Use of Corn Co-Products in Diets Fed to Swine

Hans H. Stein, Ph.D,
University of Illinois
hstein@Illinois.edu

Summary

There are a number of corn co-products available to the feed industry and most of these products may be included in diets fed to pigs. The product that is available in the greatest quantities is distillers dried grains with solubles (DDGS), which may be included in diets fed to all groups of pigs in amounts of 20 to 30% or more. The energy value of the diets will not change as DDGS is included, but the inclusion of dicalcium phosphate or monocalcium phosphate may be reduced as DDGS is used because of the high concentrations of digestible P in DDGS. The concentration of digestible Lys may be estimated using a prediction equation based on the concentration of Lys and crude protein or Lys and reactive Lys. The major challenge with feeding DDGS to pigs is that it may result in soft belly and back fat in pigs and it may, therefore, be necessary to reduce the inclusion rate during the final 3 to 4 weeks prior to slaughter. If the fat concentration in DDGS is less than 9%, the energy value will be reduced and the product has a reduced value. Only small amounts of distillers dried grains without solubles (DDG) are available, but DDG may be used at the same inclusion rates as DDGS. Other co-products from the ethanol industry include High protein distillers dried grains (HP DDG) and corn germ. In diets fed to growing pigs, at least 40% HP DDG can be used and in diets fed to finishing pigs, HP DDG may replace all the soybean meal in the diet. Corn germ may be included by at least 30% in diets fed to growing-finishing pigs without impacting growth performance, and corn germ may be included in addition to inclusion of DDGS.

Co-products from the wet milling industry include corn gluten meal, corn gluten feed, and corn germ meal. Corn gluten meal is a high protein ingredient, but because of the relatively low concentrations of Lys and Trp, usage in diets fed to swine has been limited until now. However, the amino acids in corn gluten meal are well digested by pigs and it is possible that with addition of synthetic amino acids, up to 20 or 30% corn gluten meal may be used in diets fed to growing-finishing pigs and sows. Corn gluten feed and corn germ meal are low-fat, high-fiber ingredients that are usually not included in diets fed to swine. However, the digestibility of amino acids in both ingredients is similar to that in corn and it is likely that at least 10 to 20% of these ingredients can be used in diets fed to both growing-finishing pigs and sows provided that diets are correctly balanced for digestible amino acids.

Hominy feed is a product from the dry grind industry, which has a relatively high concentration of starch. Overheating sometimes results in a low digestibility of Lys, but the concentration of amino acids in hominy feed is low. There is a lack of research to investigate effects of including hominy feed in diets fed to pigs, but a conservative estimate is that hominy feed may replace at least 50% of all the corn in diets fed to all categories of pigs.

Introduction

The traditional corn-soybean meal diet has served the U.S. swine industry well for more than 50 years and corn and soybean meal complement each other better than most other ingredients in terms of meeting the nutritional needs of growing and reproducing swine. With the recent increases in the costs of corn and soybean meal, it is, however, necessary to look for alternatives to these traditional ingredients – not to identify something that is better than corn and soybean meal, but primarily to identify ingredients that can be mixed to form a less expensive diet than the corn-soybean meal diet. Pigs are forgiving animals and they perform well on many different combinations of ingredients so the challenge for nutritionists is to identify the combination of ingredients that most economically meets the nutritional and energetic needs of the animals. There are a number of ingredients that may be combined to formulate swine diets and among these ingredients are many of the co-products from the corn-processing industry, which includes ingredients from both the dry milling and the wet milling industries. The distillation industry, which produces either ethanol or beverages and several co-products is the most important sector in the corn-milling industry if measured on quantities of co-products produced.

Co-products from the Distillation Industry

DDG, DDGS, Low-fat DDGS, and De-oiled DDGS

If corn is used for the production of ethanol or beverages, it is fermented and distilled, and carbon dioxide and ethanol or beverages are produced. Sugars and most of the starch are fermented during this process, but the protein, the lipids, the fiber, and the ash in corn is not fermented. These nutrients are instead left in the co-products from the production of ethanol and beverages.

The part of the corn kernel that is not fermented is often partially dehydrated via centrifugation and then split into a distilled grains fraction and a solubles fraction. The distilled grains may be dried and sold as distillers dried grains (**DDG**). However, the solubles may also be added to the distilled grains and dried and in that case, distillers dried grains with solubles (**DDGS**) is the product that is produced (Stein, 2011). Distillers dried grains and DDGS contain 9 to 14% crude fat and between 25 and 30% CP (Table 1). However, as is the case with other sources of corn protein, the concentrations of Lys (0.5 – 1.0%) and Trp (0.10 to 0.34) are low in DDG and DDGS compared with the requirements of pigs (Stein and Shurson, 2009). It is, therefore, necessary to include crystalline Lys and sometimes also crystalline Trp in diets containing DDG or DDGS to balance the concentrations of indispensable amino acids. The concentration of Lys in DDGS is more variable than the concentration of most other amino acids because over-heating sometimes destroys Lys in DDGS (Pahm et al., 2008a; b; Stein and Shurson, 2009). However, destruction of Lys due to over-heating is less of a problem in DDG than in DDGS because addition of the solubles to the distilled grains increases the risk of creating Maillard reactions and thereby destroying Lys (Pahm et al., 2008b).

Most amino acids in DDGS are well digested by pigs (Table 2), but if the DDGS has been over-heated, Maillard reactions may contribute to a reduction in the apparent and standardized ileal digestibility of Lys. There is, therefore, more variability in the digestibility of Lys in DDGS than in the digestibility of other amino acids (Pahm et al., 2008a), which may create problems in diet formualtions. However, the digestibility of Lys in DDGS may be estimated using the following equation (Pahm et al., 2008b):

$$\text{Standardized ileal digestible Lys (\%)} = 0.023 + 0.637 \times \text{reactive Lys (\%)}$$

Reactive Lys can be calculated from the concentration of furosine that is analyzed in DDGS after acid hydrolysis of the sample. Furosine is analyzed by HPLC and the concentration of reactive Lys in the sample is calculated from the following equation (Pahm et al., 2008b):

$$\text{Reactive Lys (\%)} = \text{analyzed Lys (\%)} - \text{furosine (\%)} / 032 \times 0.40$$

The accuracy of the above equation was recently confirmed in an experiment that included 21 sources of DDGS (Kim et al., 2010). Using this equation, it is, therefore, possible to estimate the concentration of digestible Lys in DDGS.

The concentration of digestible Lys in a given source of DDGS may also be calculated without including reactive Lys in the equation, which eliminates the need for determining the concentration of furosine in the sample. In that case, the concentration of digestible Lys is calculated from the concentration of total Lys and CP in DDGS using the following equation:

$$\text{Standardized ileal digestible Lys (\%)} = -0.636 + [0.858 \times \text{Lys (\%)}] \times [0.12 \times (100 \times \text{Lys (\%)} / \text{CP (\%)})]$$

By using one of the above equations, it is possible to predict the concentration of digestible Lys in a given source of DDGS and this value can then be used in diet formulations.

The concentration of NDF in DDGS is between 30 and 35%, and the apparent total tract fermentation of NDF in DDGS is less than 50% (Urriola et al., 2010). The reason for the relatively low fermentability of NDF is that most of the fiber in DDGS is insoluble dietary fiber, which has a low fermentability, whereas soluble dietary fiber has a much greater fermentability. Thus, it may be possible to improve the fermentability of fiber in DDGS by improving the solubility by mechanical of chemical processing of the fiber (Beltranena et al., 2009). This in turn will most likely improve the energy value of DDGS so research in this area is clearly needed.

Despite the low fermentability of fiber in DDGS, the energy value of DDGS is comparable to that of corn because the concentration of fat and crude protein is relatively high (Pedersen et al., 2007a; Stein et al., 2009). As a consequence, the concentration of energy will not change if DDGS is included in the diets.

In some ethanol plants, crude fat is skimmed off the solubles before solubles are added to the distilled grains and a low fat-DDGS is then produced. This product contains between 6 and 9% crude fat and has a reduced energy value compared with conventional DDGS, but research to quantify the energy value of this product has not been conducted. However, if the fat is extracted from the DDGS using a solvent extraction procedure, the resulting de-oiled DDGS contains between 2 and 6% crude fat and this product has a very low energy value to pigs (Jacela et al., 2011). When evaluating different sources of DDGS, it is, therefore, important to analyze for the concentration of crude fat and if that is less than 9% then the energy value of that source of DDGS is less than in conventional DDGS.

The concentration of P in DDGS is between 0.70 and 0.90%, and the standardized total tract digestibility of P in DDGS is between 50 and 70% (Stein and Shurson, 2009; Almeida and Stein, 2010a, b). The reason for this relatively high digestibility of P is that most of the phytate in the corn kernel is degraded during the fermentation process and the P in DDGS is, therefore, much more digestible than P in corn. However, the low concentration of phytate in DDGS also means that the digestibility of P is not improved by inclusion of phytase to DDGS (Almeida and Stein, 2010a, b). Nevertheless, if a diet containing corn, soybean meal, and 20% DDGS is formulated and 500 units of microbial phytase is included in the diet to improve the digestibility of P in corn and soybean meal, growing or finishing pigs do not require any inorganic P such as dicalcium phosphate included in the diet (Almeida and Stein, 2010b). Pigs fed such a diet will also reduce the excretion of P in the manure by approximately 50% compared with pigs fed a conventional corn soybean meal based diet without DDGS and microbial phytase (Almeida and Stein, 2010b). By using both DDGS and microbial phytase, it is, therefore, possible to formulate diets that are less expensive than conventional diets and also result in reduced excretion of P in the manure. Thus, use of DDGS is both economical and may contribute to a reduction of P-pollution.

If the Lys is not damaged due to over-heating, DDG and DDGS are excellent feed ingredients that may be included in diets fed to most groups of pigs by at least 20 to 30% (Stein and Shurson, 2009; Stein, 2011). Although, negative effects of including 20 to 30% DDGS in diets fed to pigs have sometimes been reported, the majority of published research has indicated that pig performance is not changed if DDGS is included in diets fed to weanling or growing-finishing pigs (Table 3, Table 4). Likewise diets fed to gestating and lactating sows may also contain at least 30% DDGS without negatively influencing sow or pig performance (Wilson et al., 2003; Greiner et al.,2008). However, under certain circumstances, diets fed to growing-finishing pigs may contain up to 45% DDGS without any major changes in pig performance (Cromwell et al., 2011). Likewise, diets fed to gestating sows may contain up to 50% DDGS without changing sow performance (Wilson et al., 2003).

It is, however, recognized that the softness of backfat and belly fat of pigs fed diets containing DDGS is increased compared with pigs fed diets based on corn and soybean meal (Whitney et al., 2006; Widmer et al., 2008). It may, therefore, be necessary to restrict the inclusion of DDGS in diets fed to finishing pigs to 15 to 20% during the final 3 to 4 weeks prior to weaning (Hill et al., 2008; Xu et al., 2010b).

HP-DDG, HP-DDGS, and Corn Germ

In some ethanol plants, corn is de-hulled and de-germed before it is fermented and distilled. This process is called “front-end fractionation” and the purpose is to reduce the concentration of un-fermentable materials (i.e., fiber and fat) that enters fermentation and have a product with a greater starch concentration enter fermentation to increase the yield of ethanol from the process. The distilled grains that are produced from this process have a greater concentration of crude protein (40 to 48%) and ash (Table 1) than the conventional distilled grains, but the concentration of lipids is reduced to less than 6% (Widmer et al., 2007; Kim et al., 2009; Jacela et al., 2010). The solubles are usually added to the hulls of the grain and marketed as corn bran, which is not fed to pigs. Solubles are, therefore, not added to the distilled grains if this process is used, and the dried grains are called high protein distillers dried grains (**HP-DDG**). However, if the solubles are added to the dried grains, high protein distillers dried grains with solubles (**HP-DDGS**) will be produced (Stein, 2011).

The concentration of digestible and metabolizable energy in HP-DDG is greater than in corn and in traditional DDGS, and the digestibility of amino acids is similar to the digestibility in conventional DDGS (Widmer et al., 2007; Kim et al., 2009; Table 2). The concentration of P in HP-DDG is less than in traditional DDGS, but the digestibility of P is similar in HP-DDG and DDGS (Widmer et al., 2007; Almeida and Stein, 2010a). If HP-DDG is included in diets that are correctly balanced for indispensable AA, HP-DDG may be included by at least 40% in diets fed to growing pigs (Widmer et al., 2008) and it may replace all the soybean meal in diets fed to finishing pigs (Widmer et al., 2008; Kim et al., 2009).

The germ that is produced in the initial de-germing of the grains may also be used as a feed ingredient in diets fed to pigs. This product contains 16 to 20% crude fat, approximately 15% CP, and has a relatively high concentration of fiber (Widmer et al., 2007; Table 1). The concentration of digestible and metabolizable energy in corn germ is similar to that in corn (Widmer et al., 2007). Corn germ contains more than 1.1% P, but the majority is bound in the phytate complex and the digestibility of phosphorus in corn germ is, therefore, low (Widmer et al., 2007). However, inclusion of microbial phytase in diets containing corn germ will increase the digestibility of P to a level that is close to that in HP-DDG and DDGS (Almeida and Stein, 2010a).

It has been demonstrated that corn germ may be included in diets fed to growing-finishing pigs by at least 10 or 15% without impacting pig performance (Widmer et al., 2008; Lee et al., 2011). However, recent data from the University of Illinois indicate that corn germ may be included by up to 30% in diets fed to growing-finishing pigs without impacting pig growth performance (Lee et al., unpublished). This inclusion rate was used in corn-soybean meal diets as well as in diets containing corn, soybean meal, and 30% DDGS, but regardless of the type of diet, pig performance was not affected by the inclusion of corn germ.

Corn Gluten Meal, Corn Gluten Feed, Corn Germ Meal, and Hominy Feed

Corn gluten meal is a co-product of the wet milling industry where it is produced after most of the starch and germ have been removed and some of the fiber has been separated off (Stock, 2000). All the protein is, however, left in the corn gluten meal that contains approximately 60% CP and has a low concentration of NDF (De Godoye et al., 2009). The balance of indispensable amino acids in corn gluten meal is not ideal relative to the requirements of pigs and there is relatively little corn gluten meal used in diets fed to pigs. However, if corn gluten meal-containing diets are fortified with crystalline Lys and Trp, diets that are balanced in indispensable amino acids may be formulated. The standardized ileal digestibility of amino acids in corn gluten meal is greater than in corn (Almeida and Stein, 2011) and the concentration of metabolizable energy is similar to that in corn and in DDGS. Up to 15% corn gluten meal may be included in diets fed to weanling pigs without impacting pig performance (Mahan, 1993), but there is a need for data demonstrating the effects of including corn gluten meal in diets fed to growing-finishing pigs and sows.

Corn gluten feed is also a co-product of the wet milling industry and is the part of the corn kernel that remains after extraction of most of the starch, germ, and gluten for production of corn starch or corn syrup. It mainly consists of corn bran, corn germ, and steep liquor (Honeyman and Zimmerman, 1991; Stock et al., 2000). Corn gluten feed is, therefore, a high-fiber feed ingredient that often contains more than 40% NDF and 20 to 25% crude protein. The standardized ileal digestibility of most amino acids in corn gluten feed is similar to that in corn, but the concentration of metabolizable energy is considerably less than in corn (Almeida and Stein, 2011). Corn gluten feed is not commonly included in diets fed to weanling or growing pigs, but it may be included in diets fed to gestating sows, where it has a relatively good energy value (Honeyman and Zimmerman, 1991). There is also a need for research to evaluate if corn gluten feed can be included in diets fed to weanling or growing-finishing pigs.

Corn germ may be produced from wet milling where germ is separated from the corn kernel during the initial steps before starch is removed (Stock et al., 2000). Corn germ may, however, also be produced during dry milling before production of corn meal, corn grits, or other corn products or in the initial steps of front-end fractionation in the ethanol industry as indicated above. Regardless of the production process, germ may undergo solvent extraction to remove the oil, which is then used for human consumption. The resulting defatted corn germ is called corn germ meal (Stock et al., 2000). Corn germ meal contains 20 to 25% crude protein, more than 50% NDF and less than 3% crude fat (Weber et al., 2010). The standardized ileal digestibility of most amino acids in corn germ meal is similar to the digestibility of AA in corn and in corn gluten feed (Almeida and Stein, 2011). However, because of the high concentration of fiber and the low concentration of fat, the concentration of metabolizable energy in corn germ meal is low and similar to that in corn gluten feed. Research to investigate effects of including corn germ meal in diets fed to pigs is limited and corn germ meal is usually not included in diets fed to pigs. However, inclusion of up to 38% corn germ meal in diets fed to growing pigs may not impact pig growth performance, but feed efficiency is reduced (Weber et al., 2010).

Hominy feed is a co-product from the dry-milling industry that is generated after production of corn flour, corn grits, or pearl hominy and consists of corn bran, broken kernels, germ residue after oil extraction, and fractions of corn germ, pericarp, and endosperm (Larson et al., 1993; Stock et al., 2000). Hominy feed contains 6 to 10% crude protein and more than 4% ether extract. The concentration of starch and NDF can vary, but most sources of hominy feed contain more than 50% starch and less than 30% NDF (Larson et al., 1993). The digestibility of amino acids in hominy feed may vary and is sometimes less than in corn (Almeida and Stein, 2011), and overheating during the production process may result in a low digestibility of Lys in some sources of hominy feed. The energy value to pigs of hominy feed may be similar to that of corn (Stanley and Ewan, 1982) although values for digestible and metabolizable energy in hominy feed that are slightly less than in corn have also been observed (Univ. of Illinois, unpublished data). Hominy feed is palatable and easily consumed by pigs and it may be included in diets fed to all groups of pigs. Research has not been conducted to investigate the impact of including hominy feed in diets fed to pigs, but a conservative estimate is that 50 to 75% of the grain can be replaced by hominy feed in diets fed to all categories of pigs.

Take Home Message

- DDGS may be included in diets fed to all categories of pigs by up to 30%. However, diets fed to growing pigs and gestating sows may be formulated to contain 45 and 50% DDGS, respectively without major changes in animal performance.
- The concentration of digestible Lys in DDGS may be calculated using a prediction equation that includes total Lys and crude protein or total Lys and reactive Lys.
- DDGS contains 0.7 to 0.9% phosphorus, which has a high digestibility.
- In diets containing DDGS and microbial phytase, no dicalcium phosphate is needed.
- HP DDG may be included in diets fed to growing pigs by at least 40% and may replace all the soybean meal in diets fed to finishing pigs.
- The concentration of metabolizable energy in HP DDG is greater than in corn and the digestibility of P is similar to that in DDGS.
- Corn germ may be included in diets fed to growing-finishing pigs by at least 30%.
- Corn gluten meal is a high-protein ingredient that contains amino acids with a high digestibility.
- The concentration of Lys and Trp is relatively low in corn gluten meal and crystalline sources of these amino acids need to be included in the diets if corn gluten meal is used.
- Corn gluten feed and corn germ meal are high-fiber, low-energy ingredients that may be used in diets fed to pigs in amounts of up to 20% if diets are correctly balanced for digestible amino acids.
- Feed efficiency may be reduced if corn gluten feed or corn germ meal is used because of the low concentration of metabolizable energy in these ingredients.
- Hominy feed has a relatively high concentration of starch and may replace at least 50% of the corn in diets fed to all categories of pigs.

References

Almeida, F. N., and H. H. Stein, 2010a. Effects of graded levels of phytase on the apparent and standardized total tract digestibility of phosphorus in corn and corn co-prodcuts. J. Anim. Sci. 88(E-suppl. 2):378 (Abstr.)

Almeida, F. N., and H. H. Stein. 2010b. Performance and phosphorus balance of pigs fed diets formulated on the basis of values for standardized total tract digestibility of phosphorus. J. Anim. Sci. 88:2968-2977.

Almeida, F. N., and H. H. Stein. 2011. Digestibility of amino acids in corn, corn co-products, and bakery meal fed to growing pigs. J. Anim. Sci. doi:10.2527/jas-4145.

Amaral, R. B., L. J. Johnson, J. E. Anderson, S. K. Baidoo, and G. C. Shurson. 2009. Effects of low-solubles distillers dried grains (LS-DDGS) in diets for growing-finishing pigs: Energy content and pig growth performance. J. Anim. Sci. 87(E-Suppl. 3):80. (Abstr.)

Augspurger, N. R., G. I. Petersen, J. D. Spencer, and E. N. Parr. 2008. Alternating dietary inclusion of corn distilelrs dried grains with solubles (DDGS) did not impact growth perforamnce of finishing pigs. J. Anim. Sci. 86(Suppl. 1):523. (Abstr.)

Barbosa, F. F., S. S. Dritz, M. D. Tokach, J. M. DeRouchy, R. D. Goodband, and J. L. Nelsen. 2008. Use of distillers dried grains with solubles and soybean hulls in nursery pig diets. J. Anim. Sci. 86(Suppl. 1):446. (Abstr.)

Beltranena, E., J. Sánchez-Torres, L. Goonewardene, X. Meng, and R. T. Zijlstra. 2009. Effect of single-or twin-screw extrusion on energy and amino acid digestibility of wheat or corn distillers dried grains with solubles (DDGS) for growing pigs. J. Anim. Sci. 87(Suppl. 3):166. (Abstr.)

Bohlke, R. A., R. C. Thaler, and H. H. Stein. 2005. Calcium, phosphorus, and amino acid digestibility in low-phytate corn, normal corn, and soybean meal by growing pigs. J. Anim. Sci. 83:2396-2403.

Burkey, T. E., P. S. Miller, R. Moreno, S. S. Shepherd, and E. E. Carney. 2008. Effects of increasing levels of distillers dried grains with solubles (DDGS) on growth performance of weanling pigs. J. Anim. Sci. 86(Suppl. 2):50. (Abstr)

Cook, D., N. Paton, and M. Gibson. 2005. Effect of dietary level of distillers dried grains with solubles (DDGS) on growth performance, mortality, and carcass characteristics of grow-finish barrows and gilts. J. Anim. Sci. 83(Suppl. 1): 335 (Abstr.)

Cromwell, G. L., M. J. Azain, O. Adeola, S. D. Carter, T. D. Crenshaw, S. W. Kim, D. C. Mahan, P. S. Miller, and M. C. Shannon. 2011. Corn distillers dried grains with solubles in diets for growing-finishing pigs: A cooperative study. J. Anim. Sci. 89:2801-2811.

DeDecker, J. M., M. Ellis, B. F. Wolter, J. Spencer, D. M. Webel, C. R. Bertelsen, and B. A. Peterson. 2005. Effects of dietary level of distillers dried grains with solubles and fat on the growth performance of growing pigs. J. Anim. Sci. 83(Suppl. 2): 79 (Abstr.)

De Godoye, M. R. C., L. L. Bauer, C. M. Parsons, and G. C. Fahey Jr. 2009. Select corn co-products from the ethanol industry and their potential as ingredients in pet foods. J. Anim. Sci. 87:189-199.

Drescher, A. J., S. K. Baidoo, L. J. Johnston, and G. C. Shurson. 2009. Effect of DDGS source on growth performance and carcass characteristics of growing-finishing pigs. J. Anim. Sci. 87(E-Suppl. 3):80. (Abstr.)

Drescher, A. J., L. J. Johnston, G. C. Shurson, and J. Goihl. 2008. Use of 20% dried distillers grains with solubles (DDGS) and high amounts of synthetic amino acids to replace soybean meal in grower-finisher swine diets. 2008. J. Anim. Sci. 86(Suppl. 2):28. (Abstr.)

Duttlinger, A. W., M. D. Tokach, S. S. Dritz, J. M. DeRouchy, J. L. Goodband, R. D. Goodband, and H. J. Prusa. 2008. Effectsof increasing dietary glycerol and dried distillers grains with solubles on growth performance of finishing pigs. J. Anim. Sci. 86(Suppl. 1):607. (Abstr.)

Fu, S. X., M. Johnston, R. W. Fent, D. C. Kendall, J. L. Usry, R. D. Boyd, and G. L. Allee. 2004. Effect of corn distiller's dried grains with solubles (DDGS) on growth, carcass characteristics, and fecal volume in growing finishing pigs. J. Anim. Sci. 82 (Suppl. 2):80. (Abstr.)

Gaines, A. M., G. I. Petersen, J. D. Spencer, and N. R. Augspurger. 2007a. Use of corn distillers dried grains with solubles (DDGS) in finishing pigs. J. Anim. Sci. 85 (Suppl. 2):96. (Abstr.)

Gaines, A. M., J. D. Spencer, G. I. Petersen, N. R. Augspurger, and S. J. Kitt. 2007b. Effect of corn distillers dried grains with solubles (DDGS) withdrawal program on growth performance and carcass yield in grow-finish pigs. J. Anim. Sci. 85 (Suppl. 1):438. (Abstr.)

Gaines, A., B. Ratliff, P. Srichana, and G. Allee. 2006. Use of corn distiller's dried grains and solubles in late nursery pig diets. J. Anim. Sci. 84 (Suppl. 2):120. (Abstr.)

Gowans, J., M. Callaahan, A. Yusupov, N. Campbell, and M. Young. 2007. Determination of the impact of feeding increasing levels of corn dried distillers grains on performance of growing-finihsing pigs reared under commercial conditions. Adv. Pork Prod. 18:A-22. (Abstr.)

Gralapp, A. K., W. J. Powers, M. A. Faust, and D. S. Bundy. 2002. Effects of dietary ingredients on manure characteristics and odorous emissions from swine. J. Anim. Sci. 80:1512-1519.

Greiner, L. L., X. Wang, G. Allee, and J. Connor. 2008. The feeding of dry distillers grain with solubles to lactating sows. J. Anim. Sci. 86(Suppl. 2):63. (Abstr.)

Jacela, J. Y., J. M. DeRouchey, S. S. Dritz, M. D. Tokach, R. D. Goodband, J. M. Nelssen, R. C. Sulabo, R. C. Thaler, L. Brandts, D. E. Little, and K. J. Prusa. 2011. Amino acid digestibility and energy content of deoiled (solvent extracted) corn dried distillers grains with solubles for swine and its effects on growth performance and carcass characteristics. J. Anim. Sci. 89:1817-1829.

Jacela, J. Y., H. L. Frobose, J. M. DeRouchey, M. D. Tokach, S. S. Dritz, R. D. Goodband, and J. L. Nelssen. 2010. Amino acid digestibility and energy concentration of high-protein corn dried distillers grains and high-protein sorghum dried distillers grains with solubles for swine. J. Anim. Sci. 88:3617-3623.

Jenkin, S., S. Carter, J. Bundy, M. Lachmann, J. Hancock, and N. Cole. 2007. Determination of P-bioavailability in corn and sorghum distillers dried grains with solubles for growing pigs. J. Anim. Sci. 85(Suppl. 2):113. (Abstr.)

Hilbrands, A. M., L. J. Johnson, G. C. Shurson, and I. Kim. 2009. Influence of rapid introduction and removal of dietary corn distillers gains with soluble (DDGS) on pig performance and carcass characteristics. J. Anim. Sci. 87(E-Suppl. 3):82. (Abstr.)

Hill, G. M., J. E. Link, D. O. Liptrap, M. A. Giesemann, M. J. Dawes, J. A. Snedegar, N. M. Bello, and R. J. Tempelman. 2008. Withdrawal of distillers dried grains with solubles (DDGS) prior to slaughter in finishing pigs. J. Anim. Sci. 86(Suppl. 2):52. (Abstr.)

Hinson, R. G. Allee, G. Grinstead, B. Corrigan, and J. Less. 2007. Effect of amino acid program (low vs. high) and dried distillers grains with solubles (DDGS) on finishing pig performance and carcass characteristics. J. Anim. Sci. 85(Suppl. 1):437. (Abstr.)

Honeyman, M. S., and D. R. Zimmerman. 1991. Metabolizable energy of corn (maize) gluten feed and apparent digestibility of the fibrous components for gestating sows. Anim. Sci. Feed Technol. 35:131-137.

Kim, B. G., G. I. Petersen, R. B. Hinson, G. L. Allee, and H. H. Stein. 2009. Amino acid digestibility and energy concentration in a novel source of high-protein distillers dried grains and their effects on growth performance of pigs. J. Anim. Sci. 87:4013-4021.

Kim, B. G., Y. Zhang, and H. H. Stein. 2010. Concentrations of analyzed or reactive lysine, but not crude protein, may predict the concentration of digestible lysine in distillers dried grains with solubles fed to pigs. J. Anim. Sci. 88(E-Suppl. 3):104 (Abstr.)

Lammers, P. J., M. S. Honeymann, and B. J. Kerr. 2009. Biofuels co-prodcuts in swine diets: Combining DDGS and glycerol. J. Anim. Sci. 87(E-Suppl. 3):90. (Abstr.)

Larson, E. M., R. A. Stock, T. J. Klopfenstein, M. H. Sindt, and D. H. Shain. 1993. Energy value of hominy feed for finishing ruminants. J. Anim. Sci. 71:1092-1099.

Lee, J. W., B. D. Keever, J. Killefer, F. K. McKeith, and H. H. Stein. 2011. Effects of including tallow, palm kernel oil, corn germ, or glycerol to diets containing distillers dried grains with solubles on pork fat quality of growing-finishing pigs, J. Anim. Sci. 89(Suppl. E-2):679 (Abstr.)

Linneen, S. K., M. U. Steidiger, M. D. Tokach, J. M. DeRouchy, R. D. Goodband, S. S. Dritz, and J. L. Nelssen. 2006. Effects of dried distillers grain with solubles on nursery pig performance. Page 100–102 in Kansas State Univ. Swine Day Report. Kansas State Univ. Manhattan.

Linneen, S. K., J. M. DeRouchy, S. S. Dritz, R. D. Goodband, M. D. Tokach, and J. L. Nelssen. 2008. Effects of dried distillers grains with solubles on growing and finishing pig performance in a commercial environment. J. Anim. Sci. 86:1579-1587.

Mahan, D. C. 1993. Evaluation of two sources of dried whey and the effects of replacing the corn and dried whey component with corn gluten meal and lactose in the diets of weanling pigs. J. Anim. Sci. 71:2860-2866.

McEwen, P. 2008. Canadian experience with feeding DDGS. Page 115-120 in Proc. 8th London swine conf. London, ON, April 1-2, 2008.

McEwen, P. L. 2006. The effects of distillers dried grains with solubles inclusion rate and gender on pig growth performance. Can. J. Anim. Sci. 86:594. (Abstr.)
NRC. 1998. Pages 110 – 142 in Nutrient Requirements of Swine. Tenth rev. ed. Natl. Acad. Press, Washington DC.
Pahm, A. A., C. Pedersen, D. Hoehler, and H. H. Stein. 2008a. Factors affecting the variability in ileal amino acid digestibility in corn distillers dried grains with solubles fed to growing pigs. J. Anim. Sci. J. Anim. Sci. 86:2180-2189.
Pahm, A. A., C. Pedersen, and H. H. Stein. 2008b. Application of the reactive lysine procedure to estimate lysine digestibility in distillers dried grains with solubles fed to growing pigs. J. Agric. Food Chem. 56:9441-9446.
Pedersen, C., M. G. Boersma, and H. H. Stein. 2007a. Digestibility of energy and phosphorus in 10 samples of distillers dried grains with solubles fed to growing pigs. J. Anim. Sci. 85:1168-1176.
Pedersen, C., M. G. Boersma, and H. H. Stein. 2007b. Energy and nutrient digestibility in NutriDense corn and other cereal grains fed to growing pigs. J. Anim. Sci. 85:2473-2483.
Sauvant, D., J. Perez, and G. Tran. 2004. Tables of composition and nutritional value of feed materials. 2nd ed. Wageningen Academic Publishers, The Netherlands.
Senne, B. W., J. D. Hancock, P. S. Sorrell, I. H. Kim, S. L. Traylor, R. H. Hines, and K. C. Behnke. 1995. Effects of distillers grains on growth performance in nursery and finishing pigs. Page 68 – 71 in Kansas State Univ. Swine Day Report. Kansas State Univ. Manhattan, KS.
Spencer, J. D., G. I. Petersen, A. M. Gaines, and N. R. Augsburger. 2007. Evaluation of different strategies for supplementing distillers dried grains with solubles (DDGS) to nursery pig diets. J. Anim. Sci. 85(Suppl. 2):96-97. (Abstr.)
Stanley, D. L., and R. C. Ewan. 1982. Utilization of hominy feed and alfalfa meal by young pigs. J. Anim. Sci. 54:1175-1180.
Stender, D., and M. S. Honeyman. 2008. Feeding pelleted DDGS-based diets for finishing pigs in deep-bedded hoop barns. J. Anim. Sci. 86(Suppl. 2):50. (Abstr.)
Stein, H. H. 2011. Feeding distillers dried grains with solubles (DDGS) and other ethanol coproducts to swine. Pages 297-316 in K. Liu and K. Rosentrater (eds): Distiller's Grains: Production, Properties and Utilization. CRC Press, Tailor and Francis Group, Boca Raton, FL.
Stein H. H., and G. C. Shurson. 2009. Board invited review: The use and application of distillers dried grains with solubles (DDGS) in swine diets. J. Anim. Sci. 87:1292-1303.
Stein, H. H., S. P. Connot, and C. Pedersen. 2009. Energy and nutrient digestibility in four sources of distillers dried grains with solubles produced from corn grown within a narrow geographical area and fed to growing pigs. Asian-Austr. J. Anim. Sci. 22:1016-1025.
Stein, H. H., C. Pedersen, M. L. Gibson, and M. G. Boersma. 2006. Amino acid and energy digestibility in ten samples of dried distillers grain with solubles by growing pigs. J. Anim. Sci. 84:853-860.
Stevens, J. G., A. P. Schinkel, M. A. Latour, D. Kelly, B. Legan, and B. T. Richert. 2009. Evaluation of distillers dried grains with soluble withdrawal programs on grow-finish pig growth performance and carcass quality. J. Anim. Sci. 87(E-Suppl. 3):82. (Abstr.)
Stock, R. A., J. M. Lewis, T. J. Klopfenstein, and C. T. Milton. 2000. Review of new information on the use of wet and dry milling feed by products in feedlot diets. J. Anim. Sci. 77:1v-12v.
Urriola, P. E., C. Pedersen, H. H. Stein, and G. C. Shurson. 2009. Amino acid digestibility of distillers dried grains with solubles, produced from sorghum, a sorghum-corn blend, and corn fed to growing pigs. J. Anim. Sci. 87:2574-2580.
Urriola, P. E., G. C. Shurson, and H. H. Stein. 2010. Digestibility of dietary fiber in distillers co-products fed to growing pigs. J. Anim. Sci. 88:2373-2381.
Weber, T. E., S. L. Trabue, C. J. Ziemer, and B. J. Kerr. 2010. Evaluation of elevated dietary corn fiber from corn germ meal in growing female pigs. J. Anim. Sci. 88:192-201.
Weimer, D., J. Stevens, A. Schinckel, M. Latour, and B. Richert. 2008. Effects of feeding increasing levels of distillers dried grains with solubles to grow-finish pigs on growth performance and carcass quality. J. Anim. Sci. 86(Suppl. 2):51. (Abstr.)
White, H., B. Richert, S. Radcliffe, A. Schinckel, and M. Latour. 2007. Distillers dried grains decreases bacon lean and increases fat iodine values (IV) and the ratio og n6:n3 but conjugated linoleic acids partially recovers fat quality. J. Anim. Sci. 85(Suppl. 2):78. (Abstr.)

Whitney, M. H., and G. C. Shurson. 2004. Growth performance of nursery pigs fed diets containing increasing levels of corn distillers dried grains with solubles originating from a modern Midwestern ethanol plant. J. Anim. Sci. 82:122-128.

Whitney, M. H., G. C. Shurson, L. J. Johnson, D. M. Wulf, and B. C. Shanks. 2006. Growth performance and carcass characteristics of grower-finisher pigs fed high-quality corn distillers dried grain with solubles originating from a modern Midwestern ethanol plant. J. Anim. Sci. 84:3356-3363.

Widmer, M. R., L. M. McGinnis, and H. H. Stein. 2007. Energy, amino acid, and phosphorus digestibility of high protein distillers dried grain and corn germ fed to growing pigs. J. Anim. Sci. 85:2994-3003.

Widmer, M. R., L. M. McGinnis, D. M. Wulf, and H. H. Stein. 2008. Effects of feeding distillers dried grains with solubles, high-protein distillers dried grains, and corn germ to growing-finishing pigs on pig performance, carcass quality, and the palatability of pork. J. Anim. Sci. 86:1819-1831.

Widyaratne, G. P., and R. T. Zijlstra. 2007. Nutritional value of wheat and corn distillers dried grain with solubles: Digestibility and digestible contents of energy, amino acids and phosphorus, nutrient excretion and growth performance of grower-finisher pigs. Can. J. Anim. Sci. 87:103-114.

Wilson, J. A., M. H. Whitney, G. C. Shurson, and S. K. Baidoo. 2003. Effects of adding distillers dried grains with solubles (DDGS) to gestation and lactation diets on reproductive performance and nutrient balance in sows. J. Anim. Sci. 81(Suppl. 2):47-48. (Abstr.)

Xu, G., S. K. Baidoo, L. J. Johnston, D. Bibus, J. E. Cannon, and G. C. Shurson. 2010a. Effects of feeding diets containing increasing content of corn distillers dried grains with solubles to grower-finisher pigs on growth performance, carcass composition, and pork fat quality. J. Anim. Sci. 88:1398-1410.

Xu, G., S. K. Baidoo, L. J. Johnston, D. Bibus, J. E. Cannon, and G. C. Shurson. 2010b. The effects of feeding diets containing corn distillers dried grains with solubles, and withdrawal period of distillers dried grains with solubles, on growth performance and pork quality in grower-finisher pigs. J. Anim. Sci. 88:1388-1397.

Table 1. Chemical composition of corn and corn co-products fed to swine (as-fed basis) [1, 2]

Item	Corn co-product									
	Corn	DDGS	DDG	HP DDG	De-oiled DDGS	Corn germ	CGM	CGF	Corn germ meal	Hominy feed
Gross energy, kcal/kg	3,891	4,776	-	4,989	-	4,919	5,229	4,334	4,259	4,072
Crude protein, %	8.0	27.5	28.8	41.1	31.2	14.0	62.9	23.0	24.8	8.7
Calcium, %	0.01	0.03	-	0.01	0.05	0.03	0.05	0.22	0.02	0.05
Phosphorus, %	0.22	0.61	-	0.37	0.76	1.09	0.44	0.83	0.59	0.43
Crude fat, %	3.3	10.2	-	3.7	4.0	17.6	1.2	1.4	0.9	4.9
Crude fiber, %	-	6.6	-	-	-	-	-	-	-	-
Starch, %	-	7.3	3.83	11.2	-	23.6	8.3	21.5	16.0	53.6
Neutral detergent fiber, %	7.3	37.6	37.3	16.4	34.6	20.4	12.9	50.5	54.1	21.6
Acid detergent fiber, %	2.4	11.1	18.2	8.7	16.1	5.6	7.0	10.2	10.9	3.4
Total dietary fiber, %	-	31.8	43.0	-	-	-	8.7	38.2	42.0	13.4
Ash	0.9	3.8	-	3.2	4.64	3.3	2.47	4.27	2.30	2.11
Indispensable amino acids, %										
Arginine	0.39	1.16	1.15	1.54	1.31	1.08	2.26	0.95	1.55	0.47
Histidine	0.23	0.72	0.68	1.14	0.82	0.41	1.31	0.61	0.64	0.24
Isoleucine	0.28	1.01	1.08	1.75	1.21	0.45	2.60	0.79	0.84	0.30
Leucine	0.95	3.17	3.69	5.89	3.64	1.06	10.09	1.86	1.86	0.91

Lysine	0.24	0.78	0.81	1.23	0.87	0.79	1.18	1.02	0.94	0.33
Methionine	0.21	0.55	0.56	0.83	0.58	0.25	1.61	0.32	0.40	0.15
Phenylalanine	0.38	1.34	1.52	2.29	1.69	0.57	4.03	0.87	1.04	0.41
Threonine	0.26	1.06	1.10	1.52	1.10	0.51	2.03	1.21	0.83	0.30
Tryptophan	0.09	0.21	0.22	0.21	0.19	0.12	0.44	0.16	0.18	0.06
Valine	0.38	1.35	1.39	2.11	1.54	0.71	2.89	1.12	1.30	0.42
Dispensable amino acids, %										
Alanine	0.58	1.94	2.16	3.17	2.13	0.91	5.30	1.48	1.38	0.60
Aspartic acid	0.55	1.83	1.86	2.54	1.84	1.05	3.85	1.44	1.68	0.60
Cysteine	0.16	0.53	0.54	0.78	0.54	0.29	1.14	0.43	0.33	0.17
Glutamic acid	1.48	4.37	5.06	7.11	4.26	1.83	12.04	2.70	2.84	1.35
Glycine	0.31	1.02	1.00	1.38	1.18	0.76	1.84	1.03	1.23	0.37
Proline	0.70	2.09	2.50	3.68	2.11	0.92	5.68	1.61	1.09	0.61
Serine	0.38	1.18	1.45	1.85	1.30	0.56	2.54	0.73	0.80	0.35
Tyrosine	0.27	1.01	-	1.91	1.13	0.41	3.27	0.64	0.67	0.27

[1] Data from NRC (1998); Sauvant et al., (2004); Bohlke et al. (2005), Stein et al. (2006, 2009), Jacela et al. (2010, 2011), Pedersen et al. (2007a, b), Widmer et al. (2007), Pahm et al. (2008a), Kim et al. (2009), Urriola et al. (2009, 2010), Almeida and Stein (2010b, 2011), and unpublished data from the University of Illinois.

[2] DDGS = distillers dried grains with solubles; DDG = distillers dried grains; HP DDG = high protein distillers dried grain; CGM = corn gluten meal; CGF = corn gluten feed.

Table 2. Concentration of digestible energy (DE) and metabolizable energy (ME), apparent total tract digestibility (ATTD) of phosphorus and standardized ileal digestibility (SID) of amino acids in corn and corn co-products (as-fed basis) [1, 2]

	Corn co-product									
Item	Corn	DDGS	DDG	HP DDG	De-oiled DDGS	Corn germ	CGM	CGF	Corn germ meal	Hominy feed
DE, kcal/kg	3,525	3,643	-	4,515	2,796	3,670	4,225	2,990	2,987	3,355
ME, kcal/kg	3,420	3,429	-	4,220	2,578	3,566	3,830	2,605	2,796	3,210
Phosphorus, ATTD, %	25	59	-	60	-	29	19	22	20	21
SID, Indispensable amino acids, %										
Arginine	87	81	83	83	82	83	94	90	90	96
Histidine	83	78	84	81	75	69	83	76	78	80
Isoleucine	81	75	83	81	75	57	86	77	77	71
Leucine	87	84	86	91	84	68	91	82	80	84
Lysine	72	62	78	64	50	58	79	69	68	59
Methionine	85	82	89	88	80	68	91	79	81	77
Phenylalanine	84	81	87	87	81	64	89	81	82	79
Threonine	74	71	78	77	66	53	84	75	71	66
Tryptophan	70	70	72	81	78	67	92	88	81	82
Valine	79	75	81	80	74	62	85	75	76	72
SID, Dispensable amino acids, %										

Alanine	83	78	82	86	77	64	88	78	76	79
Aspartic acid	80	69	74	76	61	60	83	66	66	69
Cysteine	82	73	81	82	64	64	81	65	64	76
Glutamic acid	80	80	87	88	78	72	88	77	78	83
Glycine	84	63	66	75	53	76	67	76	69	97
Proline	96	74	55	73	73	84	97	97	99	98
Serine	83	76	82	84	73	65	90	77	75	82
Tyrosine	82	81	-	88	81	59	90	81	79	78

[1] Data from NRC (1998), Bohlke et al. (2005), Stein et al. (2006, 2009), Jacela et al. (2010, 2011), Pedersen et al. (2007a, b), Widmer et al. (2007), Pahm et al. (2008a), Kim et al. (2009), Urriola et al. (2009), Almeida and Stein (2011) and unpublished data from the University of Illinois.

[2] DDGS = distillers dried grains with solubles; DDG = distillers dried grains; HP DDG = high protein distillers dried grain; CGM = corn gluten meal; CGF = corn gluten feed.

Table 3. Effects of including corn distillers dried grains with solubles (DDGS) in diets fed to weanling pigs[1]

Item	N	Response to dietary corn DDGS		
		Increased	Reduced	Not changed
ADG	12	0	0	12
ADFI	12	0	4	8
G:F	12	5	0	7
Mortality	2	0	0	2

[1]Data calculated from experiments by Senne et al. (1995), Whitney and Shurson (2004), Gaines et al. (2006), Linneen et al. (2006), Spencer et al. (2007), Barbosa et al. (2008), Burkey et al. (2008), and Almeida and Stein (2010b).

Table 4. Effects of including corn distillers dried grains with solubles (DDGS) in diets fed to growing-finishing pigs[1, 2]

Item	N	Response to dietary corn DDGS		
		Increased	Reduced	Not changed
ADG	31	1	7	23
ADFI	29	2	7	20
G:F	31	4	6	21
Dressing percentage	21	0	10	11
Backfat, mm	19	0	4	15
Lean meat, %	18	0	1	17
Loin depth, cm	17	0	3	14
Belly thickness, cm	4	0	2	2
Belly firmness	3	0	3	0
Iodine value	9	8	0	1

[1] Data based on experiments published after 2000 and where a maximum of 30% DDGS was included in the diets.

[2]Data calculated from experiments by Gralapp et al. (2002), Fu et al. (2004), Cook et al. (2005), DeDecker et al. (2005), Whitney et al. (2006), McEwen (2006, 2008), Gaines et al. (2007a, 2007b); Gowans et al.(2007), Hinson et al. (2007), Jenkin et al. (2007), White et al. (2007), Widyaratne and Zijlstra (2007), Augspurger et al. (2008), Drescher et al. (2008, 2009), Duttlinger et al. (2008), Hill et al. (2008), Linneen et al. (2008), Stender and Honeyman (2008), Weimer et al. (2008), Widmer et al. (2008), Amaral et al. (2009), Hilbrands et al. (2009), Lammers et al. (2009), and Stevens et al. (2009), Xu et al. (2010a, b), and Cromwell et al. (2011).