	1.460 a	1.008	1.039	1.003	1.053

Notes: MS = maize silage; RSM = rapeseed meal; SBM = soybean meal; RSC = rapeseed cake; ME = metabolizable energy. a,b = Different suffixes in a row within a trial indicate significant differences (P <0.05). *Sources*: Trial 1 – Ettle *et al*., 2009, working at Institute for Animal Nutrition and Feed Management, Bavarian State Research Centre for Agriculture (LfL), Poing, Germany. Trial 2 – Meyer *et al*., 2010, working at Institute of Animal Nutrition, Friedrich-Loeffler-Institut (FLI), Federal Institute for Animal Health, Braunschweig, Germany, Trial 3 – Preißinger, Spiekers and Obermaier, 2009, working at Institute for Animal Nutrition and Feed Management, Bavarian State Research Centre for Agriculture (LfL), Poing, Germany.

siderable portion of grass silage and maize silage. The proportion of distillers grain in the diets ranged from 50 g (Urdl *et al.*, 2006) to 170 g/kg DM (Franke, Meyer and Flachowsky, 2009). The feed intake in all experiments varied between 21 and 24 kg DM/day and was not influenced by protein source. Mean milk yield and milk fat concentration across studies ranged from 26 to 43 kg/day and from 33 to 45 g/kg milk. However, no significant differences were detected within the experiments. Only one study showed a lower milk protein concentration yet no lower protein yield for cows fed DDGS compared with RSM (Franke, Meyer and Flachowsky, 2009). In accordance with recommendations of Schingoethe *et al.* (2009) the outcome of the different experiments suggest that distillers grain can replace other protein supplements up to about 200 g/kg DM in dairy cow rations.

The results of trials with male calves and fattening bulls are presented in Table 6. Primarily wheat-based DDGS replaces RSM or SBM in maize silage or maize silage- and hay-based rations. The animals were fed DDGS from 140 g (Ettle *et al.*, 2009) up to 200 g/kg DM (Preißinger, Spiekers and Obermaier, 2009) of the diets. No differences between protein sources were detected in DM, CP and ME intake, nor in liveweight gain in both experiments with Simmental calves (Preißinger, Spiekers and Obermaier, 2009). Due to the higher final live weight, the mean feed intake of Simmental bulls (Ettle *et al.*, 2009) was higher (9.4 versus 7.7 kg DM/day) than that of Holstein bulls (Meyer *et al.*, 2010). Simmental and Holstein bulls showed good growth performance, and liveweight gain averaged about 1.55 and 1.40 kg/day, respectively. However, liveweight gain differed significantly within experiments. Ettle *et al.* (2009) found differences between bulls fed DDGS (1.49 kg/day) and SBM (1.60 kg/day), which might be a result of the higher energy concentration of SBM, as DM intakes were not different

across treatments. Feeding a mixture of DDGS and RSM resulted in the highest weight gain (1.46 kg/day) compared with SBM, RSM or DDGS (1.31 kg/day; Meyer *et al.*, 2010). The results of the experiments with fattening bulls showed that DDGS as the main protein source compares well with other protein supplements and is able to sustain high productive performance. This also indicates that differences between CP sources regarding the amino acid pattern of the ruminally undegraded CP (RUP) was not a constraint for intensive growth.

Nutritive value and feeding to non-ruminants – pigs

Co-products from biofuel production, such as DDGS, have also been fed to non-ruminant animals, particularly pigs (e.g. Lindermayer, 2004; Richter *et al.*, 2006a; Berk, 2007; Hackl *et al.*, 2007; Berk, Lebzien and Flachowsky, 2008; Kluge and Kluth, 2008) and poultry (e.g. Damme and Pegeanova, 2006; Richter *et al.*, 2006b; Trautwein *et al.*, 2008). Patience *et al.* (2007) summarized mainly North American results from feeding studies with DDGS in pigs.

Some authors investigated the amino acid pattern of DDGS and its praecaecal digestibility in pigs (e.g. Richter *et al.*, 2006a; Hackl, Priepke and Henning, 2007; Hackl *et al.*, 2007; Kluth, Wolf and Rodehutscord, 2009). Hackl, Priepke and Henning (2007) and Hackl *et al.* (2007) studied a wheat DDGS with 386 g CP per kg DM. Compared with wheat (32 g lysine per kg CP), DDGS contained only 17 g lysine per kg CP. The low concentration and the low praecaecal digestibility coefficient of lysine in wheat-DDGS (0.69 compared with 0.872 for wheat) underline the significance of lysine as the first limiting amino acid in DDGS for pigs. Although DDGS contains about 2.5–3 times more CP than wheat, it has only 1–1.5 times the concentration of praecaecally digestible lysine. Very low praecaecal digestibilities have been reported by Hackl, Priepke and Henning (2007) and Hackl *et al.* (2007) only for sulphur-containing amino acids (0.67–0.69), but not for most of the other essential amino acids. In broilers, however, Kluth, Wolf and Rodehutscord (2009) measured a praecaecal digestibility coefficient for lysine in DDGS of 0.79.

In a feeding trial with 80 growing-finishing pigs (40 females and 40 castrated males) from 35 kg initial live weight up to 115 kg slaughter weight, Berk (2007) partially replaced SBM and/or RSM by DDGS or a DDGS/RSM mix (Table 7). The feed in mash form and drinking water were offered for ad lib intake. Feed intake, total weight and slaughtering results were not influenced (P >0.05) by protein source. From this data it can be concluded that DDGS can partially replace SBM in diets for growing-finishing pigs in intensive production systems.

Richter *et al.* (2006a) carried out four feeding trials with piglets (0–100 g/kg DDGS in the diet; Table 8) as well three trials with growing-finishing pigs (0–250 g/kg DDGS in the diet; Table 9). The authors concluded that piglets below 10 kg live weight should not consume DDGS, and diets of heavier animals could receive DDGS up to 100 g/kg diet.

The results suggest that DDGS up to 200 g/kg in the diet of grower-finisher pigs did not influence performance. The lower recommended inclusion level for piglets is most likely due to the low lysine content of the DDGS. Hence, higher inclusion levels may be possible if lysine levels are adjusted accordingly. Kluge and Kluth (2008), Punz, Windisch and Schedle (2010) and Schedle, Mair and Windisch (2010) replaced SBM in grower-finisher diets completely by DDGS, and observed no adverse effect on fattening and slaughtering variables. Additional non-starch

TABLE 7
Protein sources for grower or finishers, feed intake, daily weight gain and some slaughter data for pigs

Protein source	Animal	Soybean	Soybean/RSM	Soybean/DDGS	SBM+RSM +DDGS
Soybean meal	Grower	15.0	6.0	8.0	6.0
	Finisher	11.0	–	5.0	3.0
Rapeseed meal	Grower	–	10.0	–	5.0
	Finisher	–	15.0	–	6.0
DDGS	Grower	–	–	8.0	5.0
	Finisher	–	–	10.0	6.0
Crude protein (g/kg DM)	Grower	178	176	178	175
	Finisher	163	166	166	169
Feed intake (kg/animal/day)	total	2.83	2.81	2.83	2.76
Weight gain (g/animal/day)		1010	959	998	940
Lean meat (%)		54.4	55.6	54.7	55.7
Backfat thickness (mm)		29.0	28.0	28.4	25.1
Backfat fatty acids (% of total)					
SFA		40.5	40.1	41.1	39.2
MUFA		47.4	49.5	46.8	48.8.
PUFA		12.1	10.4	12.0	12.4

Notes: SBM = soybean meal; RSM = rapeseed meal; DDGS = dried distillers grain with solubles; SFA = short-chain fatty acids; MUFA = mono-unsaturated fatty acids; PUFA = polyunsaturated fatty acids. *Source*: Berk, 2007.

TABLE 8
Average liveweight gain (g/day) of piglets (18–65 animals per treatment; initial age: 28–48 days; final age: 70 days) fed with various amounts of wheat-based dried distillers grain with solubles (DDGS)

Trial	DDGS (g/kg of diet)				
	0	30	50	80	100
1	480 a	440 bd	448 bc	417 d	–
2	518	–	–	–	505
3	445 a	–	408 ab	–	346 c
4	364	–	353	–	361

Notes: a,b,c,d = different suffixes indicate significant differences (P <0.05). *Source*: Richter *et al.*, 2006a.

TABLE 9
Average liveweight gain (g/day) of pigs (15–36 animals per treatment; initial live weight: 27–32 kg; final live weight: 112–121 kg) fed with various amounts of wheat-based dried distillers grain with solubles (DDGS)

Trial	DDGS (g/kg of diet)				
	0	100	150	200	250
1	791	784	787	–	–
2	834 a	–	827 a	–	745 b
3	932	905	–	939	–

Notes: a,b different suffixes indicate significant differences (P <0.05). *Source*: Richter *et al.*, 2006a.

polysaccharide (NSP) enzyme supplementation did not improve animal performance.

Another important aspect of DDGS incorporation in pig diets is P excretion, which is a major concern for the swine industry due to its potential impact on the environment. There are no European studies on this subject reported so far. A Canadian study evaluated the effect of wheat-based DDGS on P excretion patterns of grower-finisher pigs. Intake, excretion and retention of P were influenced by DDGS. Total tract P digestibility of DDGS was 40 percentage units higher than that of wheat. Similarly, daily P excretion of pigs fed DDGS was higher than that of pigs fed the wheat control diet (Widyaratne and Zijlstra, 2007). Another study conducted in North America measured, *inter alia*, P in maize-based DDGS fed to growing pigs. Apparent total tract digestibility for P in DDGS was measured at 59.1 percent while the control group fed a maize-based diet had apparent total tract digestibility of 19.3 percent. It was concluded that with DDGS a greater proportion of the organic P will be digested and absorbed, thus reducing the need to add inorganic P to pig diets (Pedersen, Boersma and Stein, 2007).

Nutritive value and feeding to non-ruminants – poultry

Richter *et al.* (2006b) included up to 200 g/kg of wheat-based DDGS in diets for chicks, pullets, laying hens and broilers. No effect of DDGS inclusion level on growth performance of chicks and pullets was observed (Table 10).

Laying intensity of hens as well as egg quality were not affected (P >0.05) by 150 g/kg DDGS in diets of laying hens (Damme and Peganova, 2006; Richter *et al.*, 2006b). Askbrant and Thomke (1986) observed no negative effect on egg yield and health of laying hens fed diets with 300 g/kg DDGS.

Richter *et al.* (2006b) carried out three feeding studies with 276 broilers per treatment (unsexed). The diets contained 0, 50, 100, 150 or 200 g/kg DDGS and was offered in pelleted form from days 1–14; mash feed was fed from days 15–33. The final live weight of the broilers amounted to 1995, 1987, 1953, 1884 and 1842 g per animal for DDGS inclusion levels of 0, 50, 100, 150 and 200 g/kg, respectively. These results suggest that diets that contain more than 100 g/kg DDGS may reduce performance, which is in agreement with Chidothe, Acamovic and McDevitt (2002), Chidothe, McDevitt and Acamovic (2002) and Trautwein *et al.* (2008).

Other authors added NSP-degrading enzymes (e.g. xylanase or xylanase mixed with other enzymes) to poultry diets rich in DDGS. In addition to an improved energy supply due to partial degradation of NSP and subsequent absorption of its constituent sugars (reviewed by Dänicke, 1999), the supplementation of xylanase is supposed to change the composition and metabolic potential of bacterial populations and may also influence fat absorption in younger animals (Hübner, Vahjen and Simon, 2002). Dalibard, Gadi and Kratz (2008) added an NSP-enzyme produced by *Penicillium funiculosum* to diets of layers containing 100 or

TABLE 10
Influence of dried distillers grain with solubles (DDGS) on live weight and feed conversion ratio (FCR) of chicks and pullets (average of two trials; 168 animals per treatment)

	DDGS in diet (g/kg)				
	0	50	100	150	200
Live weight (g) at:					
8 weeks	654	654	658	644	656
18 weeks	1432	1439	1448	1429	1435
FCR (kg/kg, feed/gain)					
0–8 weeks	3.16	3.18	3.17	3.17	3.16
0–18 weeks	5.12	5.13	5.08	5.09	5.10

Source: Richter *et al.*, 2006b.

200 g/kg maize-based DDGS. Enzyme supplementation did not increase nutrient digestibilities and energy concentration, but enzyme-supplementation of diets with 100 and 200 g/kg DDGS increased apparent ME concentration by 0.24 and 0.18 MJ/kg DM, respectively. Richter *et al.* (2006b) measured higher final live weight of chicks and pullets after enzyme supplementation in a diet with 150 g/kg DDGS. However, laying hens did not respond to enzyme supplementation. Chidothe, Acamovic and McDevitt (2002) and Chidothe, McDevitt and Acamovic (2002) measured higher liveweight gain in broilers fed with 100 and 200 g/kg enzyme-supplemented DDGS, but the gain was still below the level of the control group without DDGS. Similar results have been reported by Trautwein *et al.* (2008) after feeding diets with 100 g/kg DDGS.

Another important aspect which needs to be considered is the availability of P. Studies referring to wheat-based DDGS, the most common DDGS source in Europe, is reviewed in another chapter in this document, which provides a more in-depth account of wheat DDGS in poultry (Noblet *et al.*, this volume). Studies on maize-based DDGS reported a substantial variability in relative P bio-availability among different batches, which seems mainly due to different heating conditions employed during processing. During the process of fermentation for bio-ethanol production, small quantities of phytase are produced by the yeast, converting the P into better available forms (Martinez Amezuca, Parsons and Noll, 2004).

CO-PRODUCTS FROM BIODIESEL PRODUCTION

Glycerine

Biofuel production in the European Union is mainly based on biodiesel production from rapeseed oil, basically in the form of rapeseed oil methylester, leaving glycerine as a co-product. During biodiesel generation, fatty acids are hydrolyzed from the glycerine backbone of the triglyceride molecule by a transesterification process using methanol. Subsequent to separation of the fatty acid esters, glycerine still contains methanol and salts from the reactions. Separation or purification of glycerine can fluctuate depending on the plant and the process applied (Schröder and Südekum, 1999). Yield of glycerine from this process is approximately 1 unit per 10 units of biodiesel produced (Friedrich, 2004).

Starting around 60 years ago, researchers have shown that glycerine may help prevent ketoacidosis in the high-yielding dairy cow by increasing glucose precursors (Forsyth, 1953; Johnson, 1954; Fisher, Erfle and Sauer, 1971; Fisher *et al.*, 1973). Around 40 years ago, glycerine was registered as a feed additive (E 422) in the European Union (Anonymous, 1970) with no restrictions as to animal species and quantity added to feeds. Today, glycerine is listed as a feedstuff in the "Positive List" of authorized feed materials (Standards Commission for Straight Feeding Stuffs, 2011). Meanwhile, research expanded not only for dairy cattle but also other farm animals to elucidate the conditions under which glycerine could be used advantageously. The reader is referred to two other chapters in this book, which provide a more in-depth account of inclusion of glycerine in transition and lactating cow diets (Kalscheur *et al.*, this volume) and of swine energy value, metabolism, contaminants, feeding levels, performance and carcass composition (Shurson *et al.*, this volume).

Glycerine quality

Glycerine varies in quality, depending on the degree of refinement. Schröder and Südekum (2002) analysed the chemical composition of glycerine at different stages of the rapeseed oil methylester production process (Table 11). Important to notice is that the impure quality with elevated methanol concentrations (267 g/kg DM) was not a commodity but an intermediate product that was used for experimental purposes only. For the benefit of a fail-safe usage of glycerine in diets for all farm animals, methanol should be removed as far as is technically possible. Table 12 presents two different glycerine qualities according to the German "Positive List" (Standards Commission for Straight Feeding Stuffs, 2011). Crude glycerine is the quality currently used in farm animal feeding and it is strongly recommended that at least the specifications listed should

TABLE 11
Chemical composition of glycerine representing different stages of the rapeseed oil methylester production process

Parameter	Purity of glycerine		
	Low	Medium	High
Water (g/kg)	268	11	25
Dry matter composition (g/kg unless stated)			
Glycerine	633	853	998
Crude fat	7.1	4.4	n.a.
Phosphorus	10.5	23.6	n.a.
Potassium	22.0	23.3	n.a.
Sodium	1.1	0.9	n.a.
Lead (mg/kg)	3	2	n.a.
Methanol	267	0.4	n.a.

Notes: n.a. = not analysed; analyses were omitted because the glycerine content was close to 1000 g/kg. *Source*: Schröder and Südekum, 2002.

TABLE 12
Standardized composition (g/kg) of two different glycerine qualities according to the German "Positive List"

Parameter	Glycerine	Glycerine, crude
Glycerine	Minimum 990	Minimum 800
Water	5–100	100–150
Ash	Maximum 1.0	Maximum 100
Methanol	ND	Maximum 2.0
Other	–	NaCl, K, P, S

Notes: ND = not detected. *Source*: Standards Commission for Straight Feeding Stuffs, 2011.

be declared on each batch of crude glycerine. Due to legal restrictions on the use of animal products in farm animal feeding and because crude glycerine may contain some residual fat, the source of the glycerine must also be known and stated.

Südekum *et al*. (2008) investigated physical, chemical and hygienic quality characteristics of pelleted compound feeds with varying quality glycerine inclusion levels of 50, 100 and 150 g/kg concentrate DM. The quality of the concentrates was assessed under two environmental conditions (15 °C and 60 percent relative humidity; 20 °C and 70 percent relative humidity) and storage durations of four and eight weeks. The chemical composition was only slightly affected by concentration and purity of glycerine or by storage and duration. Moreover, the data indicated that glycerine of different purities had a preserving effect and the physical quality of the pellets was not affected by purity or concentrations of glycerine. However, Löwe (1999) noted that when pellets were produced with molasses and glycerine concentrations greater than 50 g/kg, pellets showed a rough and scaly surface. This author also remarked that when feeds are stored in meal form, concentrations greater than 50 g glycerine/kg may result in lump formation, and therefore suggested restricting glycerine concentration in pelleted compound feeds to 60–70 g/kg based on general storage behaviour, including storage in large silos.

In conclusion, glycerine of different purities as a co-product from rapeseed oil methylester production may help stabilize the hygienic quality of pelleted compound feeds without compromising physical quality of the pellets.

Rumen events when feeding glycerine

Previous studies on ruminal metabolism of glycerine indicated that glycerine is rapidly and extensively fermented in the rumen, with propionic acid as the major product of fermentation (Bergner *et al*., 1995; Kijora *et al*., 1998). However, there is controversial information regarding the exact biochemical pathway and the end products of glycerine fermentation by ruminal microbes. Ferraro *et al*. (2009) measured *in vitro* gas production from glycerine, lucerne and maize silage. Results indicated that glycerine has a long lag time and a slow rate of degradation. Moreover, glycerine fermentation resulted in reduced acetate and increased butyrate concentration. Krueger *et al*. (2010) evaluated the *in vitro* effect of two levels of glycerine (20 or 200 g/kg) on their inhibitory effect against ruminal lipolysis by mixed rumen microbes, as well as the effect of feeding various amounts of glycerine on fermentation kinetics of lucerne hay. They concluded that an inclusion rate of up to 200 g/kg decreased the rate of free fatty acid accumulation and decreased fermentation rate, but appeared to have no negative effect on NDF digestibility. The authors suggested that utilizing glycerine as a short-term feed ingredient in cattle diets can potentially inhibit bacterial fat degradation.

Schröder and Südekum (2002) evaluated *in vivo* effects of glycerine in compound feeds on nutrient turnover in the rumen and digestibilities in the whole tract of cattle. Four ruminally cannulated steers were used in a 4×4 Latin square design, and received a mixed diet consisting of 400 g/kg DM forage and 600 g/kg DM concentrate. Concentrate in pelleted form comprised either no glycerine or 150 g/kg glycerine of different purities (630, 850 or >995 g/kg glycerine). Feeding glycerine resulted in a slight shift towards a reduced ratio of acetic acid versus propionic acid. Rumen fill was slightly higher when diets contained glycerine. Furthermore, glycerine appeared to have an impact on water turnover since the proportion of bailable liquids of total ruminal contents was higher when diets contained glycerine, irrespective of quality. No effect on fermentation of fibre components was observed *in vivo*, although when glycerine was supplemented to a medium containing cellobiose as the sole energy source (Roger *et al.,* 1992) it inhibited the growth and cellulolytic activity of two rumen cellulolytic bacterial species (*Ruminococcus flacefaciens* and *Fibrobacter succinogenes*). The growth of the anaerobic fungal species, *Neocallimasix frontalis*, was inhibited as well, and its cellulolytic activity almost completely disappeared. Another study by Abo El-Nor *et al*. (2010) measured the effects of substituting maize grain with glycerine at different levels (36, 72, 108 g/kg DM) on deoxyribonucleic acid (DNA) concentration of selected rumen bacteria using continuous fermenters. The DNA concentration for *Butyrivibrio fibrisolvens* (fibre degradation) and *Selenomonas ruminantium* (starch and sugar degradation) were reduced when glycerine at levels of 72 and 108 g/kg DM was incorporated. However, the implications of this data concerning the inhibition of bacterial and fungal growth are that it could be caused both by specific *in vitro* conditions, such as the single species, and by sole substrate conditions.

The *in vivo* data indicated that there should be no negative effects on ruminal turnover and digestibilities of organic matter constituents in the total tract when glycerine is used as a substitute for rapidly-fermentable starch sources like wheat or maize grain. Further, possible effects of glycerine on rumen microbial protein metabolism may require more detailed investigations. Paggi, Fay and Fernandez (1999) investigated the *in vitro* effect of increasing levels of glycerine (50, 100, 200 or 300 mM) on the proteolytic activity of bovine rumen fluid and found that all concentrations of glycerine reduced proteolytic activity by 20 percent. Kijora *et al*. (1998) infused 400 g glycerine per day (corresponding to 100 g/kg DM intake) into the rumen of growing bulls fed on a hay-grain diet. They observed lower concentrations of isobutyric and isovaleric acid in the rumen and concluded that fewer branched-chain amino acids had been degrad-

ed. A slower rumen microbial crude protein and amino acid degradation would primarily increase the protein value of fermented forages.

Dairy cow performance in response to glycerine

Previous studies have shown that glycerine may help to prevent ketoacidosis in high yielding dairy cows by increasing glucose precursors (Forsyth, 1953; Johnson, 1954; Fisher, Erfle and Sauer, 1971; Fisher *et al.*, 1973; Sauer, Erfle and Fisher, 1973). In the majority of these trials, glycerine was applied as an oral drench. Recent research has focused on using glycerine either as a dietary supplement or as a partial replacement for starchy dietary ingredients.

Khalili *et al*. (1997) fed grass silage for ad libitum consumption and 7 kg per day of a barley-based concentrate to mid-lactation Friesian cows. Barley was partially replaced with either glycerine, a fractionated vegetable fatty acid blend or a 1:1 mixture of glycerine and free fatty acids. Glycerine intakes (150 g/day) had no effects on intake or performance, although the combination of glycerine and free fatty acids tended to increase milk yield. DeFrain *et al*. (2004) fed complete diets to Holstein cows from 14 days pre-partum to 21 days post-partum. Diets were top-dressed with 860 g maize starch (control), 430 g maize starch and 430 g glycerine, or 860 g glycerine (per day per cow). Rapidly fermentable glycerine replaced a slowly and incompletely fermentable carbohydrate source. Pre-partum dry matter intake was greater for cows fed the control when compared with the two glycerine-supplemented diets. Rumen fluid collected post-partum from cows who received a glycerine supplemented diet had greater total volatile fatty acids, greater molar proportions of propionate and a decreased ratio of acetate to propionate. Furthermore, concentrations of butyrate seemed to be greater in rumens of cows fed glycerine-supplemented diets. Yield of energy-corrected milk during the first 70 days post-partum tended to be greatest for cows fed the control diet. Since the only observed effect of glycerine-supplemented diets pre-partum was on dry matter intake, the authors suggested that glycerine should be delivered as a drench in hypoglycaemic dairy cows and not fed as a component of transition dairy cow diets. Bodarski *et al*. (2005) observed an increase in β-hydroxybutyrate in blood serum as well after adding 500 mL glycerine per day for the first 70 days post-partum. However, glycerine supplementation decreased total non-esterified fatty acid levels when compared with the non-supplemented controls. Bodarski *et al.* (2005) observed that cows that consumed the glycerine diet exhibited a higher dry matter intake and gave 13 to 18 percent more milk than the control groups.

Recently, two German groups investigated glycerine in diets for dairy cows in direct comparison with propylene glycol. Engelhard *et al.* (2006) supplemented the same calculated amounts per cow of both glycerine and propylene glycol pre-partum (150 g/day) and post-partum (250 g/day). Energy-corrected milk yields as well as concentrations of milk fat and protein were not different between cows fed propylene glycol or glycerine. Nevertheless, the authors observed that older cows (>second lactation) that received the glycerine-supplemented diet consumed more DM, and hence energy. Blood level indices of ketosis such as β-hydroxybutyrate and non-esterified fatty acids were not different between groups.

Rapeseed meal and rapeseed cake – ruminants

Rapeseed meal is still considered to be an important source of high-quality protein for all farm animal species, and especially for ruminants. Approximately 4.4 million tonne of RSM was produced in Germany in 2008, of which 3 million tonne was used for domestic consumption exclusively (Weiß and Schwarz, 2010). It can be assumed that the main part was utilized as protein supplements in ruminant nutrition. One of the main reasons for this may be the low cost of RSM in comparison with imported SBM. Moreover, techniques to extract RSM, including physical pressure and high temperatures, result in an increased fraction of CP protected from ruminal degradation.

Protein values of SBM and RSM published in feeding value tables and research papers differ markedly. The concentration of RUP is considered to be 350 g/kg CP for SBM and 250 g/kg CP for RSM (Universität Hohenheim – Dokumentationsstelle, 1997). Similarily, mean values calculated from data reported in the feed composition table of the AFRC (1993) resulted in 280 g RUP/kg CP for RSM and 370 g RUP/kg CP for SBM at a rumen outflow rate of 5 percent per hour.

However, more recent experiments indicate that the considerable differences between the tabulated ruminal degradability values of the two meals in favour of SBM no longer reflect the current situation. A cross-sectional study conducted by Südekum *et al.* (2003; Table 13) covered all oil mills processing rapeseed and soybean in Germany, and in addition encompassed some imported SBM samples.

A total of 15 studies published between 1983 and 1997 could be identified (Rooke, Brookes and Armstrong, 1983;

TABLE 13
Protein value of contemporary qualities of rapeseed (RSM) and soybean (SBM) meals as compared with feeding table values

Parameter	RSM	SBM
Mean RUP (g/kg CP)	300	300
DLG Table values	250	350
Mean uCP (g/kg DM)	231	288
DLG Table values	219	298–308

Notes: RUP = ruminally undegraded crude protein; uCP = utilizable crude protein at the duodenum (sum of microbial and RUP). *Sources*: Südekum *et al.,* 2003. DLG Table is from Universität Hohenheim – Dokumentationsstelle, 1997.

Mir *et al*., 1984; Voigt *et al*., 1990; Kendall, Ingalls and Boila, 1991; Tuori, 1992; Zinn, 1993; Khorasani, Robinson and Kennelly, 1994; Liu, Steg and Hindle, 1994; Moss and Givens, 1994; Vanhatalo, Aronen and Varvikko, 1995; Stanford *et al*., 1995, 1996; Gralak *et al*., 1997; Mustafa *et al*., 1997; Zebrowska *et al*., 1997). Nine studies observed greater RUP values (g/kg CP) for SBM than RSM, three studies reported the opposite, and three studies noticed no differences between RUP values for SBM and RSM. Moreover, RUP values varied greatly in all studies; more precisely, results for SBM ranged between 200 and 500 g/kg CP and RSM from 120 to 560 g/kg CP. Thus, data reported by Südekum *et al.* (2003) appear acceptable and may more closely mimic recent and current SBM and RSM qualities than historical tabular values. In conclusion, it can be stated that it is currently recommended to state a mean RUP concentration of 300 g/kg CP for RSM and SBM (Südekum and Spiekers, 2002).

Other recent experiments tested the hypothesis that SBM can be fully replaced by RSM in dairy cow diets when fed on an approximate isonitrogenous and isocaloric basis (without considering differences in ruminal degradation or amino acid pattern, or both. Table 14 summarizes the data and indicates that milk yield and milk component concentrations were similar for diets containing SBM or RSM, and thus the hypothesis can still be sustained. The energy concentration of the whole diet seems to be a key factor for the successful replacement of RSM for SBM, as lower energy concentrations generally mean insufficient DM intakes, and this may be further aggravated if RSM (moderate energy density) is included at the expense of SBM (high energy density).

Steingass *et al.* (2010) tested at what concentrations rapeseed cake could replace SBM. A feeding trial, with 60 dairy cows and 7 time periods (4 control + 3 periods with rapeseed cake or rapeseed cake+RSM) revealed higher DM intake and milk yield, as well as lower milk fat and protein values, when rapeseed cake was fed. The authors suggested that even though rapeseed cake and RSM differ widely in their protein values, both feedstuffs can be regarded as suitable full protein supplements in diets for dairy cows.

Moreover it should also be pointed out that the overall quality of RSM and rapeseed cake depends also on the concentration of glucosinolates and, in case of rapeseed cake, the content and quality of the lipid proportion. Generally, average glucosinolate concentrations of RSM are low while glucosinolate concentrations of rapeseed cake are considerably higher. However, there is great variation for both feedstuffs. In addition, crude fat in rapeseed cake fluctuates, making ration formulation a difficult task. Increasing crude fat content lowers CP concentrations and vice versa. Hence, grouping of rapeseed cakes according to crude fat concentration (g/kg) appears necessary. Additionally, storage stability should also be considered, since the fat is in a non-protected form after the mechanical extraction of the seed. It has also been reported by farmers and consultants that physical characteristics resulting from plaque forming during oil extraction may handicap rapeseed cake handling, e.g. a homogenous distribution in complete diets or silage mixtures is difficult to achieve.

Rapeseed cake and meal – pigs and poultry

Pigs and poultry react more sensitively than ruminants to the glucosinolate content in rapeseed meal and cake. Even though the amino acid composition in rapeseed products is well balanced and favourable for monogastric animals, there are two limiting factors: the concentration and structural type of glucosinolates, and the dietary fibre. There are two different types of glucosinolate: aliphatic glucosinolate derived from methionine, and indole glucosinolate derived from tryptophan. Aliphatic glucosinolate, which has the most negative antrinutritive

TABLE 14
Comparison of rapeseed (RSM) and soybean (SBM) meals in diets for high-producing dairy cows – summary of German trials

Location, duration of trial and diet	Protein supplement (kg/day/cow)	Milk (kg/day)	Fat (g/kg milk)	Protein (g/kg milk)
LWZ Haus Riswick; lactation weeks 5–35. Basal diet of1/3 MS + 2/3 GS	SBM 2.3 kg	31.1	39	31
	RSM 3.1 kg	31.3	39	32
LWZ Haus Riswick; lactation weeks 2–44. TMR with 50% MS + 25% GS	SBM 1.6 kg	25.2	42	34
	RSM 2.2 kg	25.8	41	34
TMR with 40% (MS + EMS) + 25% GS	SBM 4.0 kg	40.0	38	33
	RSM 4.3 kg	40.5	39	33
LVA Köllitsch; 17 weeks. Basal diet of 50% MS + 50% GS	SBM 1.6 kg	31.2	39	34
	RSM 2.0 kg	32.7	40	34
Universität Hohenheim; duration not specified. TMR with 22% MS + 21% GS	SBM 1.2 kg	30.9	45	35
	RSM 1.8 kg	32.4	43	35

Notes: MS = maize silage; GS = grass silage; TMR – totally mixed ration; EMS – ear-maize silage. *Locations*: LWZ = Chamber of Agriculture of North Rhine-Westphalia, Landwirtschaftszentrum (LWZ) Haus Riswick, Kleve, Germany; LLFG = Centre for Livestock Husbandry and Equipment, Regional Institute for Agriculture, Forestry and Horticulture Saxony-Anhalt (LLFG), Iden, Germany. LVA = State Office for Environment, Agriculture and Geology, Lehr- und Versuchsgut (LVA) Köllitsch, Germany. Institute of Animal Nutrition, University of Hohenheim, Stuttgart, Germany. *Sources*: Spiekers and Südekum, 2004; Steingass *et al.,* 2010.

TABLE 15
Amino acid profiles (g/100 g crude protein) of rapeseed meal, soybean meal and wheat

	Rapeseed meal	Soybean meal	Wheat
Lysine	5.6	6.3	2.8
Methionine+Cysteine	4.6	3.0	3.8
Threonine	4.4	4.0	2.9
Tryptophan	1.3	1.3	1.2

Source: Degussa Feed Additives, 1996.

effect, may be reduced by plant breeding to levels close to zero, while indole glucosinolate contributes 2–4 µmoles/g seed (Sørensen, 1990). The high content of fibre and fibre-associated CP contributes to relatively low digestibility for CP and energy in RSM. This is mainly due to the high lignin content of the hulls, which vary considerably (47–517 g/kg) depending on genotype and processing of the seed (Jensen, Olsen and Sørensen, 1990). Table 15 presents average amino acid contents of SBM, RSM and wheat. The lysine content of RSM is slightly less than that of SBM, but threonine and sulphur amino acids (methionine, cysteine) are greater in RSM.

The acceptance of using RSM in pig diets has increased greatly in recent years. This is mainly due to the beneficial price as well as reduced concentration of glucosinolates and improved quality monitoring. Moreover, RSM shows similar values for protein quality compared with SBM, although lysine concentration and digestibilities are lower in RSM. For practical use, this means that other protein supplements or free amino acids are needed to compensate for the loss. In contrast, RSM includes higher concentrations of sulphur amino acids than SBM.

Several trials throughout Germany were performed in order to ascertain the tolerance for the maximum supplementation of RSM in pig diets. In early trials, amounts of 50 g/kg for growing and 100 g/kg RSM for finishing pigs replaced SBM as a protein supplement in the diet. The result was that no differences were observed between groups receiving RSM or SBM. The next trial increased the amount of RSM to 100 g/kg for growing pigs and to 150 g/kg for finishing pigs. Again, no differences in performance and carcass quality were observed when compared with pigs that were fed SBM. It was concluded that diets can contain 100 g/kg RSM in grower diets (40–70 kg live weight) and 150 g/kg RSM in finishing diets (70–120 kg live weight). It is recommended that piglets, which are more sensitive to glucosinolate and high fibre concentrations, can receive up to 50 g/kg RSM in diets, and can tolerate levels of up to 100 g/kg RSM (12–15 kg live weight). However, levels of glucosinolates should not exceed 10 mmol/kg RSM (Weiß and Schöne, 2008; Weber, 2010; Weber *et al.,* 2011).

Other than RSM, rapeseed cake is only produced at smaller oil mills and represents around one tenth of the total rapeseed feed consumption. The major difference to RSM is that rapeseed cake has a much higher and varying concentration of crude fat (100–160 g/kg vs 20 g/kg in RSM), as well as twice the glucosinolate concentration (6.2–9.4 mmol/kg RSM vs 11.6–17.1 mmol/kg cake). Recommendations for the practical use of rapeseed cake depend mainly on glucosinolate levels. If the acceptable amount is exceeded, animals react with decreased feed intake and performance, and in the worst case an enlargement of the thyroid. Weiß and Schöne (2010) summarized five different trials that were carried out in order to estimate the maximum supplementation of rapeseed cake. It was concluded that fattening pigs may receive between 70 and 100 g/kg rapeseed cake, while sows and piglets may be fed between 50 to 100 g/kg rapeseed cake. The exact amount depends on the glucosinolate level, which should not exceed 1.5 mmol/kg diet. Moreover, crude fat content should be more standardized to be able to use the commodities more easily and reliably.

Rapeseed products are least used in poultry nutrition. For this reason not much research has been conducted, and results vary greatly. Unfortunately, no declaration on glucosinolate levels in the RSM used are reported in most of the literature. Richter *et al.* (1996) noticed a decrease in performance when adding 50 g/kg RSM, while Faghani and Kheiri (2007) observed no differences when RSM was added at a level of 100 g/kg. A few studies with rapeseed cake revealed that it is possible to use approximately 150 g/kg diet without no loss in performance (Peter and Dänicke, 2003). Jeroch, Jankowski and Schöne (2008) reviewed several trials and concluded that broilers, when fed rapeseed cake, tolerate between 3 and 5 mmol/kg glucosinolate. Moreover, it is highly important to add iodine, since glucosinolates act as antagonists. It is suggested that iodine supplementation should be twice general recommendations (GfE, 1999). However, if glucosinolates are present in high concentrations, the negative effects may not be compensated for, even if iodine is supplemented at high levels.

Concluding, it is evident from these data that more widespread use of RSM and rapeseed cake in diets for pigs and poultry requires further reduction in glucosinolate levels.

ENERGY UTILIZATION EFFICIENCY AND SUSTAINABILITY OF CO-PRODUCTS FROM BIOFUEL PRODUCTION IN ANIMAL NUTRITION

The biofuel yield per tonne of rapeseed varies between 250 and 350 kg rapeseed oil, and bio-ethanol yield per tonne of maize or wheat grain is between 300 and 350 kg (Pinkney, 2009). Some losses are caused by CO_2 escape during alcohol fermentation. All other products may be considered as co-products, and may be used in various ways as feedstuff in animal nutrition in wet or dry form, or as fertilizer. Biofuel

co-products can be considered as valuable protein sources for farm animals. Their CP concentration varies between 300 and 400 g/kg DM. Land use scenarios using wheat for biofuel or using wheat and soybean meal to match animal feed value of DDGS have been evaluated by Pinkney (2009). The most effective way to utilize the DGS resulting from biofuel production in large plants is feeding this low DM material (80 g DM/kg) to farm animals. As it is unrealistic to distribute large amounts of DGS in the vicinity of the biofuel plant and due to its short shelf-life, it becomes necessary to dry the material in order to preserve the co-product. Therefore, additional energy expenditures and GHG emissions must be considered in any assessment of ecobalances (carbon footprint, life-cycle assessment) of the co-products or the whole biofuel production chain.

To date, no definite regulations exist in order to classify emissions of the main product and the co-product (Bockisch *et al.*, 2000; Flachowsky *et al.*, 2011). When operating on a causation principle, the producer or the responsible party should be accountable for all emissions. However, drying of DGS is only of interest if the products will be utilized as feedstuffs for animals, and thus emissions associated with processing of co-products are not of interest or necessity for biofuel producing companies.

KNOWLEDGE GAPS AND FUTURE RESEARCH NEEDS

Even though, much research has already been conducted in the utilization of bio-ethanol and biodiesel co-products for animal nutrition, there are important aspects that need further consideration. Dose-response studies are required for all co-products covered in this chapter, in order to evaluate the exact mode of action as well as the appropriate inclusion level in diets of farm animals. More precisely, this means that methanol must be removed from glycerine as far as technically possible, since separation or purification of glycerine can be fluctuating depending on the plant and the applied process. Rapeseed products fed to pigs and poultry should contain as little glucosinolate as possible. This might be achieved through the breeding process, while the antinutritive impact of the remaining glucosinolates may be compensated for by iodine addition.

Further attention should also be paid to the influence of processing conditions on composition and nutritive value of co-products, depending on raw materials. In particular, rapeseed cake needs further consideration and more reliable data because variations in the processing conditions result in very varying chemical composition, particularly regarding crude fat and CP content. This leads to difficulties in predicting the feeding value of rapeseed cake for all categories of farm animals, and could also affect storage stability. Therefore, the value of rapeseed cake would benefit from a standardization of composition. Similarly, standardization of processing would be desirable, using constant proportions of raw materials for the production of distillers grain.

Future research should also focus on measuring additional expenditures of the processing of co-products in order to be able to evaluate the carbon footprint and to identify GHG reduction potentials. Factors like harvesting, pressing, drying, conservation and transportation should be accounted for in the same way as animal emissions and manure management, since focusing on single factors does not provide an assessment that reflects the complexity of this subject.

CONCLUSIONS

The results of a number of experiments with lactating dairy cows and fattening bulls suggest that distillers grain as the main protein source could support high productive performance. Trials with grower-finisher pigs suggest that DDGS up to 200 g/kg diet do not influence growth performance and fattening and slaughtering variables. Similarly, laying intensity of hens as well as egg quality and health were not affected by inclusion levels ranging from 150 g/kg to 300 g/kg diet. Trials with broilers suggest that diets that contain more than 100 g/kg DDGS may lower performance. Hence, it is recommended to add non-starch polysaccharide (NSP)-degrading enzymes (e.g. xylanase or xylanase mixed with other enzymes) to poultry diets rich in DDGS.

Table 16 summarizes current German recommendations for rapeseed products in diets for cattle and pigs. Pigs would particularly benefit from breeding or production progress in further reduction of glucosinolate levels, whereas in cattle, a safer quality assessment of the rapeseed cake is needed.

The chapter reviewed also the use of glycerine as a co-product from biodiesel production, as well as rapeseed products such as rapeseed meal and cake for farm animals. For the benefit of fail-safe usage of glycerine in diets for all farm animals, methanol should be removed as far as technically possible. Glycerine at different purities may help to stabilize the hygienic quality of pelleted compound

TABLE 16
Practical recommendations for daily amounts or dietary concentrations (as-fed basis for dry diets) of rapeseed products for cattle, pigs and poultry

Animal category	Rapeseed meal, solvent-extracted	Rapeseed cake, mechanically extracted
Dairy cow	Maximum 4 kg	1.5–2.0 kg
Beef cattle	Maximum 1.2 kg	1 kg
Fattening pigs	Maximum 100 g/kg	70–100 g/kg
Sows	50–100 g/kg	50–100 g/kg
Piglets	Maximum 50 g/kg	50–100 g/kg
Broiler	50–150 g/kg	50–100 g/kg
Laying hens	0–100 g/kg	0–50 g/kg

Sources: Weiß, 2007; Jeroch, Jankowski and Schöne, 2008.

feeds without compromising physical quality of pellets. Furthermore, glycerine is no direct competitor of propylene glycol, since data on ruminal turnover suggest that glycerine, other than propylene glycol, should replace rapidly fermentable carbohydrates. Mature cattle may consume up to 1 kg glycerine per day, while it may still be necessary to investigate if the sweet taste of glycerine may improve feed intake of diets with inferior palatability.

In conclusion, glycerine can be used as a versatile feedstuff, in particular for ruminants, but further research is required to explore the full potential of glycerine in dairy cows.

Other rapeseed products for ruminants, such as rapeseed meal, compare well with soybean meal for dairy cows. Recent research on rapeseed meal has shown that it can fully replace soybean meal within dairy cow diets when fed on an approximately isonitrogenous and isocaloric basis, i.e. without considering differences in ruminal degradation or amino acid pattern, or both. Moreover, milk and milk component yields were similar for diets containing soybean meal or rapeseed meal.

Nevertheless, rapeseed cake needs further consideration and more reliable data because variations in the processing conditions result in varying chemical composition, particularly regarding the crude fat and protein content. These circumstances currently lead to difficulties in predicting the feeding value of rapeseed cake for all categories of farm animals, and could also affect storage stability. Therefore, the value of rapeseed cake would benefit from standardization of composition

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Chapter 12

Utilizing co-products of the sweet sorghum-based biofuel industry as livestock feed in decentralized systems

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ABSTRACT

Sweet sorghum-based decentralized crushing and syrup-making units are a major component of sweet sorghum value chains in India. Apart from the main product, syrup, there are several co-products, including grain, bagasse, vinasse, steam, foam and froth. This chapter looks at the state of the art in utilization of these products in livestock feed, as well as exploring emerging opportunities. If the policy framework of the country supports decentralized models, this co-products utilization not only improves economic viability but also has environmental benefits by way of reduced greenhouse gas (GHG) emissions, which are yet to be quantified.

INTRODUCTION TO THE SWEET SORGHUM VALUE CHAIN

Renewable energies are critical contributors to the energy supply portfolio as they contribute to global energy security, reduce dependency on fossil fuels and provide opportunities for reducing emissions of greenhouse gases (GHG), and are expected to play major roles in energy strategies of nations to mitigate adverse global climatic change (Reddy *et al*., 2008; Srinivasa Rao *et al*., 2009). The price volatility of global crude oil is more unprecedented and unpredictable than ever before, as seen during the last decade. Hence many policy-makers consider renewable indigenous sources of energy, like biofuels, would be a viable option for energy security. Since biofuels can be produced from diverse crops, each country is adopting a strategy that exploits the comparative advantages it holds with respect to such crops. For example, sugar cane and maize are the main feedstocks for ethanol in Brazil and US respectively, while rapeseed in Europe and palm oil in Malaysia are the main feedstocks for biodiesel. In India, sugar cane, sweet sorghum and tropical sugarbeet are the major bio-ethanol feedstocks, while biodiesel is produced on a limited scale from *Jatropha* (Srinivasa Rao *et al*., 2010). More than 95 percent of the bio-ethanol in India is produced from molasses, a co-product of the sugar industry, by over 1500 distilleries spread across the country (Aradhey, 2010). As sugarbeet is being grown only on an experimental scale in India the co-products are not available to explore, while *Jatropha* oilcake contains toxins and antinutrient factors such as phorbol esters, trypsin inhibitors, lectins and phytates, and hence is not suitable for animal feed (Reddy *et al*., 2008). However, the detoxified *Jatropha* cake, i.e. *Jatropha* meal, can be used as feed. There are currently two models of operation in sweet sorghum value chains, namely a Centralized model and a Decentralized model. This chapter primarily discusses the co-products of sweet sorghum in a decentralized model of the sweet sorghum value chain.

SWEET SORGHUM AS BIO-ETHANOL FEEDSTOCK

Sorghum (*Sorghum bicolor* (L) Moench) is one of the most important food, feed and fodder crops in arid and semi-arid regions of the world. Globally, it was cultivated on about 39.96 million hectares in 2009, with Africa and India accounting for about 80 percent of the global acreage (FAOSTAT data). Although sorghum is best known as a dual-purpose grain and fodder crop, the sweet-stalked sorghums, referred to as sweet sorghums, are similar to the grain sorghums, but possess sweet juice in their stalk tissues, and are traditionally used as livestock fodder due to their ability to form excellent silage; the stalk juice is extracted and fermented and distilled to produce ethanol (Table 1). Thereafter the juice, grain and bagasse (the fibrous residue that remains after juice extraction) can be used to produce food, fodder, ethanol and cogeneration. The ability of sweet sorghum to adapt to drought; to saline and alkaline soils; and to waterlogging has been proven by its wide prevalence in various regions of the world. The

MAIN MESSAGES

- **Sweet sorghum is a climate change-ready crop owing to its resource use efficiency and wide adaptability, in addition to apart biotic and abiotic stress tolerance.**
- **In poor soils with limited inputs, sweet sorghum-based agro-enterprises offer both food for humans and fodder (bagasse) for their livestock, forming a resilient mixed crop-livestock system.**
- **The sweet sorghum value chain offers immense opportunities to the marginal farmers of the semi-arid tropics as sweet sorghum offers food, feed, fodder and fuel.**
- **The centralized and decentralized systems complement each other, and benefits percolate down to the associated farming communities.**
- **The socio-economic, environmental and ecological benefits from sweet sorghum production and processing can be large, and need to be quantified from a systems perspective.**
- **To benefit from all the above on a large scale in farmers' fields, well structured, sustained, supportive policies and R&D programmes with inclusive market-oriented approaches are required at both national and international levels.**

TABLE 1
Favourable traits of sweet sorghum cultivation as biofuel feedstock compared with popular biofuel feedstocks such as sugar cane, maize and sugarbeet

As crop	As ethanol source	As Bagasse	As raw material for industrial products
• Short duration (3–4 months) • C_4 dryland crop • Good tolerance of biotic and abiotic constraints • Meets fodder and food needs • Non-invasive species • Low soil N_2O and CO_2 emission • Seed propagated	• Amenable to eco-friendly processing • Less sulphur in ethanol • High octane rating • Automobile friendly (up to 25% of ethanol-petrol mixture without engine modification)	• High biological value • Rich in micronutrients • Use as feed, for power co-generation or bio-compost • Good for silage making	• Cost-effective source of pulp for paper making • Dry ice, acetic acid, fusel oil and methane can be produced from the co-products of fermentation • Butanol, lactic acid, acetic acid and beverages can be manufactured.

Notes: For further details see Srinivasa Rao *et al*., 2009). N_2O = nitrous oxide; CO_2 = carbon dioxide.
Sources: Reddy *et al*., 2005; Srinivasa Rao *et al*., 2009, 2010.

per-day ethanol productivity of sweet sorghum is higher than sugar cane (Srinivasa Rao *et al*., 2010, 2011), as well as having a shorter growing period (four months) and a low water requirement of 8000 m^3/ha (over two crops annually) that is only 25 percent of that required for sugar cane, which has a 12–16-month growing season and needs 36 000 m^3 water/ha. It translates to sugar cane needing 900 m^3 water for producing 1 tonne of dry matter (DM) while sorghum requires only 200 m^3 water, based on productivity of sugar cane at 40 t/ha and sorghum at 20 t/ha.

Sweet sorghum's lower cost of cultivation compared with sugar cane and sugarbeet, and farmer familiarity with cultivation of sorghum, aid in greater adoption of sweet sorghum.

Mixed crop-livestock systems are the dominant form of agricultural production in dryland Africa and Asia. Integrating crops and livestock on the same farm helps small-scale farmers to diversify their sources of income and employment. Livestock act as a storehouse of capital and an insurance against crop production risks, and thus provide a coping mechanism against livelihood shocks as well as a vital source of dietary protein. Development of the livestock sector provides new livelihood opportunities for women, who otherwise often lack access to and control over land-based means of production. For the majority of small-scale farmers, crop residues from dual-purpose crops constitute 40–60 percent of total dry matter intake in their animal feed rations. The rest is made up from other sources.

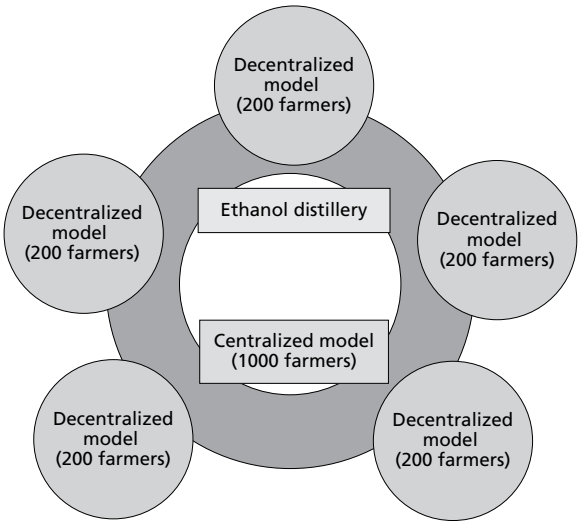
Sweet sorghum supply chain

Sweet sorghum feedstock supply chains have primarily two models of operation (Figures 1 and 2). These are considered below.

The centralized model

The sweet stalk is directly supplied to the plant from the farmers' fields, and the juice is extracted and fermented to ethanol and allied co-products. Its operational area is generally limited to a 40–50 km radius around the plant owing to high transportation costs involved in bulky raw

FIGURE 1
Linkage between centralized model and decentralized models of the sweet sorghum supply chain

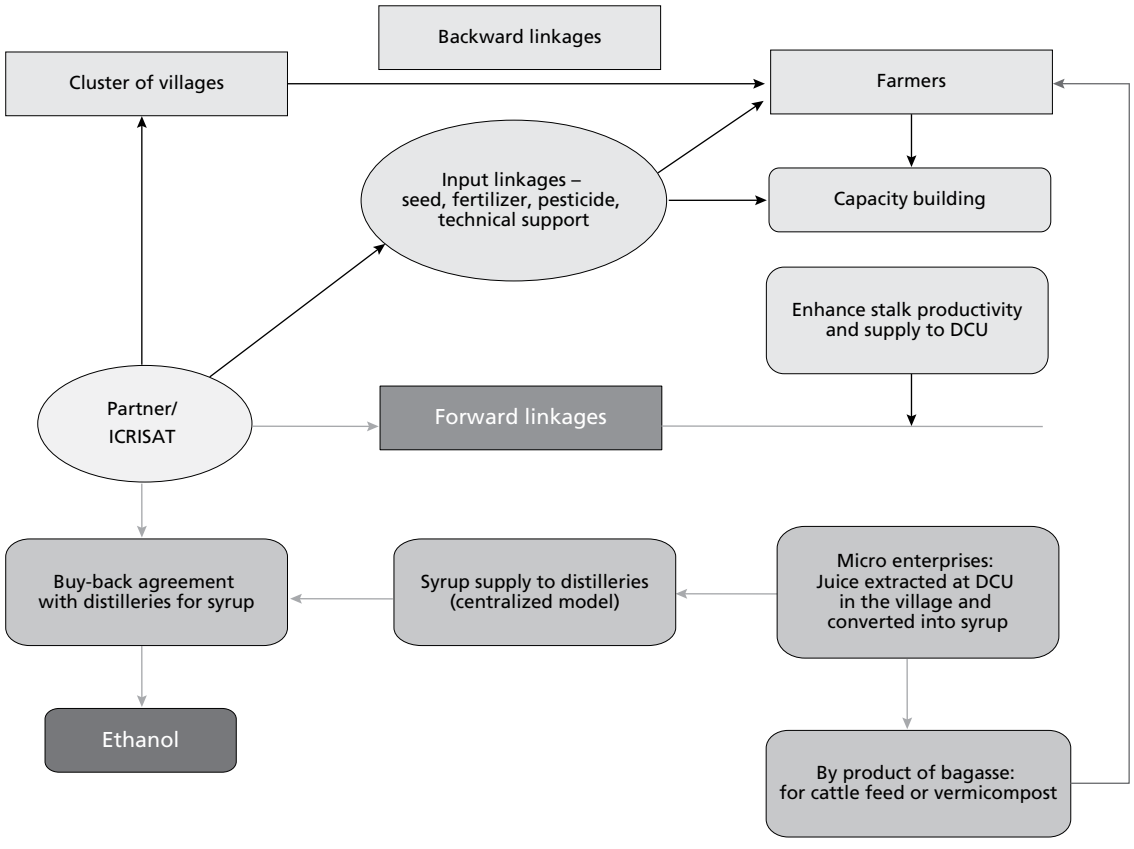


material supply. Examples of such centralized plants include Rusni Distilleries Ltd, Sangareddy, Medak District, Andhra Pradesh, India; Tata Chemicals Ltd, Nanded, Maharashtra, India; and ZTE Ltd, Inner Mongolia, China.

The decentralized model

Figure 1 illustrates the overlap of the two models, showing linkages of hundreds of farmers to decentralized crushing units (DCU), while thousands connect to a central distillery. The finer details reflect productivity, capacity utilization and other factors. In simple terms a DCU comprises the crusher and boiling unit, and essentially crushes the stalks to extract juice. The extracted juice is either concentrated to syrup or fermented *in situ* to alcohol. The forward and backward linkages of DCU are illustrated in Figure 2. Sweet sorghum is a seasonal crop that in India can be cultivated in three seasons a year (rainy, post-rainy and summer) to supply raw material for 3 to 4 months annually for ethanol production (Kumar *et al*., 2010). The grain and sugar yields are best in the rainy and summer seasons, whereas in the post-rainy season the grain yield is high, but with less stalk and sugar yield. A commercial ethanol distillery requires

FIGURE 2
Decentralized model. A village enterprise to crush stalks and produce syrup, linked with a centralized unit to produce ethanol from syrup



feedstock year round – for at least 10 months annually – for economical operation. However, in regions with short harvest windows, smaller acreages or with low plantation densities, a typical centralized model with a 30 kilolitres per day (KLPD) processing plant dedicated to sweet sorghum ethanol production could operate only seasonally, requiring a high capital investment that might not be cost effective. In areas with low plantation densities, the transportation costs associated with supplying the plant with sweet sorghum feedstock become prohibitive. Transportation costs are a significant cost factor in all sweet sorghum models studied, with costs ranging from US$ 34 to US$ 107 per tonne of fermentable carbohydrates (Bennett and Anex, 2009). Larger plant sizes may not benefit from traditional economies of scale because of the increased transportation costs associated with longer travel distances. Due to these limitations, alternative processing options have been investigated. In view of the need for regular supply of feedstock to the distillery, it is widely believed that DCUs help in sustainability of the supply chain. The juice obtained after crushing the stalks is boiled in pans to produce concentrated syrup (~60 percent Brix) (Photo 1), which is supplied to a distillery for ethanol production (Reddy *et al*., 2009).

Alternatively, extracted juice can also be fermented *in situ*, resulting in a fermentation mash containing 6–10 percent ethanol. Studies have shown that non-sterile fermentation in the field is possible, with very good ethanol conversion efficiencies, as demonstrated by a research group at the University of Oklahoma, USA (Kundiyana *et al*., 2006). As an alternative to fermentation of the sweet sorghum liquids, several groups have investigated the solid-phase fermentation of sweet sorghum for production of ethanol as it (i) has greater ethanol production per unit volume of the fermenter, (ii) has reduced fermentation capacity requirement, (iii) has no nutrient supplementation requirement, (iv) has lower production costs, (v) leaves smaller volumes of stillage for disposal, and (vi) needs less energy for distillation (Gibbons, Westby and Dobbs, 1986). In these systems, shredded sweet sorghum is injected into a solid-phase fermenter, inoculated with yeast, and mixed during fermentation. Fermenters have been of varied sizes and configurations, including rotary drums and screw augers (Gibbons, Westby and Dobbs, 1986). Solid-phase fermentations typically result in higher ethanol yield than fermentation of the juice alone (78 percent of theoretical ethanol yield in solid state versus 75 percent in juice fermentation) (Bryan, Monroe and Caussanel, 1985), but may have higher capital costs and lower throughput. Other variations to the system have included operating in a semi-continuous rather than batch mode, and application of immobilized yeast in the system, both of which improved system performance.

Potential advantages of small-scale, decentralized ethanol processing are:

- Promotes biodiversity by using more diverse feedstock.
- Enhances food security and food system resilience by ensuring that geographically diverse farms have access to locally-produced renewable fuel for food production.
- Promotes resource cycling by keeping nutritious co-products of ethanol production close to their farm source, where they can be returned to farms for feed or fertilizer.

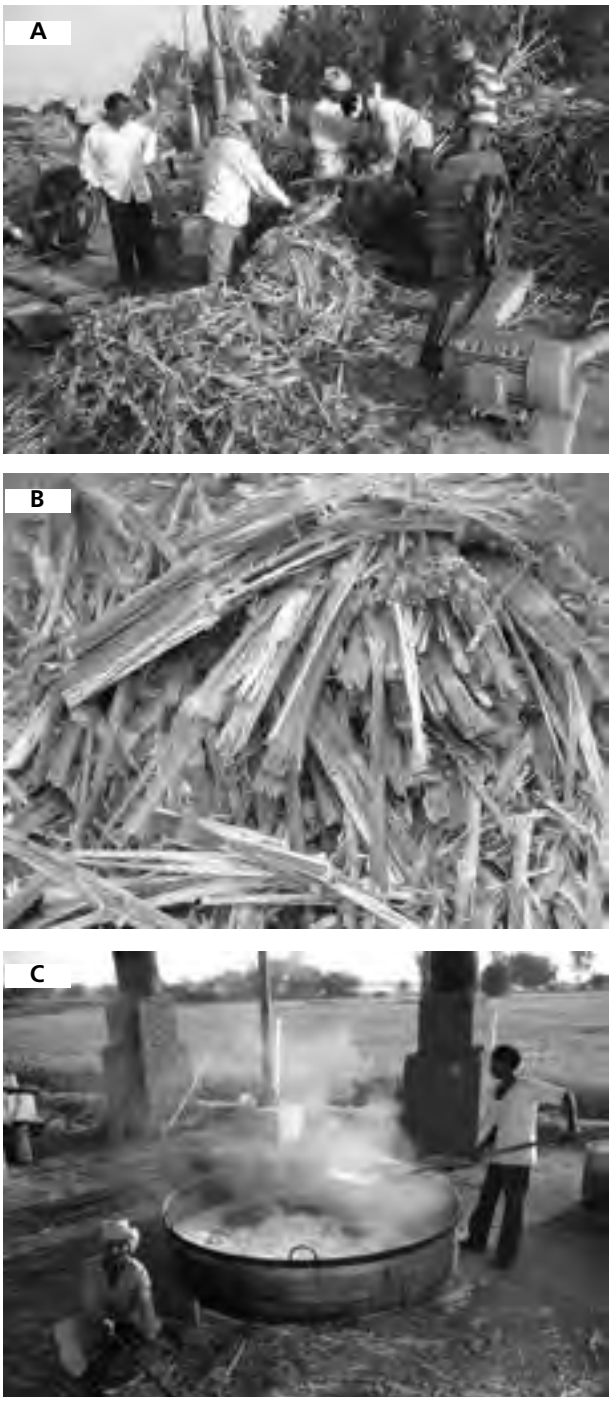


Photo 1
Decentralized sweet sorghum crushing unit. A. Crushing. B. Bagasse. C. Boiling the juice to produce syrup

- Produces feedstock on small farms, which tend to use land more efficiently than large farms.
- Co-products remain with the farmers.
- Reduces farm input needs through promotion of regionally-appropriate, low-input feedstock crops.
- Promotes equitable distribution and greater retention of wealth by rural communities.

CO-PRODUCTS

The processing options discussed above focus on the liquid carbohydrate portion of the sweet sorghum, but do not address the use of grain, the solid bagasse and steam that are generated during the pressing process, or the waste vinasse that is generated during the dewatering process. An ideal system will utilize as many crop components as possible to create a closed-loop system (Worley, Vaughan and Cundiff, 1992).

Grain

Currently the stalk from rainfed sweet sorghum grown in the rainy season is the source of raw material for the decentralized units in India. The grain is considered a co-product here as sweet sorghum is basically grown for production of ethanol by fermenting extracted juice from the sugary stalks. Mould-affected grain can be used as raw material for ethanol production, while mould-free grain can be used for human consumption. The primary product in DCU is syrup, which can be used either in ethanol production or in the food and pharmaceutical industries.

Grain from the rainy season crop is mostly mould-affected due to rains during grain development, maturation and harvest. Grain and stover yield are statistically unrelated in both hybrids and varieties (Blümmel *et al*., 2009). Stover yield is directly proportional to realizable bagasse yield (Kumar *et al*., 2010). High grain yields could be associated with above average stover yields. In a recent comprehensive investigation of grain-stover relationships in (non-sweet) sorghum cultivars tested by the Directorate of Sorghum Research (DSR), formerly the National Research Center for Sorghum (NRCS), Hyderabad, India, during the 2002–2006 period, Blümmel and co-workers (2010) observed that grain yields accounted for only 14 percent of the variation in stover yield, i.e. grain and stover yields in sorghum were only weakly positively associated. These findings suggest that grain and stover yield should both be recorded in sorghum improvement, since stover yields cannot be accurately predicted by grain yield measurements. Grain yields do not need to be achieved at the expense of fodder for livestock or feedstock for ethanol production, and vice versa.

Bagasse

The solid bagasse that remains after pressing sweet sorghum has several potential uses. One potential use is as animal feed, directly after chopping or after ensiling (Linden, Henk and Murphy, 1987). It has also been used as a source of pulp for the paper industry (Belayachi and Delmas, 1997). Another potential use of the bagasse is as a fuel source for the processing plant. With the addition of a solid-fuel boiler, the bagasse can be used to provide process heat to run the plant. With its heating value it is likely to require only 20–30 percent of the available biomass to fuel the plant (Bennett and Anex, 2009). In addition, processes for conversion of lignocellulosic material to ethanol are becoming more economically viable, making sweet sorghum bagasse a possible source of biomass for such a process. Studies have demonstrated that a large portion of the insoluble carbohydrate (cellulose and hemicellulose) from sorghum can be readily converted to ethanol (Sipos *et al*., 2009).

Foam and froth

Lot of foam and froth is generated during juice boiling. This can be collected separately and used to feed livestock or as organic fertilizer.

Steam

The steam generated during concentration of juice to syrup is a good source of energy, which can be used for several purposes, such as boiling water, which in turn can be used to increase juice extraction, heat treatment of juice before boiling, etc., by installing the necessary equipment to capture the outgoing steam.

Vinasse

Vinasse, also known as stillage, is the liquid co-product after removal of the final products during sugar processing. In a distillation process, vinasse is the liquid remaining after separation of ethanol. In the decentralized model of sorganol production, the dewatering and/or distillation system will produce 10–15 litre of waste vinasse (distillate) for every litre of ethanol produced in the later stages, depending on the initial ethanol concentration of the fermentation broth. The large volume generated and the high organic loading in the waste water make it a major environmental challenge for most commercial applications. Reports of bagasse characterization for sugar cane feedstocks show biochemical oxygen demand (BOD) levels ranging from 25 to 60 g/L, with nitrogen levels from 300 to 2500 mg/L and phosphorus levels from 10 to 300 mg/L. The limited data on sweet sorghum bagasse show comparable results, with BOD = 46 g/L, nitrogen = 800 mg/L and phosphorus = 1990 mg/L (Wilkie, Riedesel and Owens, 2000). Due to its high BOD, disposal into waterways is not an option. One potential option is land application of the vinasse as irrigation water and fertilizer. Several reports suggest that both dilute and concentrated vinasse (from sugar cane)

can be used on agricultural fields (Parnaudeau *et al*., 2008; De Resende *et al*., 2005). The vinasse or stillage produced from distillation of sweet sorghum ethanol has been reported to contain 0.2 percent nitrogen, 0.22 percent P_2O_5 and 0.3 percent K_2O. A study conducted in Brazil to determine the long-term effects of disposal of this material onto sugar cane fields found that vinasse applications of 80 m^3/ha increased mean yields of both cane and sugar by 12–13 percent (De Resende *et al*., 2005). A number of other disposal options could be considered, such as anaerobic digestion for production of methane (biogas), on-site combustion for production of energy, or composting to produce bio-fertilizers.

GRAIN UTILIZATION

Rainy season sweet sorghum grain is subject to mould damage if rainfall coincides with grain development, maturation and harvest, which often happens in major sorghum growing regions of India. The moulds have detrimental effects on yield and quality of sorghum grain, including decreasing its nutritive value, and producing mycotoxins and other toxic metabolites. Hence, it is not fit for human consumption, but preferred for alcohol production, and farmers use it as livestock and poultry feed, as the mycotoxins are below permissible threshold levels, and such grain is also inexpensive (Bandyopadhyay *et al.,* 1998; Reddy *et al.,* 2000; Thakur *et al.,* 2006). However, non-mouldy grain from where grain maturation does not coincide with rains and the grain from mould-tolerant sweet sorghum cultivars can be used as food for human consumption by making products like porridge, flat bread (*roti*), *bhakri* (stiff *roti*), flakes, chips, papad, baked products including yeast-leavened breads, cakes, muffins, cookies, biscuits, pasta and health foods. The grain yields among sweet sorghum cultivars vary widely and are cultivar (Table 2) and environment dependent. Hybrids have on average higher grain yield than the original varieties, but all other productivity-related variables were higher in the original varieties. Average grain yields were 10.8 percent (hybrids) and 6.0 percent (varieties) of total biomass yield. This proportionally low partitioning into grain yields probably reflects a sweet sorghum breeding target of high sugar yields in stems. Still, grain yields of up to 2.6 t/ha were recorded in both cultivar types (Table 2) and sweet sorghum grain can contribute significantly to rural food security. Mean juice yield in hybrids amounted to about 47 percent of stem yield, while it was 54 percent for the older varieties. Yields of bagasse plus stripped leaves were on average higher than the juice yields in both hybrids and the varieties, potentially providing 5.8 t/ha (hybrids) and 6.7 t/ha (varieties) of fodder (Table 2).

Grain structure and composition

The sorghum kernel is a naked caryopsis and consists of three main anatomical parts: pericarp (outer layer), endosperm (storage tissue) and germ (embryo), which generally account for 6, 84 and 10 percent of the seed mass, respectively. Sorghum is the only cereal grain known to have starch in the mesocarp layer of the pericarp. The endosperm, composed of the aleurone layer and peripheral corneous and floury areas, is the main storage tissue. The 1000-grain weight of sorghum varieties ranges from 19.0 to 28.5 g (Sehgal, Kawatra and Singh, 2004). Starch is the major grain component in sorghum, followed by protein. Most of the sorghum starch contains 70–80 percent branched amylopectin and 20–30 percent amylose. Waxy or glutinous sorghum varieties contain starch that is 100 percent amylopectin. Sorghum contains high levels of insoluble fibre with low levels of beta glucans. Most of the crude fibre is present in the pericarp and endosperm cell walls. This fibre is composed mainly of cellulose, hemi-cellulose and small quantities of lignin (Table 3).

TABLE 2
Yields of grain, leaf, stem, stover, juice, bagasse and bagasse plus stripped leaves (B+L) in 34 cultivars of sweet sorghum at Directorate of Sorghum Research (DSR) in 2005

	Mean (and range) in dry matter yields (t/ha)						
	Grain	Leaf	Stem	Stover	Juice	Bagasse	B+L
Hybrids (H)							
Mean	1.6 (10.8%)	1.5 (10.1%)	8.1 (54.7%)	11.7 (79%)	3.8 (25.7%)	4.3 (29%)	5.8 (39%)
Range	0.8–2.6	0.6–2.5	4.7–12.4	7.1–14.9	1.3–7.1	2.6–5.5	3.8–7.9
P	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.009
LSD (*P* <0.005)	0.6	0.5	2.0	2.9	1.8	0.1	2.2
Varieties (V)							
Mean	1.0 (6%)	1.8 (10.8%)	10.7 (64%)	13.9 (83.2%)	5.8 (34.7%)	4.9 (29.3%)	6.7 (40.1%)
Range	0.1–2.6	0.9–2.6	6.9–14.7	8.5–18.8	2.8–8.6	3.2–6.1	4.5–8.1
P	<0.0001	<0.0001	0.03	0.05	0.12	0.02	0.005
LSD (*P* <0.005)	0.5	0.57	4.2	5.15	–	1.9	2.1
P (H vs V)	0.007	0.07	0.002	0.02	0.002	0.05	0.02

Notes: Stover yield estimates include panicles after grain removal; values in parentheses are proportion of each component in the total biomass. *P* = probability; LSD = least square difference. *Source*: Blümmel *et al*., 2009.

TABLE 3
Typical composition of sorghum and sweet sorghum grain

Constituent	Mean	Range	Constituent	Mean	Range
Proximate analyses			**Protein fractionation**		
Protein (%)	11.6	8.1–16.8	Prolamine (%)	52.7	39.3–72.9
Ether extract (%)	3.4	1.4–6.2	Glutelins (%)	34.4	23.5–45.0
Crude fibre (%)	2.7	0.4–7.3	Albumins (%)	5.7	1.6–9.2
Ash (%)	5.8	1.2–7.1	Globulins (%)	7.1	1.9–10.3
Nitrogen-free extract (%)	79.5	65.3–81.0	Prolamine (%)	52.7	39.3–72.9
Fibre			**Essential amino acids (as g/16 g N)**		
Dietary insoluble fibre (%)	7.2	6.5–7.9	Lysine	2.1	1.6–2.6
Dietary soluble fibre (%)	1.1	1.0–1.2	Leucine	14.2	10.2–15.4
Acid-detergent fibre (%)	3.3	2.9–3.6	Phenylalanine	5.1	3.8–5.5
			Valine	5.4	0–5.8
			Tryptophan	1	0.7–1.3
			Methionine	1	0.8–2.0
			Threonine	3.3	2.4–3.7
			Histidine	2.1	1.7–2.3
			Isoleucine	4.1	2.9–4.8

Notes: As data from sweet sorghum grain is limited, data are mostly from grain sorghum. All values are expressed on a dry matter basis. *Sources*: Bach Knudsen and Munck,1985; Rooney, Kirleis and Murty, 1986; Monti, Di Virgilio and Venturi, 2008.

TABLE 4
Ash and mineral concentrations in the grain of grain sorghum and sweet sorghum

Sorghum type	Ash	N	C	Al	Ca	Cl	Fe	K	Mg	Na	P	S	Si
Grain sorghum	47	13	434	242	1824	6252	141	5587	2451	192	2150	1084	10671
Sweet sorghum	58	14	424	218	2417	5129	159	7125	2895	171	2620	1000	14321

Notes: Ash, N and C are expressed as g/kg DM; the other elements as mg/kg DM. *Sources*: Jambunathan and Subramanian, 1988; Monti, Di Virgilio and Venturi, 2008.

Utilization as ruminant feed

Both feed and food uses of sweet sorghum grain are compatible; not all grains will have desirable food processing properties, so the poorer quality grain might go into feeds. Obviously, care must be taken to avoid problems with mycotoxins. Sorghum grain is rich in many minerals, including Ca, Mg, P and K (Table 4). Sorghum is a very good feed grain as long as it is properly supplemented for the particular species being fed. Sorghums without a pigmented testa have 95 percent or greater of the feeding value of yellow dent maize for all species of livestock. In India, on average, 250 g grains are consumed per dairy animal per day. Consumption of sorghum grain by dairy cattle is highest in northern India and lowest in southern India. Considering the large population of animals and government policy in support of milk production, the requirement of grains by feed industries will be quite high. Considering the nutritional value of sorghum (Tables 3 and 4) and the probable shortage of grain and roughages, coupled with limitations on other fodder crops cultivation in Asia and sub-Saharan Africa, there is wide scope for more inclusion in feed formulations of sorghum grain harvested from decentralized sweet sorghum production systems.

Utilization as poultry feed

The demand for sorghum for poultry feed largely depends on the price and availability of maize. Inclusion of sorghum at up to 10 percent for layers and 15 percent for broilers is common. However, this rate increases in years of higher maize price. The present non-food share of sorghum grains usage in India is predicted at 77 percent for poultry, 16 percent for dairy, 6 percent for ethanol production and 1 percent for starch production (Dayakarrao *et al*., 2003). The chemical composition and nutritive value of sweet sorghum grain means it is rich in proteins, starch, fibre, vitamins and minerals. Anti-nutritional factors can be broadly classified as those naturally present in the grains and those developed due to contamination, which modify the nutritive value. Some of them have serious health consequences. Phytic acid, a major phosphorous store in the grain, is present at levels on par with that in maize and is not a problem in diets for chickens. Polyphenols (luteoforol and apiforol) in the seed coat confer bird and mould tolerance (Reddy *et al*., 2007). However, these compounds reduce digestibility and lead to growth retardation in chickens. Detoxifying methods such as moisturizing with alkali, dilute aqueous ammonia, sodium carbonate solution, formaldehyde, etc., reduce tannins (polyphenols) to tolerable levels in the diet (below 0.26 percent tannins). Aflatoxin contamination is

frequent in mouldy sorghum grain (Waliyar *et al*., 2008). Published data indicate that sorghum grain can replace up to 60 percent of maize in broiler diets and up to 100 percent in the diet of layers without affecting performance (Reddy and Rao, 2000). However, to be competitive, the sorghum grain market price needs to be about 10 percent lower than that of maize.

Other alternative uses

Sweet sorghum grain can be processed into diverse products to exploit its nutritive value. If the toxin levels are high, it is safe to process sorghum grain to produce ethanol or alcohol and vinegar. Sorghum grain is usually processed by dry milling to make flour for bread. Other processing methods include rolling, steaming, flaking, popping, parching, malting, brewing and fermentation. In rural areas, dehulling (pearling) is practised. These processing techniques, alone or in combination, result in a variety of products and co-products from sorghum grain, such as leavened bread, *injera*, porridge, pasta, grits (semolina), starch, glucose powder, liquid glucose, high fructose syrup, glue, xylitol, spirit, alcohol, beer and non-alcoholic beverages (malta, milo). In 2010, the state government of Maharashtra in India announced a US$ 0.25 promotional benefit per litre of ethanol produced from mouldy sorghum grains by the distilleries. This is expected to boost rainy season sweet sorghum cultivation, as the stalk will be purchased by the ethanol distillery and the grain by other distilleries and feed manufactures. However, in view of the shortage of human labour, this will be feasible only if mechanical harvesters are available.

Utilization of bagasse

Farmers in the drylands require varieties specifically developed with appropriate combinations of food, feed and fodder traits for use in crop-livestock systems, which will increase farmer income from the sale of grain, feed and fodder. From DCUs the major co-product is bagasse – the fibrous matter that remains after sweet sorghum stalks are crushed to extract their juice. For each 10 t of sweet sorghum crushed, the DCU produces 5 to 6 t of wet bagasse, depending on the genotype, season of crushing, juice extraction efficiency, temperature, etc. The high moisture content of wet bagasse, typically 40 to 50 percent, makes it unsuitable for direct use as a fuel. However, such fresh bagasse is preferred for use as livestock feed. Fodder from crop residues such as stover and straw does not require the allocation of additional land and water because they are a co-product of grain production. This makes crop residues and co-products the single most important – and affordable – fodder resource for small-scale farmers. Thus, any improvement in the nutritive value of crop residues, however small, can have considerable value and impact. Although cereal crop residues generally have low nutritive quality, genetic variation is being exploited to develop dual-purpose types that combine improved fodder quality with acceptable grain production. In many regions of sub-Saharan Africa and Asia the contribution of pastures to livestock feed has declined and been replaced by feed grains, crop residues and other concentrates (Parthasarathy Rao and Birthal, 2008). The problem of finding enough feed for animals raised by small-scale farmers is becoming almost as acute and politically significant as ensuring food security for people. While crop residues, particularly straw, already provide a large component of livestock feed, their nutritive value is often so low that farmers must supplement livestock diets with feed grain and other concentrates.

Bagasse fodder quality and composition

The potential feed value of sweet sorghum bagasse-based livestock feed is described in Table 5 (Blümmel *et al*., 2009). Nitrogen content was increased in bagasse residue plus stripped leaves (BRSL) compared with whole stover because of the higher leaf content in the BRSL, but all other laboratory fodder quality traits were higher in stover than in BRSL. For example, mean *in vitro* digestibility values for BRSL were around 5 percentile units lower than those of whole stover (Table 5). This reduction in fodder quality seems insignificant considering that highly digestible carbohydrates must have been removed in the extract, which amounted to 47 and 54 percent of stem yields in hybrids and varieties, respectively. This loss of highly digestible carbohydrates was perhaps compensated for by physical changes in the bagasse, facilitating faster and higher microbial colonization and ultimately digestion of residual fibre particles.

The chemical composition and physical properties of sweet sorghum bagasse (Table 6) shows that it has low ash and sulphur content, while being rich in minerals like Ca, Mg, Fe, Na and Zn (Negro *et al*., 1999).

Bagasse vs forage crops

Fresh bagasse can be sold directly to fodder traders, as shown by an arrrangement faciliated in 2009 and 2010 by the International Livestock Research Institute (ILRI) and partners in the National Agricultural Innovation Project (NAIP) decentralized sweet sorghum project set up in Ibrahimbad, Andhra Pradesh, India. After some iterations in fine-tuning bagasse to fodder transactions, an arrangement was implemented in 2010 to sell fresh bagasse leaving the crushing unit to fodder traders from Hyderabad at a rate of 70 paise per kg (US$ 0.016). The fodder traders chopped the bagasses and transported it by lorry to their customers, 70 km away in Hyderabad. The price of 70 paise per kg fresh bagasse is remarkable given that the whole (i.e. unextracted) sweet sorghum stalks were valued only slightly higher, at 80 paise (US$ 0.018) per kg, but probably reflects the substantially lower water content of the fresh bagasse.

TABLE 5
Nutritional parameters in hypothetical diets composed of bagasse and leaves of 34 cultivars of sweet sorghum

	Morphological and nutritional composition of bagasse residue and the stripped leaves (BRSL)							
	Bagasse (%)	**Leaf (%)**	**N%**	**NDF (%)**	**ADF (%)**	**ADL (%)**	**IVOMD (%)**	**ME** (MJ/kg)
Hybrids (H)								
Mean	73.7	26.3	0.73	64.5	41.4	4.9	44.6	6.5
Range	56.1–83.9	16.1–43.9	0.58–1.04	59.2–71.0	36.9–47.5	4.1–6.0	39.3–49.1	5.7–7.3
P	<0.0001	<0.0001	0.001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
LSD	8.6	8.6	0.22	3.4	2.4	0.44	2.6	0.43
Varieties (V)								
Mean	72	28	0.83	64.6	39.8	4.9	46.6	6.8
Range	60.5–81.9	18.1–39.5	0.73–0.92	60.6–70.9	36.7–45.0	4.3–6.0	42.0–50.4	6.1–7.5
P	0.0005	0.0005	0.75	0.0001	0.0006	<0.0001	0.0002	0.0003
LSD	8.6	8.6		3.8	0.63	0.55	4.04	3.37
P (H vs V)	0.55	0.55	0.0004	0.82	0.11	0.82	0.03	0.02

Notes: N = Nitrogen; NDF = neutral-detergent fibre; ADF = acid-detergent fibre; ADL = acid-detergent lignin; IVOMD = *in vitro* organic matter digestibility; ME = metabolizable energy; *P* = probability; LSD = least significant difference at *P* <0.005. *Source*: Blümmel *et al*., 2009.

TABLE 6
Chemical and physical properties of sweet sorghum bagasse

Parameter	**Value**	**Parameter**	**Value**
pH (H_2O)	6.8	S (%)	<0.01
Electrical conductivity (S/m)	0.027	P_2O_5 (%)	0.08
Organic matter (%)	95.2	K_2O (%)	0.20
Total nitrogen (%)	0.5	Na_2O (%)	0.08
Ash (%)	4.8	Mg (as MgO, %)	0.08
Ether-soluble fraction (%)	10.9	Ca (as CaO, %)	0.19
Ethanol-toluene extracts (%)	8.7	Cu (ppm)	48
Cellulose (%)	41.7	Zn (ppm)	35
Klason lignin (%)	18.9	Cr (ppm)	29
Elemental analysis		Pb (ppm)	20
C (%)	45.4	Fe (as Fe_2O_3, %)	0.15
N (%)	0.5	Mn (as MnO, %)	<0.2
H (%)	6.1	Cd (ppm)	<3.0

Source: Negro *et al*., 1999.

Silage making and quality assessment

For silage preparation, the recommended moisture level is generally 60 percent, and the fodder is chopped for better compaction and anaerobic fermentation, leading to better quality silage. For fresh bagasse leaf residue (BLR), it was observed that the moisture content was 48–52 percent, and experiments were conducted to ensile the fresh material, both whole and chopped, with no further processing (moisture addition or silage additives) to make it as cost effective and practicable as possible. The results showed that ensiling of whole and chopped BLR for 30 days without any additives resulted in good quality silage as assessed by the appearance and smell of the silage. The quality of silage was assessed further by feeding experiments with 4 adult Deccani rams, where the silage was supplemented with 150 g concentrate/animal/day. The trial lasted for 21 days. Intake and nitrogen balance of chopped sweet sorghum BLR was similar to the silage prepared from whole BLR and the intake on a dry matter basis as a percentage of body weight was 2.5 percent (Table 7) (Kumar *et al*., 2010).

ANIMAL STUDIES WITH SWEET SORGHUM BAGASSE

Nitrogen content, *in vitro* digestibility and metabolizable energy (ME) content of the sweet sorghum bagasse plus stripped leaves-based feed block (BRSLB) were significantly lower than in the commercial sorghum stover-based feed block (CFB), and the BRSLB was significantly superior to normal sorghum stover, but there were no differences in the NDF contents (Table 8). As expected, the laboratory quality indices were lowest for the sorghum stover. An important aspect of the work was to investigate the palatability of feed blocks when sorghum stover was entirely replaced by BRSL. The feeding trials with five murrah bulls (14 day adaptation period and 10 day collection period) showed that there was no (statistical) difference in feed intake between the CFB and the BRSLB (Table 8). For both blocks, the voluntary dry matter feed intake was high at 3.5 (CFB) and 3.7 percent (BRSLB) of animal live weight. Intakes of crop residues by non-lactating livestock are commonly around 2.0 percent or less of live weight (McDonald,

TABLE 7
Performance of sheep fed sweet sorghum bagasse and leaf residue as whole and chopped silage

Sweet sorghum bagasse and leaf residue	Dry matter intake (g/d)	Dry matter intake (as % body weight)	Dry matter digestibility (%)	Organic matter digestibility (%)	Nitrogen balance (g/d)
Chopped	415.4	2.5	59.3 a	60.2 a	5.7
Whole	414.0	2.5	63.1 b	64.3 b	4.8

Notes: a, b = Values followed by different letters in columns denote significant differences (P <0.05). *Source*: Kumar *et al.,* 2010.

TABLE 8
Comparative feeding results in bulls fed a marketed commercial sorghum stover-based feed block (CFB), an experimental sweet sorghum bagasse/stripped leaves-based feed block (BRSLB) and sorghum stover of the type used in the CFB

Diet	Nitrogen (% DM)	NDF (% DM)	*In vitro* digestbility (% DM)	ME (MJ/kg)	Intake (kg/day)	Intake (g/day per kg LW)	Weight change (kg/day)
CFB	1.81 a	56.1 a	57.5 a	8.21 a	7.31 a	35 a	0.82 a
BRSLB	1.65 b	56.2 a	54.6 b	7.77 b	7.52 a	37 a	0.73 a
Sorghum stover	0.45 c	70.2 b	50.5 b	7.30 b	2.31 b	13 b	-0.38 b

Notes: NDF = neutral-detergent fibre; DM = dry matter; ME = metabolizable energy; LW = live weight; CFB = commercial sorghum stover-based feed block; BRSLB = experimental sweet sorghum bagasse plus stripped leaves-based feed block; sorghum stover is the type used in the CFB. Different suffixes in columns denote significant differences (P <0.05). *Source*: Blümmel *et al*., 2009).

Edwards and Greenhalgh, 1988). In fact, the intake of sorghum stover when fed as sole feed was only 1.3 percent of live weight (Table 8). However, when fed as part of the well-balanced CFB, stover intake was increased. Since sorghum stover was more than 50 percent of the CFB, the intake of sorghum stover was more than 1.75 percent of the live weight in CFB-fed bulls. These findings underline the importance of balanced supplementation in improving the utilization of a basal diet and in optimizing the utilization of crop residues for livestock production. There was no significant difference between the daily liveweight gain of the bulls fed CFB (0.82 kg/day) and the bulls fed BRSLB (0.73 kg/day), which confirms the value of BRSL as a feed block ingredient.

Addition of non-protein nitrogen sources like ammonium sulphate and biuret, either alone or in combination with urea, calcium carbonate or starch sources can also be tried to further improve digestibility, N-content and intake while making silage.

The nutrient digestibility and nutritive value of sweet sorghum bagasse was determined in sheep (deccani rams) and buffalo (murrah bulls) through a digestion-*cum*-metabolism trial using a difference technique. A 7-day adaptation period, 14-day preliminary period and 7-day collection period was used for the trial. The results show that the dry matter intake (as percentage of body weight) with sweet sorghum bagasse was 1.43 in buffaloes and 1.60 in sheep (Table 9). The digestibility (percent) values of proximate nutrients and fibre fractions of sweet sorghum bagasse calculated by different methods in sheep and buffaloes are presented in Table 10. The digestible crude protein (DCP) of sweet sorghum bagasse was 1.0 percent in both sheep and buffaloes, while the total digestible nutrients (TDN) value was 50.7 percent in sheep and 51.8 percent in buffaloes (Kumar *et al.,* 2010).

In another animal experiment, fresh unchopped BLR when supplemented with 500 g cotton cake in milch buffaloes resulted in feed intakes of 22 to 26 kg (fresh matter basis), corresponding to 3.3 percent intake when expressed as a percentage of body weight, indicating that BLR is quite palatable and well accepted by the milch buffaloes (Kumar *et al.,* 2010). The level of milk production was around 3 L/day, and during the one-month feeding period the body condition of the animals also improved, as indicated by the heart girth measurements and the condition of the body coat. After the experiment the animals were fed as per the farmer's usual practice of grazing supplemented with paddy straw and limited rice bran, and it was observed that animals on average lost around

TABLE 9
Effect of supplementing sunflower cake to sweet sorghum bagasse (SSB) on dry matter intake in graded Murrah buffalo bulls and Deccani rams

Parameter	Buffalo	Sheep
Body weight (kg)	344.2 ± 5.99	43.2 ± 1.31
DMI (kg/day)		
Roughage	4.91 ± 0.13	0.69 ± 0.03
Concentrate	0.72 ± 0.00	0.19 ± 0.00
Total	5.63 ± 0.13	0.88 ± 0.03
DMI (g/kg body weight)		
Roughage	61.5 ± 1.21	40.9 ± 1.25
Concentrate	9.0 ± 0.24	11.4 ± 0.25
Total	70.5 ± 1.32	52.3 ± 1.25
DMI (as % body weight.)		
Roughage	1.43 ± 0.03	1.60 ± 0.05
Concentrate	0.21 ± 0.01	0.45 ± 0.01
Total	1.64 ± 0.04	2.04 ± 0.05

Notes: DMI = dry matter intake. Each value is an average of four observations. *Source*: Kumar *et al.,* 2010

TABLE 10
Nutrient digestibility and nutritive value of sweet sorghum bagasse in graded Murrah buffalo bulls and Deccani rams

Nutrient component	Digestibility (%)	
	Buffalo bulls	Deccani rams
Dry matter	52.47 ± 1.39	50.75 ± 1.84
Organic matter	58.96 ± 0.26	58.82 ± 0.69
Crude protein	40.19 ± 0.83	41.61 ± 0.80
Ether extract	60.97 ± 1.61	58.14 ± 0.31
Crude fibre	51.54 ± 0.40	52.23 ± 0.83
Nitrogen-free extract	58.40 ± 0.84	55.72 ± 1.02
Nutritive value (%)		
DCP	0.98 ± 0.02	1.02 ± 0.02
TDN	51.78 ± 0.43	50.67 ± 0.42

Notes: DCP = digestible crude protein; TDN = total digestible nutrient. Each value is an average of four observations. *Source*: Kumar *et al., 2010*.

20 kg within the first 15 days. Farmers appreciated that fresh sweet sorghum bagasse and leaf residue was well accepted by the buffaloes, but pointed out that chopping would have further improved the intake and reduced the refusal of thick stalk pieces. Interestingly, farmers observed that the milk of the fresh BLR fed animals was creamier than those on the previous grass diet due to increased fat content (Kumar *et al.,* 2010).

Other uses

Sweet sorghum bagasse, other than for animal feed, can be used as raw material for a range of purposes, including biofertilizer production, paper making and co-generation. One of the options for bagasse utilization is as organic soil amendment. However, the direct incorporation into the soil of raw wastes such as the bagasse is not usually suitable because they may cause undesirable effects, such as phytotoxicity and soil nitrogen immobilization. It is well known that composting is one of the most suitable ways of transforming wastes into more stable products that are safe and beneficial to plant growth. The finished compost has a low C/N ratio of 13, compared to 90 in the original substrate bagasse, and also has improved levels of macro- and micro-nutrients (Negro *et al*., 1999).

For the paper industry, cereal straw and sugar cane bagasse are two abundant raw materials in addition to wood from the forest. However, these raw materials are in short supply due to restrictions on cutting trees in the forest, electricity generation from bagasse and residues, and residue use as livestock feed. Hence, sweet sorghum bagasse was assessed for its suitability for paper making (Belayachi and Delmas, 1997). The quality of the pulp obtained from sweet sorghum bagasse is excellent for the paper industry. The pulp exhibits a degree of cohesion higher than 80 percent; a low kappa number, indicating good delignification; a high degree of polymerization; and exceptional physico-mechanical properties, meeting the requirements of the paper industry, and is expected to be the best alternative to sugar cane bagasse and cereal residues.

Co-generation is the simultaneous production of electricity and process heat from a single dynamic plant. Globally, biomass-based co-generation has been widely applied in forest industries and agro-industries such as sugar factories, rice mills and palm oil factories. The 30 KLPD Tata Chemicals Limited (TCL) plant at Nanded, Maharashtra, India, has a 2 MW per hour power generation capacity using bagasse, thus making it self-sufficient in energy.

Sweet sorghum bagasse, with a bulk density of 70–90 kg/m^3 and ash levels of 4–5 percent, is highly suitable for gasification (Rajavanshi and Nimbkar, 2005).

UTILIZATION OF FOAM, VINASSE AND STEAM

Literature is scanty in these areas. The foam, froth and vinasse that is taken out during concentration of juice to syrup is rich in nutrients and can be used in composting of bagasse as well as directly as organic fertilizer. Vinasse needs to be subjected to nutrient analysis. Similarly the steam generated while boiling can be captured and used as a source of heat. This heat can be channelled to warm water when the DCU is aiming for more juice extraction efficiency. Alternatively, it can be used for pre-heating of the juice before boiling.

ECONOMIC IMPORTANCE OF BAGASSE FOR THE SWEET SORGHUM VALUE CHAIN IN THE DECENTRALIZED SYSTEM

The current rate of conversion of a tonne of sweet sorghum stalk to juice is 26.9 percent (269 litres) with 700 kg available as wet bagasse. After drying, about 30 percent (210 kg) of that wet bagasse (700 kg) is available as fuel or as fodder for livestock. In DCUs, about 45 percent of the dry bagasse (95 kg) is utilized as fuel (heating the pans) for converting juice to syrup, and the remaining 55 percent (115 kg) of the bagasse can be used or sold as fodder for livestock. During the early phases of DCU development, bagasse was sold direct to fodder traders with no value addition, and at a low price. However, during subsequent seasons, based on feedback from traders, dried bagasse of sweet sorghum was chopped to realize a higher value. Accordingly, efforts were made toward chopping sweet sorghum bagasse, doubling returns to Rs. 1/kg (US$ 0.0022) for chopped sweet sorghum bagasse. This value addition through change in physical form of the bagasse increases the overall income from sweet sorghum in the ethanol value chain under the decentralized system. Additionally, sweet sorghum bagasse sold as fodder in the region of sorghum-based crop-livestock systems also helps in meeting the fodder requirements for the growing population of milch animals.

Reduction in cost of syrup production from sale of bagasse

The sale of chopped bagasse as fodder reduces the overall cost of processing syrup for ethanol production. The value realized for 115.5 kg of bagasse that is left over after use as fuel for the pans will be Rs. 115.5 (US$ 2.6) at current rate of Rs. 1/kg of fodder (costs of chopping not accounted for). Hence, the cost of processing a tonne of stalk, which is currently Rs. 1231 (US$ 28) (for both raw material and processing), will reduce by Rs. 115.5 (1231 115.5 = 1115.5) and thus the unit cost of syrup production, which was Rs. 25.65 (US$ 0.58) will reduce to Rs. 23.23 (US$ 0.53), a reduction of Rs. 2.40/kg (US$ 0.05) or 9 percent decline in cost. Since there is further scope for value addition from bagasse sold for fodder (pellets), higher returns can be realized by selling a better product and thus further reducing syrup cost.

KNOWLEDGE GAPS AND FUTURE RESEARCH NEEDS

The commercial viability of the decentralized model of the sweet sorghum value chain depends on the efficient utilization of co-products in addition to the efficiency of operation and price of the main product, i.e. syrup. The following gaps have been identified based on several years of operation of DCUs in India:

- At present, there is a very limited period of operation of the crushing unit (less than 20–25 days) as the cultivar maturity window is not large. Research should aim at developing sweet sorghum genotypes with adaptability across seasons and months of the year.
- DCUs are being operated only for the rainy season crop (June–September). The post-rainy and summer season crops require an assured irrigation source, thereby increasing the cost of cultivation. Currently there are no suitable sweet sorghum cultivars adapted to post-rainy season conditions. The lower temperatures and shorter day lengths of this season hinder both biomass production and sugar accumulation in the tropical sweet sorghums, which are thermosensitive.
- The majority of the existing sweet sorghum cultivars are not multi-purpose, so do not meet the varying needs of the local agricultural systems. For example, high IVOMD, along with high sugar and biomass yield, are preferable for ensiling to meet livestock feed requirement. In areas where bio-composting is common, biomass with a high C:N ratio is not preferred. Research on hay-type sorghum species suggests that between 1950 and 2000 stem and leaf crude protein decreased and leaf NDF increased due to overemphasis on biomass quantity rather quality (Bolsen *et al*., 2003).
- Juice extraction efficiency and syrup conversion efficiency are low. A scenario analysis conducted at ICRISAT showed that improving these even by 5 percent has significant bearing on the economics of the whole value chain.
- As syrup is the main product of a DCU, its quality parameters need to be improved to meet the requirements of diverse end users (such as suitability for use in food, beverage and pharmaceutical industries). Research also needs to focus on improving organoleptic characteristics.
- Commercial dairies are increasingly using the fresh bagasse, after chopping, to feed cattle. Education and training is needed for farmers to raise awareness of the multiple uses of bagasse, such as for feed block making, ensiling or bio-composting.
- Little or no information is available on the utilization of co-products like vinasse, steam, foam and froth. Hence research efforts are needed in using steam for heating or boiling the juice, and in exploring the use of nutrient-rich vinasse, foam and froth as livestock feed and biofertilizers.
- Capacity building of staff at every step – not only syrup production, but also co-product utilization – would go a long way toward improving the operational efficiency and economic viability of DCUs.
- The varied products and co-products of the DCU need to be positioned to exploit locally existing market opportunities, i.e. an inclusive market-oriented development (IMOD) approach, as this brings the DCU closer to the rural farming communities.
- There are no studies on life cycle assessment (LCA) of DCUs with reference to carbon and energy balances. Such assessment studies would help all the stakeholders to understand the real value of this novel system, aside from economic viability analysis.

CONCLUSIONS

The potential uses of co-products from sweet sorghum DCUs for livestock feeding are unequivocally established. Considering the available genetic variability for fodder traits and ensiling parameters of sweet sorghum, the novel DCU system offers unforeseen opportunities, not only for meeting livestock feed demand of poor farmers, but also for offering an environmentally sound agro-enterprise that has tremendous implications for organic recycling related to carbon sequestration, GHG emissions and ecological balance. However, challenges remain pertaining to economic viability and marketability of the products and co-products of DCUs, requiring better linkages of poor and marginal farmers with emerging markets. These challenges must be addressed as a priority if there is to be greater involvement of rural agrarian communities in sweet sorghum cultivation.

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