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BOARD-INVITED REVIEW: The use and application of distillers dried grains with solubles in swine diets

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ABSTRACT: Distillers dried grains with solubles (DDGS) may be included in diets fed to pigs in all phases of production. The concentrations of DE and ME in DDGS are similar to those in corn. Phosphorus in DDGS is highly digestible to pigs and apparent total tract digestibility values of approximately 60% have been reported. The concentration of starch in DDGS is low (i.e., between 3 and 11%), but the concentration of fat in DDGS is approximately 10% and the concentrations of ADF, NDF, and total dietary fiber in DDGS are approximately 3 times greater than those in corn (9.9, 25.3, and 42.1%, respectively). The apparent total tract digestibility of dietary fiber is less than 50%, which results in reduced digestibility values for DM and energy in DDGS. The concentrations of most AA in DDGS are approximately 3 times greater than those in corn, but the standardized ileal digestibility of most AA is approximately 10 percentage units less than in corn. Nursery pigs from 2 to 3 wk postweaning, and growing and finishing pigs may be fed diets containing up to 30% DDGS without any negative impact on growth performance. However, the carcass fat in pigs fed diets containing DDGS has a greater iodine value than the carcass fat in pigs not fed DDGS. It may,

therefore, be necessary to withdraw DDGS from the diet of finishing pigs during the final 3 to 4 wk before slaughter to achieve the desired pork fat quality. Lactating sows can also be fed diets containing up to 30% DDGS, and DDGS can replace all the soybean meal in diets fed to gestating sows without negatively affecting sow or litter performance. Inclusion of DDGS in diets fed to pigs may improve immune system activation, but more research is needed to elucidate the mechanisms responsible for these effects. Manure volume will increase when DDGS is included in the diets because of the reduced digestibility of DM in DDGS. Nitrogen excretion may also increase, but this can be prevented by the use of crystalline AA 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. In conclusion, DDGS can be included in diets fed to growing pigs in all phases of production, beginning at 2 to 3 wk postweaning, in concentrations of up to 30% DDGS, and lactating and gestating sows can be fed diets containing up to 30 and 50%, respectively, without negatively affecting pig performance.

Key words: distillers dried grains with solubles, ethanol, performance, pig

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INTRODUCTION

Research with distillers coproducts fed to swine has been conducted for more than half a century. Early work focused on evaluating the feeding value of distillers coproducts such as distillers dried solubles, distillers dried grains, and distillers dried grains with solubles (DDGS) fed to growing pigs (Fairbanks et al., 1944, 1945; Livingstone and Livingstone, 1969). Additional studies focused on “unidentified growth factors” sus-

pected to be present in distillers coproducts (Gage et al., 1961), but it was later determined that such factors were not present in these products (Conrad, 1961).

Construction of large-scale ethanol plants in the 1970s increased the production of DDGS. This led to research elucidating the effects of adding DDGS to grower-finisher diets (Wahlstrom et al., 1970; Smelki and Stothers, 1972; Cromwell et al., 1983) and to starter diets (Wahlstrom and Libal, 1980; Orr et al., 1981; Cromwell et al., 1985). Results from those studies revealed that DDGS is limiting in Lys when fed to pigs, and subsequent studies focused on measuring the effects of adding crystalline Lys to DDGS-based diets (Wahlstrom and Libal, 1980; Cromwell et al., 1983). It also became evident that the processing and heating

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Table 1. Concentration of energy in corn and 10 sources of corn distillers dried grains with solubles (DDGS) fed to growing pigs¹

| Item | DDGS | | | | |
|--------------------------------|-------|---------|-------------|----------------|------|
| | Corn | Average | Least value | Greatest value | SD |
| GE, kcal/kg of DM | 4,496 | 5,434 | 5,272 | 5,592 | 108 |
| ATTD ² of energy, % | 90.4 | 76.8 | 73.9 | 82.8 | 2.73 |
| DE, kcal/kg of DM | 4,088 | 4,140 | 3,947 | 4,593 | 205 |
| ME, kcal/kg of DM | 3,989 | 3,897 | 3,674 | 4,336 | 210 |

¹Data from Pedersen et al. (2007). n = 11.

²ATTD = apparent total tract digestibility.

procedures used to produce DDGS could affect the nutritional quality (Cromwell et al., 1993).

During the last decade, many new dry-grind fuel ethanol plants have been constructed, and there are now approximately 165 plants in the United States, projected to produce more than 18 million t of DDGS in 2008 (Renewable Fuels Association, 2008). Much research has been conducted during recent years to further evaluate the nutrient concentration, nutrient digestibility, feeding value, and unique properties associated with feeding DDGS to pigs.

It is the objective of this review to summarize results from recent North American research in which DDGS was fed to weanling, growing, and reproducing swine. The review is based on literature that was published before August, 2008. Whenever possible, peer-reviewed literature was used in the review, but the majority of the research in this area has been published in abstracts and research reports that have not been peer-reviewed. Although information from many non-peer-reviewed sources was included in the review, references that did not provide a complete description of experimental conditions or that did not include proper controls in the experiment were not used in the review.

NUTRIENT COMPOSITION AND ENERGY AND NUTRIENT DIGESTIBILITY

In North America, most ethanol is produced from corn, but sorghum and wheat are also used, and some plants use blends of different cereal grains to produce ethanol. The DDGS produced by these ethanol plants is characterized by the nutrient composition of the grain used to produce the ethanol, but even when the same grain is used, variability in the chemical composition of DDGS has been observed among ethanol plants (Spiels et al., 2002). Analyzed concentrations of energy and nutrients in several DDGS samples are presented in Tables 1 to 4, along with measured concentrations of DE and ME and the digestibility of fiber, P, and AA.

The average concentration of GE in DDGS is approximately 5,434 kcal/kg of DM. This value is greater than the concentration of GE in corn. However, the digestibility of energy, measured as percentage of GE, is less in DDGS than in corn, and the measured concentra-

tions of DE and ME in DDGS are 4,140 and 3,897 kcal/kg of DM, respectively (Pedersen et al., 2007). These values are similar to the DE and ME in corn (Table 1). Values for NE in DDGS have not been determined, but research to measure such values is currently being conducted.

Most of the starch in the grain is converted to ethanol during the fermentation process and only a small amount of starch is present in DDGS (Table 2). However, the fiber in corn is not converted to ethanol, and as a result, DDGS contains approximately 35% insoluble and 6% soluble dietary fiber. The apparent total tract digestibility (**ATTD**) of dietary fiber is 43.7% (Table 2), and this reduced digestibility of fiber results in a reduced digestibility of DM and is also the reason the digestibility of energy in DDGS is reduced compared with many other feed ingredients.

The concentration of P in DDGS ranges from 0.60 to 0.70% and the ATTD of P in DDGS is approximately 59% (Table 3). This value is much greater than in corn (Pedersen et al., 2007). The ATTD of P in DDGS corresponds to bioavailability values between 70 and 90% relative to P bioavailability in dicalcium phosphate (Burnell et al., 1989; Whitney and Shurson, 2001). Therefore, when DDGS is included in diets fed to swine, the utilization of organic P will increase and the need for supplemental inorganic P will be reduced.

The concentration and standardized ileal digestibility of AA have been measured in 39 sources of corn DDGS, in 1 source of sorghum DDGS, and in 2 sources of wheat DDGS (Table 4). Results showed that even when the DDGS was produced from the same type of grain, variation existed in AA digestibility among different samples of DDGS (Stein et al., 2005, 2006; Fastinger and Mahan, 2006; Urriola et al., 2007c; Pahm et al., 2008). This was particularly true for Lys, which was more variable in digestibility than all other indispensable AA (Fastinger and Mahan, 2006; Stein et al., 2006; Pahm et al., 2008). The reason for the greater variation in Lys digestibility compared with the digestibility of other AA is believed to be that some sources of DDGS have been heat damaged (Cromwell et al., 1993; Stein et al., 2006). Most AA in DDGS have a digestibility that is approximately 10 percentage units less than in corn, which may be a result of the greater concentration of dietary fiber in DDGS than in corn.

Table 2. Concentration of carbohydrates and apparent total tract digestibility (ATTD) of dietary fiber in corn distillers dried grains with solubles¹

| Item | Average | Least value | Greatest value | SD |
|----------------------------------|---------|-------------|----------------|------|
| Total starch, % | 7.3 | 3.8 | 11.4 | 1.4 |
| Soluble starch, % | 2.6 | 0.5 | 5.0 | 1.2 |
| Insoluble starch, % | 4.7 | 2.0 | 7.6 | 1.5 |
| ADF, % | 9.9 | 7.2 | 17.3 | 1.2 |
| NDF, % | 25.3 | 20.1 | 32.9 | 4.8 |
| Insoluble total dietary fiber, % | 35.3 | 26.4 | 38.8 | 4.0 |
| Soluble total dietary fiber, % | 6.0 | 2.36 | 8.54 | 2.1 |
| Total dietary fiber, % | 42.1 | 31.2 | 46.3 | 4.9 |
| ATTD, total dietary fiber, % | 43.7 | 23.4 | 55.0 | 10.2 |

¹Unpublished data from the University of Illinois (Urbana, IL). n = 46 for data on starch, ADF, and NDF; n = 8 for data on insoluble, soluble, and total dietary fiber.

However, except for Lys, the variability among different DDGS sources is within the normal range of variation observed in other feed ingredients. Often, sources of DDGS that have a low digestibility of Lys also have a low concentration of Lys, which is the reason the Lys-to-CP ratio gives an estimate of the quality of the Lys in the sample (Stein, 2007). The digestibility of AA in sorghum DDGS and the digestibility in wheat DDGS are close to the values measured in corn DDGS (Urriola et al., 2007c; Lan et al., 2008; Widyaratne and Zijlstra, 2008).

Color measurement with Minolta or HunterLab spectrophotometers may sometimes be used to predict the digestibility of Lys in DDGS (Cromwell et al., 1993; Fastinger and Mahan, 2006). Dark-colored DDGS has less AA digestibility, which may lead to reduced growth performance when fed to swine compared with light-colored DDGS (Cromwell et al., 1993; Fastinger and Mahan, 2006). However, determination of optical density and front-face fluorescence may more accurately predict the digestibility of Lys and other AA in DDGS than color measured by Minolta and Hunter scores (Urriola et al., 2007a,b). The color of DDGS may also be predicted by measuring ADIN, and chickens fed diets containing DDGS with small ADIN values had greater growth performance than chicks fed diets containing DDGS with greater ADIN values (Cromwell et al., 1993). Enzyme assays such as IDEA (immobilized digestive enzyme assay) and pepsin-pancreatin (Pedersen et al., 2005; Schasteen et al., 2005), or the reactive Lys procedure (Pahm et al., 2006) are promising in vitro techniques for predicting digestible CP and AA concen-

trations in DDGS, but the accuracy of these procedures needs to be validated.

INCLUSION OF DDGS IN DIETS FED TO WEANLING PIGS

Inclusion of corn DDGS in diets fed to weanling pigs has been reported from 10 experiments (Table 5). Diets that contained between 0 and 25% DDGS were used by Whitney and Shurson (2004) in 2 experiments. Each experiment fed common phase 1 diets for 4 d postweaning before allotting pigs to experimental phase 2 and phase 3 diets, which were fed for 18 and 21 d, respectively. Measured over the entire experimental period, no differences in pig performance were observed in either experiment. Likewise, the inclusion of 10% DDGS in diets fed to weanling pigs from 10 d postweaning (Linneen et al., 2006) or the inclusion of 22.5 to 30% DDGS (Gaines et al., 2006; Spencer et al., 2007; Barbosa et al., 2008; Burkey et al., 2008) from approximately 3 wk postweaning did not affect ADG of the pigs. The ADFI was reduced in 2 experiments as DDGS was included in the diet (Gaines et al., 2006; Barbosa et al., 2008), but G:F 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). Pig mortality in the nursery was reported in only 2 experiments, and no effects of DDGS on nursery pig mortality were observed in either of these experiments.

Effects of introducing diets containing DDGS to weanling pigs at different times postweaning were investigated by offering pigs a 4-phase nursery program in

Table 3. Concentration and digestibility of P in 10 sources of corn distillers dried grains with solubles fed to growing pigs¹

| Item | Average | Least value | Greatest value | SD |
|---------------------------------------|---------|-------------|----------------|------|
| Total P, % | 0.61 | 0.51 | 0.74 | 0.09 |
| Total P, % of DM | 0.70 | 0.57 | 0.85 | 0.10 |
| Apparent total tract digestibility, % | 59.1 | 50.1 | 68.3 | 5.18 |
| Digestible P, % | 0.36 | 0.28 | 0.47 | 0.06 |

¹Data from Pedersen et al. (2007). n = 11.

Table 4. Concentration and standardized ileal digestibility (SID) of CP and AA in distillers dried grains with solubles (DDGS) fed to growing pigs¹

| Item | Concentration of CP and AA, % | | | SID of CP and AA, % | | |
|------------------|-------------------------------|--------------|------------|---------------------|--------------|------------|
| | Corn DDGS | Sorghum DDGS | Wheat DDGS | Corn DDGS | Sorghum DDGS | Wheat DDGS |
| CP | 27.38 | 31.50 | 40.67 | 72.8 | 71.4 | 72.2 |
| Indispensable AA | | | | | | |
| Arg | 1.14 | 1.06 | 1.53 | 81.1 | 78.2 | 83.4 |
| His | 0.71 | 0.68 | 0.92 | 77.1 | 70.6 | 74.2 |
| Ile | 1.00 | 1.31 | 1.35 | 75.3 | 72.7 | 77.2 |
| Leu | 3.11 | 4.02 | 2.66 | 83.5 | 76.3 | 81.4 |
| Lys | 0.76 | 0.66 | 0.65 | 60.6 | 62.0 | 47.7 |
| Met | 0.54 | 0.51 | 0.53 | 81.8 | 75.4 | 79.5 |
| Phe | 1.32 | 1.62 | 1.92 | 80.8 | 75.8 | 85.1 |
| Thr | 1.04 | 1.03 | 1.21 | 70.4 | 68.6 | 72.5 |
| Trp | 0.21 | 0.34 | 0.40 | 69.6 | 70.4 | 80.4 |
| Val | 1.34 | 1.59 | 1.70 | 74.4 | 72.3 | 80.1 |
| Dispensable AA | | | | | | |
| Ala | 1.89 | 2.79 | 1.48 | 78.1 | 73.4 | 68.0 |
| Asp | 1.80 | 2.09 | 1.92 | 68.1 | 68.0 | 56.7 |
| Cys | 0.52 | 0.47 | 0.73 | 72.5 | 65.6 | 71.6 |
| Glu | 4.24 | 6.08 | 9.81 | 80.4 | 75.5 | 86.3 |
| Gly | 1.02 | 0.99 | 1.62 | 63.2 | 66.9 | 67.8 |
| Pro | 2.06 | 2.41 | 4.11 | 74.1 | 83.1 | 81.0 |
| Ser | 1.14 | 1.35 | 1.88 | 75.9 | 72.5 | 77.0 |
| Tyr | 1.00 | — | — | 80.9 | — | — |

¹Data for corn DDGS (39 sources) from Stein et al. (2005, 2006), Fastinger and Mahan (2006), Urriola et al. (2007c), and Pahlm et al. (2008). Data for sorghum DDGS (1 source) from Urriola et al. (2007c). Data for wheat DDGS (2 sources) from Widyaratne and Zijlstra (2007, 2008) and Lan et al. (2008).

which DDGS was introduced in either phase 1 (7.5%), phase 2 (15%), or phase 3 (15%; Spencer et al., 2007). A control treatment consisting of diets that contained no DDGS in any phase was also included in the experiment. There were no differences in growth performance among treatments, which indicated that DDGS may be introduced immediately after weaning without compromising pig performance. This result, however, could not be verified by Burkey et al. (2008), who reported that inclusion of DDGS in diets fed to pigs before d 21 postweaning resulted in a reduction in pig performance.

Inclusion of sorghum DDGS in diets fed to weanling pigs has been investigated in 3 experiments. In the first experiment, pigs were offered diets containing 0, 10, or

20% sorghum DDGS from d 7 to 29 postweaning, and no differences in ADG, ADFI, and G:F were observed among treatments (Senne et al., 1995). In a subsequent experiment, pigs were fed diets containing 0, 15, 30, 45, or 60% sorghum DDGS from d 7 to 29 postweaning (Senne et al., 1996). Quadratic reductions in ADG and G:F were observed in this experiment, with the performance of pigs fed up to 30% DDGS being similar to the performance of pigs fed the control diets, whereas inclusion of 45 or 60% DDGS reduced ADG and G:F. However, Feoli et al. (2008a) also reported that inclusion of 30% sorghum DDGS in diets fed to weanling pigs would negatively affect growth performance compared with pigs fed diets containing no DDGS. It is possible that differences in the quality of the DDGS used or differences in the way the diets were formulated contributed to these different responses.

Table 5. Effects of including corn distillers dried grains with solubles (DDGS) in diets fed to weanling pigs¹

| Item | n | Response to dietary corn DDGS, No. of experiments | | |
|-----------|----|---|---------|-------------|
| | | Increased | Reduced | Not changed |
| ADG | 10 | 0 | 0 | 10 |
| ADFI | 10 | 0 | 2 | 8 |
| G:F | 10 | 5 | 0 | 5 |
| Mortality | 2 | 0 | 0 | 2 |

¹Data 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).

INCLUSION OF DDGS IN DIETS FED TO GROWER-FINISHER PIGS

Effects of DDGS on Growth Performance

In the last decade, results from at least 25 experiments in which growth performance (i.e., ADG, ADFI, and G:F) of grower-finisher pigs fed diets containing corn DDGS was measured have been reported (Table 6). In 23 of these experiments, the DDGS was included in diets based on corn and soybean meal, but wheat- and field pea-based diets were used in 2 experiments. There are also reports from 8 experiments that included

sorghum DDGS in diets fed to grower-finisher pigs and from 2 experiments that used wheat DDGS.

Corn DDGS. Early research evaluating the addition of corn DDGS to diets fed to grower and finisher pigs showed that growth performance could be maintained when up to 20% DDGS was included in the diets, whereas performance would be reduced when 40% was used (Cromwell et al., 1983). Results from subsequent experiments conducted in commercial facilities showed that inclusion of 15% DDGS in a diet fed to pigs from 50 to 76 kg of BW resulted in no difference in ADG, ADFI, or G:F compared with pigs fed a corn- and soybean meal-based control diet (Linneen et al., 2008). Inclusion of 0, 5, or 10% DDGS in diets fed to finishing pigs (88 to 105 kg) and 19% DDGS in diets fed to grower pigs (30 to 60 kg) also resulted in no changes in pig performance (Gralapp et al., 2002; Jenkin et al., 2007). These observations are in agreement with studies showing that up to 20% DDGS could be included in diets fed throughout the grower-finisher period without reducing ADG, ADFI, and G:F, provided that diets were adequately fortified with AA (McEwen, 2006, 2008; Augspurger et al., 2008; Drescher et al., 2008; Duttlinger et al., 2008; Widmer et al., 2008). It was also demonstrated that inclusion of up to 30% DDGS in corn- and soybean meal-based diets fed to grower-finisher pigs did not affect pig performance (Cook et al., 2005; DeDecker et al., 2005). Likewise, ADG was not changed, but ADFI was reduced and G:F was linearly improved in pigs fed diets containing 0, 10, 20, or 30% DDGS (Xu et al., 2007a). In 2 experiments in which the performance of finishing pigs fed diets containing 0 or 30% DDGS was compared, no changes in ADG and ADFI were observed, 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. (2007a) indicated that the energy concentration might have varied among the DDGS sources used in these experiments. Linear increases in ADG and G:F were also observed when a barley-, wheat-, and field pea-based diet was fortified with 0, 5, 10, 15, 20, or 25% corn DDGS and fed to pigs from 36 to 90 kg (Gowans et al., 2007). Thus, several experiments have included between 5 and 30% corn DDGS in grower-finisher diets, and the results have shown no differences in pig growth performance.

In contrast to those results, data from other experiments that used 10, 20, or 30% DDGS in diets fed to grower-finisher pigs showed a linear reduction in ADG (Fu et al., 2004; Whitney et al., 2006c; Linneen et al., 2008; Weimer et al., 2008). A linear reduction in ADFI was also observed in 2 of these experiments (Fu et al., 2004; Linneen et al., 2008). These observations are in agreement with results reported by Hinson et al. (2007), who showed that the inclusion of 0, 10, or 20% DDGS linearly reduced ADG and ADFI of grower-finisher pigs. Inclusion of 40%, but not 20%, DDGS also reduced ADG and ADFI in finishing pigs (Stender

Table 6. Effects of including corn distillers dried grains with solubles (DDGS) in diets fed to growing-finishing pigs¹

| Item | n | Response to dietary corn DDGS, No. of experiments | | |
|---------------------|----|---|---------|-------------|
| | | Increased | Reduced | Not changed |
| ADG | 25 | 1 | 6 | 18 |
| ADFI | 23 | 2 | 6 | 15 |
| G:F | 25 | 4 | 5 | 16 |
| Dressing percentage | 18 | 0 | 8 | 10 |
| Backfat | 15 | 0 | 1 | 14 |
| Lean meat, % | 14 | 0 | 1 | 13 |
| Loin depth | 14 | 0 | 2 | 12 |
| Belly thickness | 4 | 0 | 2 | 2 |
| Belly firmness | 3 | 0 | 3 | 0 |
| Iodine value | 8 | 7 | 0 | 1 |

¹Data from experiments by Gralapp et al. (2002), Fu et al. (2004), Cook et al. (2005), DeDecker et al. (2005), McEwen (2006, 2008), Whitney et al. (2006c), 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. (2007a,b, 2008a,b), Augspurger et al. (2008), Drescher et al. (2008), Duttlinger et al. (2008), Hill et al. (2008a), Linneen et al. (2008), Stender and Honeyman (2008), Weimer et al. (2008), and Widmer et al. (2008).

and Honeyman, 2008). Inclusion of 25% DDGS in a wheat- and field pea-based diet fed to pigs from 52 to 85 kg also reduced ADG and ADFI compared with results obtained for pigs fed a diet containing no DDGS (Widyaratne and Zijlstra, 2007).

In summary, data have been reported from 25 experiments in which growth performance of grower-finisher or finisher pigs fed diets containing corn DDGS were compared with performance of pigs fed diets containing no DDGS. Average daily gain was improved in 1 experiment, reduced in 6 experiments, and not affected by treatment in the remaining 18 experiments. The G:F was improved in 4 experiments, reduced in 5 experiments, and not affected by dietary treatments in 16 experiments. Data for ADFI were reported in only 23 experiments; ADFI was increased in 2 experiments, reduced in 6 experiments, and not affected by dietary DDGS inclusion in 15 experiments.

On the basis of the data provided from these 25 experiments, it is not possible to pinpoint an obvious reason why pig performance was maintained in most, but not all, experiments. It is possible that the DDGS used in the experiments in which performance was decreased may have been of poorer quality (less nutrient digestibility) than expected. For example, if one of the sources of DDGS used contained a low concentration of digestible Lys, pig performance would be expected to be reduced. In some experiments in which poor performance was obtained when DDGS was used, diets were formulated in such a way that dietary CP increased as DDGS was included in the diets. In such diets, DDGS inclusion was confounded by CP concentration, and it is not possible to determine whether the reduced per-

formance was caused by the increase in DDGS concentration or by the increase in CP concentration.

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 diets containing DDGS. It has been demonstrated that when given a choice, pigs prefer to consume diets containing no DDGS (Hastad et al., 2005; Seabolt et al., 2008).

Sorghum DDGS. Results from the 8 experiments in which sorghum DDGS was included in diets fed to grower-finisher pigs demonstrated that when sorghum DDGS was used at concentrations of 30% or less, no differences in pig performance were observed (Senne et al., 1995, 1996). However, when greater inclusion rates were used, ADG was reduced (Senne et al., 1996, 1998; Feoli et al., 2007b,c, 2008a,b,c). Likewise, G:F was not affected when the inclusion of sorghum DDGS was limited to 30% (Senne et al., 1995, 1996), but G:F might be reduced when 40% was used (Senne et al., 1998; Feoli et al., 2008a), although this was not always the case (Feoli et al., 2007c, 2008b,c). Average daily feed intake was not affected by sorghum DDGS when 30% or less was included in the diet (Senne et al. 1995), but at greater inclusion concentrations, ADFI might be reduced (Senne et al., 1996; Feoli et al., 2007c, 2008b).

Wheat DDGS. The inclusion of 25% wheat DDGS in a wheat- and field pea-based diet fed to pigs from 52 to 85 kg did not affect ADG or G:F (Widyaratne and Zijlstra, 2007). In contrast, inclusion of 0, 5, 10, 15, 20, or 25% wheat DDGS in wheat- and soybean meal-based diets fed to grower pigs (20 to 51 kg) linearly reduced ADG and ADFI, whereas G:F was not affected (Thacker, 2006). When the inclusion of DDGS was reduced to 0, 3, 6, 9, 12, or 15% during the finishing phase (52 to 113 kg), no differences in performance were observed (Thacker, 2006). The diets used by Widyaratne and Zijlstra (2007) were formulated based on concentrations of digestible AA measured in the batch of DDGS fed to the pigs, whereas the diets used by Thacker (2006) were formulated based on total AA. This may explain why different responses were obtained in these experiments, because it has been shown that wheat DDGS sometimes has a low Lys digestibility (Nyachoti et al., 2005; Lan et al., 2008).

Effects of DDGS on Carcass Composition and Quality

The dressing percentage of pigs has been reported from 18 experiments in which corn DDGS was included in the diets. In 10 of these experiments, no difference in dressing percentage was observed (Fu et al., 2004; McEwen, 2006, 2008; Xu et al., 2007b; Augspurger et al., 2008; Drescher et al., 2008; Duttlinger et al., 2008; Hill et al., 2008; Stender and Honeyman, 2008; Widmer et al., 2008), whereas a reduced dressing percentage in DDGS-fed pigs was observed in 8 experiments (Cook et al., 2005; Whitney et al., 2006c; Gaines et al.,

2007a,b; Hinson et al., 2007; Xu et al., 2007a; Linneen et al., 2008; Weimer et al., 2008). For pigs fed sorghum DDGS, the dressing percentage increased in 1 experiment (Senne et al., 1996), was unaffected by dietary DDGS inclusion in 1 experiment (Senne et al., 1998), and was reduced in 5 experiments (Feoli et al., 2007b,c, 2008a,b,c). For pigs fed wheat DDGS, dressing percentage was also reduced (Thacker, 2006). It has been suggested that the inclusion of fiber-rich ingredients in diets fed to pigs may reduce the dressing percentage because of increased gut fill and increased intestinal mass (Kass et al., 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 corn DDGS was reduced in 1 experiment (Weimer et al., 2008), but in 14 other experiments, no differences in backfat thickness were observed. Loin depth was not affected by the inclusion of corn DDGS in 12 experiments, but it was reduced in 2 experiments (Whitney et al., 2006c; 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 decreased ADG in these experiments and therefore being marketed at a lighter BW. Of the 14 experiments that reported the lean percentage of pigs fed diets containing corn DDGS, only 1 experiment (Gaines et al., 2007b) reported a reduction in lean percentage, whereas no differences were reported in the remaining experiments. Lean percentage was also reported for pigs fed sorghum DDGS (3 experiments) and wheat DDGS (1 experiment), but no effects of DDGS inclusion were observed in these experiments.

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

Adjusted belly firmness of pigs fed diets containing corn DDGS has been reported in 3 experiments (Whitney et al., 2006c; Xu et al., 2007a; Widmer et al., 2008), and in all 3 experiments, adjusted belly firmness was reduced in pigs fed diets containing DDGS compared with pigs fed diets containing no DDGS. 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., 2006c; White et al., 2007; Xu et al., 2007a, 2008a; Hill et al., 2008a; Linneen et al., 2008; Stender and Honeyman, 2008). The iodine value has also been reported to increase in pigs fed sorghum

DDGS (Feoli et al., 2007c, 2008b,c). The changes in fat iodine values in pigs fed diets containing DDGS are most likely a result of the relatively large quantities of unsaturated fatty acids, particularly C18:2, in corn 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 less valuable bellies and loins, and research has been directed toward evaluating alternative nutritional strategies to reduce the negative effects of DDGS on iodine values. The inclusion of up to 5% tallow in diets containing 40% sorghum DDGS did not reduce the iodine value in jowl fat (Feoli et al., 2007c), even though tallow contains a high proportion of SFA. In contrast, the addition of 1% CLA to diets containing 20 or 40% corn DDGS for 10 d before pigs were slaughtered reduced fat iodine values and the n-6:n-3 ratio (White et al., 2007). This observation is consistent with the observation that CLA may reduce the activity of the Δ^9 -desaturase enzyme, which is responsible for desaturation of de novo-synthesized fatty acids (Gatlin et al., 2002). Thus, addition of CLA to diets containing DDGS fed during the late finisher phase may be used to reduce iodine values in carcass fat. Removal of DDGS from the diet during the final 3 to 4 wk before slaughter 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., 2008b).

No information is available 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 corn 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 when corn or sorghum DDGS is used.

INCLUSION OF DDGS IN DIETS FED TO SOWS

Early work showed that the inclusion of 40 to 80% DDGS in diets fed to gestating sows did not affect farrowing rate, feed intake, sow BW gain, litter size at farrowing, or litter BW at farrowing (Thong et al., 1978; Monegue and Cromwell, 1995). Sows used in these studies were offered a corn-soybean meal diet containing no DDGS during the lactation period, and no differences in performance were reported regardless of the gestation treatment (Thong et al., 1978; Monegue and Cromwell, 1995). Later work confirmed that gestating sows could be fed diets containing 50% DDGS without any negative impact on sow performance (Wilson et al., 2003). Results of the latter experiment indicated that when sows were fed DDGS during 2 parities, litter size was improved in the second parity, but there are no other experiments in which DDGS was fed to sows for more than 1 reproductive cycle. The reason for the

improved litter size in sows fed diets containing DDGS is not known, but it may be related to the increase in dietary fiber concentration resulting from the inclusion of DDGS in the diets. It has been demonstrated that sows fed gestation diets containing increased concentrations of dietary fiber, compared with a corn-soybean meal control diet, often have increased litter size (Ewan et al., 1996; Grieshop et al., 2001). More research is necessary to determine if this response is repeatable, and to determine the length of time diets containing DDGS must be fed to achieve an increase in litter size in sows.

Two experiments were conducted to compare the performance of sows fed lactation diets containing 15% DDGS with the performance of sows fed a diet containing 5% sugarbeet pulp or a corn-soybean meal diet (Hill et al., 2008b). In these experiments, no DDGS was included in the gestation diets. In both experiments, sow lactation performance was similar for sows fed diets without or with DDGS and no differences were observed in litter BW gain, preweaning pig mortality, or sow BW loss.

In the experiment by Wilson et al. (2003), in which sows were fed diets containing 0 or 50% DDGS in gestation, sows were allotted to lactation diets containing 0 or 20% DDGS in a 2 × 2 factorial arrangement. Sows were kept on their respective dietary treatments for 2 consecutive reproductive cycles. Preweaning mortality was greater for sows fed the 50% DDGS gestation diet and a 20% DDGS lactation diet compared with the other treatment combinations during the first reproductive cycle, but this was not the case during the second cycle. Sows that had been fed DDGS during the previous gestation period also had a smaller weaning-to-estrus interval than sows fed no DDGS in gestation or lactation. Sows that were fed DDGS only in lactation had reduced feed intake during the initial 7 d of the lactation period in the first reproductive cycle, but not in the second cycle. It was concluded from this experiment that DDGS could be included in lactation diets in amounts of at least 20%, but that feed intake might be depressed during the immediate postpartum period if no DDGS is included in gestation diets.

In more recent experiments, sows were fed diets containing 0, 10, 20, or 30% DDGS during lactation (Song et al., 2007a; Greiner et al., 2008). No differences among dietary treatments in feed intake, change in backfat thickness, piglet and litter BW gain, preweaning mortality, or weaning-to-estrus interval were observed in these experiments. In the experiment by Greiner et al. (2008), sow BW gain during lactation was linearly increased and the weaning-to-estrus interval was linearly reduced by the inclusion of DDGS in the diet, but these effects were not reported by Song et al. (2007a). The inclusion of DDGS in the diet fed to lactating sows did not affect milk composition, N digestibility, or N retention, but sows fed diets containing 20 or 30% DDGS had smaller blood urea N values than sows fed the control diet (Song et al., 2007b).

In conclusion, DDGS may be included in gestation diets in amounts sufficient to replace all the dietary soybean meal without negatively affecting sow performance, and it may increase litter size. Lactation diets may contain up to 30% DDGS without negatively affecting sow or litter performance, but when DDGS is included in lactation diets, it may be necessary to acclimate sows to diets containing DDGS during gestation to avoid a reduction in feed intake.

EFFECTS OF DDGS ON HEALTH OF PIGS

Distillers coproducts contain residual yeast cells and yeast cell components, and approximately 3.9% of the dry weight of DDGS is contributed from yeast cell biomass (Ingledeew, 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 AA, vitamins, and trace minerals, which may also affect the activity of the immune system when fed to pigs (Stone 1998).

Whitney et al. (2006a,b) conducted 2 experiments to investigate if adding 10 or 20% DDGS to the diet of young growing pigs would be effective in reducing the prevalence, length, or severity of intestinal lesions produced by porcine proliferative enteropathy (ileitis) after pigs were challenged with *Lawsonia intracellularis*. In the first experiment, 80 pigs were weaned at 17 d of age and randomly allotted to 1 of 4 treatment groups. The negative control group was not infected with *L. intracellularis* and was fed a control corn-soybean meal diet. The remaining 3 groups were orally inoculated with 1.5×10^9 *L. intracellularis* per pig after a 4-wk dietary adaptation period and were fed a corn-soybean meal diet or a diet containing 10 or 20% DDGS. On d 21 postchallenge, all pigs were killed and intestinal mucosa was examined for the presence of lesions. Infecting pigs with *L. intracellularis* resulted in a 25% reduction in ADFI, a 55% reduction in ADG, and a 40% reduction in G:F during the 3-wk postchallenge period, but dietary treatment did not affect growth performance. Gross lesions were observed in 63% of the challenged pigs compared with 0% in the negative control group. The addition of DDGS to the diet did not affect the prevalence, length, or severity of lesions, or the proliferation of *L. intracellularis*.

In the second experiment, 100 pigs were managed similarly to the first experiment, except that the *L. intracellularis* dosage rate for challenging pigs was reduced by 50%. Treatment groups consisted of a negative control group and 4 dietary treatments for pigs infected with *L. intracellularis* in a 2×2 factorial arrangement. The 4 factors were 0 or 10% DDGS in the diets, and no antibiotic treatment or treatment with bacitracin methylene disalicylate (30 mg/kg of diet) throughout the experiment and pulsing with chlortetracycline at

500 mg/kg from 3 d before the challenge until 11 d after the challenge. Feeding diets containing 10% DDGS reduced the prevalence and severity of intestinal lesions, and feeding the antimicrobial diets reduced the length and severity of lesions. However, there were no additive effects of feeding a diet containing the combination of DDGS and the antimicrobials. These results indicate that dietary inclusion of DDGS may aid in resisting a moderate ileitis challenge similarly to an approved antimicrobial regimen, but DDGS may not be effective under more severe challenges.

Knott et al. (2005) measured growth performance, gut morphology, organ weights, intestinal length, acute-phase protein serum concentrations, and circulating IGF-1 concentrations to determine the effectiveness of 3 corn distillers solubles by-products as potential replacements for carbadox and spray-dried porcine plasma in diets fed to early-weaned pigs. The 3 by-products were spray-dried condensed distillers solubles, a spray-dried, high-lipid fraction of condensed distillers solubles, and a residual solubles fraction of condensed distillers solubles after the lipid was removed. Pigs fed diets containing any of these by-products had growth performance similar to that of pigs fed diets containing carbadox, but had less 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 villus height and a greater villus height:crypt depth ratio compared with pigs fed diets containing carbadox.

In conclusion, results from 1 study indicate that feeding a diet containing DDGS may be effective in reducing the incidence, severity, and length of lesions caused by a moderate *L. intracellularis* infection. The mode of action of this response is unknown, but it seems that compounds in a fraction of condensed distillers solubles may improve the villus height:crypt depth ratio in the proximal portion of the small intestine. It is not known if diets containing DDGS are effective in reducing the negative effects of other enteric diseases.

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

Odor and gas characteristics of swine manure, and energy, N, and P balances were measured in pigs fed a corn-soybean meal diet or a diet containing DDGS (Spiehs et al., 2000). Dietary treatment had no effect on H₂S, NH₃, or odor detection concentrations over the 10-wk experimental period. Pigs fed the diets containing DDGS had greater N intake, but ADFI and percentage of N retention were not different between treatments. Feeding diets containing DDGS diets tended to increase N excretion, but P retention was not different between dietary treatments. Gralapp et al. (2002) fed diets containing 0, 10, or 20% DDGS to finishing pigs

to determine the effects on growth performance, manure characteristics, and odor emissions. There were no differences in total solids, volatile solids, chemical oxygen demand, or total N or P concentration of manure among dietary DDGS concentrations. However, there was a trend for increasing odor concentration with increasing dietary concentrations of DDGS. Inclusion of DDGS in diets fed to lactating sows also reduced the concentration of P in the feces (Hill et al., 2008b), but it is unknown if total P excretion was reduced because DM digestibility of the diets was not determined.

Four experiments were conducted to evaluate the effects of diet formulation method, dietary concentration of DDGS, and the use of microbial phytase on nutrient balance in nursery and grower-finisher pigs (Xu et al., 2006a,b,c,d). Nursery pigs were fed a corn-soybean meal control diet or a diet containing 10 or 20% DDGS formulated on a total P basis or based on a relative P bioavailability value of 90% for DDGS (Xu et al., 2006c). Phosphorus digestibility, retention, and fecal and urinary excretion were similar for pigs fed the control diet and pigs fed diets containing DDGS. Within a dietary DDGS concentration, 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 bioavailable 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 diet containing DDGS without or with phytase had reduced DM digestibility compared with pigs fed corn-soybean meal diets without or with phytase, which resulted in the excretion of a greater volume of manure (Xu et al., 2006a). 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% 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., 2006b). Dietary DDGS and phytase resulted in greater P digestibility and reduced P excretion compared with corn-soybean meal diets containing no DDGS or phytase. Nitrogen and Zn digestibility were not affected by dietary treatments, but Ca digestibility was greater for corn-soybean meal diets than for DDGS diets. There were no interactions between dietary DDGS and phytase and the Ca:available P ratio, indicating that the range of Ca:available P ratios (2:1 to 3:1) established by NRC (1998) are acceptable when 20% DDGS and phytase are added to nursery diets to minimize P excretion in the manure.

The effects of feeding corn-soybean meal diets containing 20% DDGS and phytase on DM, N, and P digestibility in grower-finisher pigs have also been measured (Xu et al., 2006d). Unlike for nursery-aged 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.

CONCLUSIONS AND PERSPECTIVES

Distillers dried grains with solubles is an excellent source of energy and digestible P in diets fed to swine in all production phases. Nutrient concentration and digestibility vary among sources, and accurate *in vitro* methods need to be developed to estimate AA digestibility among sources. Acceptable growth performance can be achieved by adding up to 30% DDGS in diets fed to nursery pigs and to grower-finisher pigs. Pork fat becomes softer when DDGS is included in diets fed to finisher pigs because of the high concentration of linoleic acid in the oil in DDGS, and this may result in pork fat iodine values that are not acceptable when more than 20% DDGS is included in diets fed to finisher pigs. Withdrawing DDGS from the diet at least 3 wk before slaughter or adding CLA to the late finishing diet may prevent this problem.

Dietary inclusion of up to 50% DDGS in gestation diets and up to 30% in lactation diets does not affect sow and litter performance, or may even increase litter size and improve reproductive performance of the sows. There is some evidence that feeding DDGS diets may enhance the gut health of growing pigs, but more research is needed to determine whether or not this response is repeatable. Formulating diets containing DDGS on a digestible P basis reduces manure P concentration, but because of reduced DM digestibility, manure volume is increased in pigs fed diets containing DDGS. Adding DDGS to swine diets seems to have a minimal impact, if any, on gas and odor emissions from manure and, with the exception of the concentration of P, the chemical composition of manure is not changed. Research is needed to determine practical ways to enhance DM and energy digestibility in DDGS because there is great potential for improving the feeding value of DDGS if DM digestibility can be improved. An improvement in the digestibility of the insoluble fiber fraction is, therefore, needed.

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