Title: Sulfur Concentration in Distiller's Dried Grains with Soluble (DDGS) and Its Impact on Palatability and Pig Performance – **NPB #08-093**

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Industry Summary

The study has provided a comprehensive investigation on whether or not increasing concentrations of sulfur in distillers dried grains with solubles (DDGS) can impact the palatability and performance of weanling and growing-finishing pigs. The study also has provided in-depth information on various chemical forms of sulfur in DDGS and the cause for increasing sulfur levels in DDGS.

While the majority of production experiments have confirmed that 20 to 30% DDGS in diets fed to growing pigs has resulted in no detrimental effects on performance, some reports have shown reduced feed intake, and thus, reduced pig performance with DDGS included in the diets. To find out if the sulfur in DDGS is the culprit for reduced palatability and performance, we performed feed preference experiments and feed performance experiments with weanling pigs and growing barrows. In both experiments, the pigs fed the control diet (corn and soybean meal) gained more weight and had greater feed efficiency compared with those fed diets containing DDGS. However, there were no differences in performance between pigs fed a diet containing low or high levels of sulfur and it is, therefore, unlikely that the sulfur in DDGS is reducing the palatability of the diet. Producers, therefore, do not need to worry about the levels of sulfur in DDGS because pigs do not reduce performance when fed diets containing DDGS with a high sulfur level compared with pigs fed a diet containing DDGS with a low sulfur level.

Results of the experiment also indicated that the intrinsic sulfur in DDGS, around 0.2 % (wt/wt, as received basis), is contributed from the organic sulfur, mainly cysteine and methionine in corn. However, the major source of sulfur in DDGS is the inorganic sulfur or sulfate and that originates from sulfur that is added during production of ethanol. The inorganic sulfur level in DDGS can vary from almost zero to 0.8 % or higher. The corn to ethanol production process is the main factor responsible for the relatively high sulfur levels in some sources of DDGS.

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Based on the results of this experiment, the level of sulfur that are commonly present in DDGS is not a concern for swine palatability and performance with 20 to 30 % DDGS included in the diets. Additional research is currently being conducted to investigate the impact of sulfur in DDGS on tissue levels of sulfur in pigs.

Stated Objectives from original proposal

The first objective of this research is to determine the concentration of total sulfur and the different forms of sulfur (i.e., amino acid bound sulfur, sulfates, and sulfides) in dried distillers grains with solubles (DDGS). The second objective is to add increasing concentrations of sulfur to diets fed to weanling and growing pigs to investigate the influence of sulfur on palatability of feed and on pig performance.

The overall objective of this project is to evaluate the extent of variation in sulfur concentration in DDGS and to provide data on how elevated sulfur levels in swine diets impact the performance of weanling and growing-finishing pigs.

Final Reports

Report from NCERC

1. Scientific abstract

Because of the large supply of DDGS and the increasing costs of corn and soybean meal, it is expected that DDGS will be included in diets fed to animals in greater quantities in the future. However, potential risk factors, like high sulfur in DDGS, could reduce feed intake of diets containing DDGS, and also reduce animal performance. In this study, we have evaluated the extent of variation in sulfur concentration in DDGS based on a large collection of representative DDGS samples from the ethanol industry. For the first time, we have provided the typical ranges for sulfur in DDGS to the feed industry. Furthermore, we have determined the different forms of sulfur, i.e., amino acid bound sulfur, sulfates, in DDGS, as well as determined how much of each form of sulfur is intrinsic to DDGS or a result of the production process. In conclusion, we found that the intrinsic sulfur in DDGS, around 0.2 % (wt/wt, as received basis), is contributed from the organic sulfur, mainly cysteine and methionine in corn; while the major source of sulfur, the inorganic sulfur or sulfate in DDGS, comes from corn to ethanol production; and the inorganic sulfur level can vary from non-detected to 0.8 % or higher. The corn to ethanol production is the main factor controlling elevated sulfur level in DDGS.

2. Introduction

Sulfur is an essential non-metallic element for animals and plants. Most of the S in diets fed to monogastric animals is included in the form of s-containing AA (methionine and cysteine). Sulfur is intrinsic in DDGS because the corn kernel contains about 0.1% S and it is usually concentrated by a factor of 3 in DDGS. There are several sources which could contribute to the inorganic S in DDGS. During corn to ethanol production, sulfur can enter into the product stream from the use of water, sulfuric acid for pH adjustment, bisulfites for air scrubbers, sulfamic acid/sodium bisulfate for cleaning heat exchangers, etc. (1). Another potential source for the sulfate in DDGS is the sulfuric acid added to the distillation column. The insoluble precipitates of organometallic salts, *i.e.* calcium oxalate (beer stone), calcium / magnesium phytate, left from the fermentation beer and coated on the surface of the distillation column, can impair heat transfer and cause production interruptions. To prevent and decrease the formation of the deposits, a large amount of sulfuric acid is added to the distillation column continuously. Recently, we helped an ethanol plant to conduct mass balance calculation on sulfur from incoming corn to the production of DDGS, and learned that, (1) 80% of total sulfur introduced to the corn to ethanol production was from the distillation column and the sulfur form was sulfate; (2) almost all of the total sulfur introduced to the corn to ethanol production ended in DDGS.

Excessive amounts of sulfur may impair animal performance by reducing the availability and absorption of other minerals. It is well known that a high sulfur level in cattle feed can lead to polioencephalomalacia. The NRC (1996) recommends a maximum tolerable level of 0.4% of the dry matter in rations fed to cattle, but there are no recommendations on the concentration of sulfur that is tolerable to pigs. Some sources of DDGS may contain up to 0.74% sulfur (2). If these sources of DDGS are used in swine feed at concentrations of 30% by weight, the total concentration of sulfur in the diet will be between 0.4 and 0.5%. If sulfur is also present in the drinking water, the daily intake of sulfur may be relatively high.

There are numerous analytical methods available for the analysis of total sulfur, inorganic sulfur and organic sulfur in DDGS (3 - 6). At the NCERC lab, a sulfur analyzer was chosen for the determination of total sulfur content in DDGS, due to its high accuracy and high sample throughput (7). For inorganic sulfur in DDGS, an ion chromatography was used for testing sulfur based anions, since IC has been widely used for the detection and quantitation of sulfide and sulfate in aqueous solution (8). Finally, we have developed a quantitation method for the analysis of cysteine and methionine in DDGS with performic acid oxidation for hydrolysis (AOAC 994.12), and quantitation using liquid chromatography / mass spectrometry / mass spectrometry (LC/MS/MS).

3. Methods and results

An analytical method for the determination of total sulfur in DDGS was developed using a Rapid S Sulfur Analyzer (Elementar). A DDGS sample went under catalytic tube combustion in an oxygenated atmosphere at 1200^oC, and the sulfur containing components were quantitatively reduced to SO_2 which was detected with an infrared detector. The sample preparation procedure was optimized for DDGS matrix. The quantitation was based on an external calibration using five standards with a matrix similar to DDGS spiked with synthetic sulfur compounds, resulting in a correlation coefficient (R^2) of 0.99 for a linear model. An NIST RM 8418 (wheat Gluten) was used as a quality control sample for each batch of run, and the recovery was between 95% and 105%. For within batch repeatability, the relative standard deviation for five replicates of the quality control sample was around 5%. A total of 40 DDGS samples were analyzed for total sulfur content (Table 1), and the data were used by the co-PI, Dr. Stein to design and perform the animal trials at Univ. of Illinois (see the section from U. of I.). Besides the total sulfur contents, the proximate compositions, such as moisture, crude fat, crude protein, neutral detergent fiber, acid detergent fiber and residual sugars were also obtained from the same DDGS samples (Table 1). The testing methods used for the proximate analysis were methods recommended by the American Feed Industry Association or/and adapted from the official methods of the Association of Official Analytical Chemists (AOAC) (10 - 15).

The determination of the sulfur bound anions in DDGS, was developed using an ICS-2000 Ion Chromatograph (Dionex). An aqueous extract of a DDGS sample was injected into the ICS-2000 system with a mobile phase of 8 mM Na_2CO_3 / 1 mM $NaHCO_3$ at a flow rate of 1.2 ml/min; both a guard and analytical column (IonPac AS14A) were utilized at 35^oC. The analyte was detected using a conductivity detector with suppressor (AMMS III with 50 mN H_2SO_4). The quantification was performed with an external calibration with four standards made of pure $Na_2SO_4.10H_2O$ in deionized water, resulting in a correlation of 0.99 for a linear model. Based on this method, sulfate was the only sulfur-bearing anion detected in DDGS aqueous extract, and the limit of quantitation for this method was about 0.01% in DDGS. A DDGS aqueous extraction trial was conducted in order to optimize the extraction time and the mass ratio of DDGS sample to deionized water. A quality control standard made of pure $Na_2SO_4.10H_2O$ in deionized water was used with each batch of run, and the recovery was between 98% - 102%. For within batch repeatability, the relative standard deviation for three replicates of a DDGS sample was around 2%. A total of 29 DDGS samples were analyzed for sulfate content and the results are listed in Table 2.

The determination of cysteine and methionine, the organic sulfur form in DDGS, was performed using LC/MS/MS. According to the AOAC method (6), a ground DDGS sample was oxidized in performic acid at 0^oC for 16 hrs before it was hydrolyzed in 6 N HCL at 110^oC for 24 hours. The hydrolysate with oxidized form of cysteine and methionine, cysteic acid and methionie sulfone, was diluted 10 times using 1% ammonium acetate, and homocysteic acid was added in the hydrolysate as an internal standard for the analysis of cysteic acid. The final sample was run on reversed phase HPLC with gradient mobile phase (0.1% ammonium acetate in water for mobile phase A and 0.1% ammonium acetate in methanol for mobile B), and detected by MS/MS in the multiple reaction monitoring (MRM) operation mode. The quantitation was performed based on an external calibration with five standards made of pure cysteic acid (homocysteic acid added as internal standard) and methionine sulfone, and the correlation coefficient for both curves was 0.99 for a linear model. An NIST SRM 2387 (peanut butter) was used as a quality control standard with each batch of run, and the relative standard deviation for a triplicate was 2% for cysteine and 4% for methionie; and the recovery for cysteine was between 90% and 110%, and only about 85% for methionie. A total of 29 DDGS samples were analyzed for cysteine and methionine and the results are listed in Table 2.

4. Discussion

The 40 DDGS samples selected for the total sulfur study came from 12 states in the Midwest of the U.S., and the plants from which the samples came represented the geographical distribution of dry grind ethanol plants nationwide (16). The mean content of the total sulfur in the 40 samples was 0.59 % (wt/wt, as received basis) with a range from 0.27 to 0.91 %. The mean and the range of total sulfur in DDGS obtained in this study are very close to the literature values (17). Our study showed that the majority of the DDGS samples contained total sulfur content within the range of 0.40 to 0.80 % (Fig. 1). Besides DDGS, we also tested total sulfur content in corn, and it was found to be 0.06 ± 0.01 % (based on three data points). The mean content of the sulfate in 29 samples was 0.30% (wt/wt, as received basis) with a range from 0.04 to 0.66 %. The majority of the DDGS samples contained sulfate content within the range of 0.2 to 0.5 % (Fig. 2).

To make it easy for calculation, we use sulfur content contributed from both cysteine and methionine to represent organic sulfur. The organic sulfur in 29 DDGS samples were very close with a mean of 0.18% (Table 2), which was about 3 times of the organic sulfur content in corn reported by Feedstuff (18), and about 3 times of the total sulfur in corn (data from this study) considering the analytical error. It seems that the total sulfur in corn mainly comes from sulfur in cysteine and methionine, which is in organic form; during fermentation and back end process for DDGS production, the organic sulfur in corn do not change much and they become the intrinsic sulfur in DDGS with a level of three times as high in in corn.

In order to understand the correlation between total sulfur and different sulfur forms in DDGS, we plot the sulfate in DDGS versus total sulfur in DDGS (Fig. 3). The correlation is close to linear with a correlation coefficient of 0.94. When we subtract the sulfate content from the total sulfur content in DDGS (Table 2), the difference is very consistent for the 29 DDGS samples with a mean of 0.26 % (± 0.06), and this mean value is very close to the mean of organic sulfur in DDGS (Table 2). The existing data suggest that the total sulfur in DDGS comprises of two parts, the organic sulfur and the inorganic sulfur. The organic sulfur is controlled by the incoming feedstock, in this case, corn and it is very consistent with a mean of 0.2% in DDGS. The inorganic sulfur level varies greatly, depending on the addition of inorganic sulfur, mainly sulfuric acids to the corn to ethanol production. The higher the sulfate addition to the corn to ethanol production, the higher the sulfate level in DDGS, therefore, the higher the total sulfur level in DDGS. Furthermore, we have observed that the addition of sulfuric acid to the corn to ethanol production can vary temporally within the same ethanol plant (Table 2).

In summary, our data showed that the total sulfur in DDGS comprises of two parts, the organic sulfur mainly from cysteine and methionine, and the inorganic sulfur, mainly in sulfate form. The organic sulfur is intrinsic and is controlled by the feedstock with a mean level of 0.20%; while the inorganic sulfur is contributed from the corn to ethanol production and can vary from non-detect to 0.7% or higher. The ethanol production is the main contributor for the elevated sulfur in DDGS.

Table 1. Total Sulfur and Proximates in DDGS (%, wt/wt, on as-received basis)*

Plant Number	Total Sulfur	Moisture	Crude fat	NDF	ADF	Crude Protein	Residual Sugars
1	0.91	10.2	9.2	22.4	13.4	27.4	8.6
2	0.66	8.8	10.9	26.3	12.3	27.8	7
3	0.72	10.7	9.4	24.8	9.8	24.2	14.6
4	0.84	10.2	9.6	23.4	12.7	26.1	5.4
5	0.59	10.6	8.3	28.6	11.2	34.0	6.8
6	0.53	11.0	9.5	30.0	15.1	26.5	7.2
7	0.53	11.0	10.8	26.5	13.7	26.9	6.1
8	0.69	10.5	11.6	25.4	12.0	27.7	6.5
9	0.46	10.8	12.1	26.4	11.1	26.5	6.6
10	0.73	10.5	12.0	26.7	12.1	26.9	5.9
11	0.34	10.5	10.3	25.0	13.5	28.0	5.5
12	0.67	10.3	10.5	30.2	11.5	26.2	10
13	0.40	14.7	11.7	25.1	13.6	26.7	3.5
14	0.86	13.8	9.5	24.2	13.0	25.7	3.9
15	0.76	11.4	7.3	28.8	12.8	29.0	5.9
16	0.52	9.0	11.1	29.4	10.3	25.9	7.5
17	0.52	14.3	7.7	28.5	12.1	27.6	6.5
18	0.68	9.0	10.1	29.3	11.6	29.7	6.5
19	0.72	10.3	10.7	29.6	11.7	27.3	5.4
20	0.58	7.8	8.8	26.8	13.4	28.8	6.1
21	0.77	7.5	10.9	29.8	10.3	28.5	7.9
22	0.53	11.0	10.4	31.7	11.8	25.3	5.4
23	0.81	9.9	10.6	24.8	12.6	27.7	6.6
24	0.30	9.8	9.3	31.5	14.3	27.3	7.7
25	0.27	9.4	9.3	23.6	10.7	25.6	14.1
26	0.32	12.4	9.6	25.2	15.8	25.0	8.2
27	0.57	9.0	9.4	26.4	10.7	27.5	6.2
28	0.34	10.4	8.0	26.9	13.7	29.2	9.8
29	0.59	9.1	8.6	27.6	4.3	27.6	8.1
30	0.68	13.7	8.6	28.7	8.2	29.8	4.1
31	0.54	10.4	10.5	33.3	15.1	25.8	6
32	0.45	12.9	7.8	31.9	11.6	24.4	6.7
33	0.39	9.8	11.2	25.4	13.8	25.5	5.4
34	0.55	9.7	9.1	29.7	11.8	27.9	8.6
35	0.61	11.0	10.8	25.4	11.3	26.9	5.9
36	0.68	9.2	10.8	27.0	10.9	26.4	7.4
37	0.51	10.1	10.8	28.9	13.8	27.6	5.6
38	0.63	9.8	10.8	26.8	12.5	29.1	4.9
39	0.61	8.5	9.4	23.0	12.7	27.3	6.6
40	0.62	10.2	10.5	22.3	12.8	27.4	7.0

* **Methods for the tests:** Total S: combustion, Elementar S Analyzer; Moisture: NFTA 2.2.2.5; Crude Fat: AOAC 945.16; NDF: AOAC 2002.04; ADF: AOAC 973.18; Crude Protein: AOAC 990.03; Residual Sugars: modified AOAC 996.11

Table 2. Total Sulfur, Inorganic Sulfur (sulfate) and Organic Sulfur in DDGS (%, wt/wt, on as-received basis)

Plant Number	Total Sulfur	Inorganic Sulfur	Organic Sulfur	Total Sulfur minus Inorganic Sulfur
1	0.91	0.54	0.26	0.37
5	0.59	0.29	0.21	0.3
8	0.69	0.34	0.17	0.35
8b*	0.63	0.36	0.15	0.27
8c*	0.50	0.29	0.20	0.21
15	0.76	0.44	0.19	0.32
18	0.5	0.31	0.19	0.19
20	0.58	0.36	0.18	0.22
20b	0.71	0.43	0.16	0.28
20c	0.52	0.35	0.21	0.17
21	0.77	0.42	0.17	0.35
23	0.81	0.45	0.16	0.36
24	0.30	0.06	0.14	0.24
26	0.24	0.04	0.15	0.2
26b	0.26	0.07	0.26	0.19
26c	0.32	0.13	0.13	0.19
31	0.52	0.30	0.17	0.21
31b	0.54	0.31	0.19	0.24
31c	0.64	0.35	0.19	0.29
32	0.44	0.22	0.24	0.22
35	0.61	0.33	0.17	0.28
35b	0.70	0.43	0.16	0.27
35c	0.40	0.19	0.17	0.21
36	0.68	0.37	0.29	0.31
37	0.51	0.28	0.26	0.23
41	0.46	0.26	0.12	0.20
42	0.96	0.66	0.29	0.30
mean	**0.55**	**0.30**	**0.18**	**0.26**
s.d.	**0.18**	**0.14**	**0.04**	**0.06**

* DDGS samples were sent to NCERC multi-times.

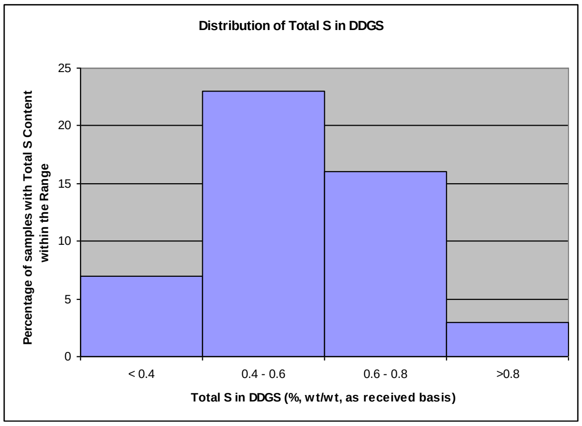

Fig. 1 Distribution of Total S in DDGS (representing 40 ethanol plants in the U.S.)

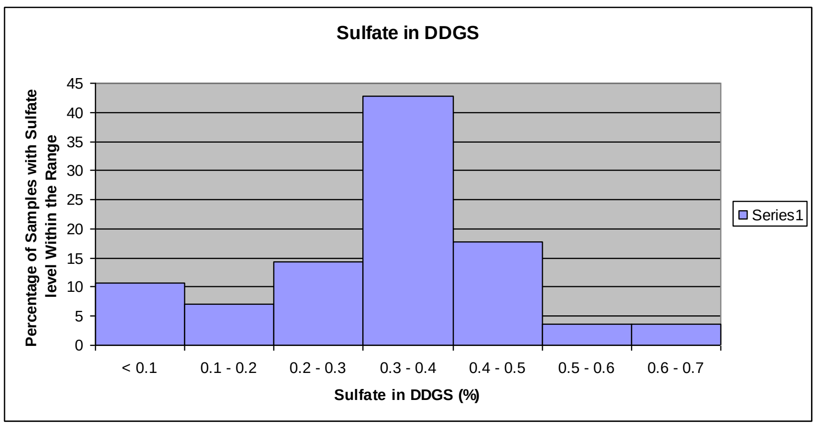

Fig. 2 . Distribution of Sulfate Content in DDGS (representing 21 ethanol plants in the U.S.)

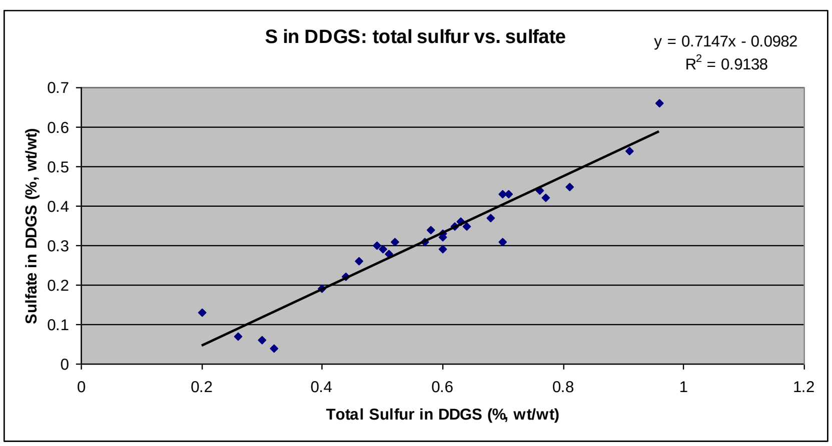

Fig. 3 The correlation between total sulfur and sulfate in DDGS (representing 21 ethanol plants in the U.S.)

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Report from the University of Illinois

1. Industry summary

In many production experiments, 20 to 30% distillers dried grains with soluble (DDGS) in diets fed to growing pigs has resulted in no detrimental effects on performance. However, reduced feed intake, and thus, reduced pig performance, has been reported from others experiments. It has also been reported that pigs sometimes prefer to eat diets containing no DDGS rather than diets containing DDGS. However, specific reasons for the reduced feed intake or the preference are unknown. It has been suggested that the concentration of S in DDGS may be associated with the feed palatability. In cattle diets, 0.4% of S is recommended as a maximum tolerance level, but no such information is available for swine diets. In this study, therefore, we hypothesized that the reduced palatability of diets containing DDGS may be due to the high concentration of S in DDGS. The objective was to provide data on how elevated S levels from DDGS in swine diets impact the feed preference and the performance of weanling and growing-finishing pigs.

Three diets were formulated for the experiments with weanling pigs: 1) the control diet based on corn and soybean meal, 2) the DDGS diet containing 20% of DDGS, and 3) the DDGS + S diet. The same structure of treatments was used for grow-finishing experiments, except that the inclusion level of DDGS was 30%.

Two 2-choice feed preference experiments were conducted using 48 weanling barrows (20.1 kg) and 30 growing barrows (49.6 kg). In weanling pigs, the feed preference (intake of the individual diet ÷ intake from the both diets in the pen × 100%) for the DDGS diet and the DDGS + S diet versus the control diet was 35.2 and 32.6%, respectively. However, there was no feed preference between the DDGS diet and the DDGS + S diet. In growing pigs (49.6 kg), similarly, the feed preference for the DDGS diet and the DDGS + S diet over the control diet was 29.8 and 32.9%, respectively. However, the feed preference was unaffected by the additional S.

Two feeding experiments were conducted using 90 weanling barrows (10.3 kg) and 120 growing barrows (34.2 kg). In both experiments, the pigs fed the control diet gained more weight and had greater feed efficiency compared with those fed the DDGS diet or the DDGS + S diet. Based on the present research, the inclusion of 20 to 30% DDGS in swine diets may decrease the palatability and negatively affect the growth performance. But, the S concentration in DDGS may not be the reason for the detrimental effects of DDGS.

2. Scientific abstract

Four experiments were conducted to investigate the effect of elevated S levels in diets on the feed palatability and the performance in weanling and grow-finishing pigs. In a 10-d feed preference experiment (Exp. 1), 48 weanling barrows (20.1 ± 2.16 kg BW) were grouped into 8 blocks by initial BW and allotted to 3 groups with 2 pigs per pen. Three diets were prepared: 1) the control diet based on corn and soybean meal, 2) the distillers dried grains with soluble (DDGS) diet containing 20% of DDGS, and 3) the DDGS + S diet. Sulfur was added as calcium sulfate to mimic the DDGS containing 0.9% S which was the highest level from the 35 DDGS sources in the United States. Two diets were provided in separate feeders in each pen: 1) the control diet and the DDGS diet, 2) the control diet and the DDGS + S diet, and 3) the DDGS diet and the DDGS + S diet. The feed preference for the DDGS diet and the DDGS + S diet versus the control diet was 35.2 and 32.6%, respectively ($P < 0.05$). However, there was no feed preference between the DDGS diet and the DDGS + S diet. In a 28-d feeding experiment (Exp. 2), 90 weanling barrows (10.3 ± 1.44 kg BW) were allotted to 3 dietary treatments, 10 blocks based on BW, and 3 pigs per pen. The same diets as in Exp. 1 were used, and only 1 diet was provided to each pen. Pigs fed the control diet gained more weight (497 vs. 423 and 416 g/d; $P < 0.05$) and had greater G:F (0.540 vs. 0.471 and 0.455; $P < 0.05$) compared with the other two treatment groups. In another 10-d feed preference experiment (Exp. 3), 30 growing barrows (49.6 ± 2.32 kg BW) were allotted into 10 blocks and 3 treatment groups. The treatment structure and experimental procedures are the same as in Exp. 1 except that 30% of DDGS was included in the DDGS and DDGS + S diets. The feed preference for the DDGS diet and the DDGS + S diet compared with the control diet was 29.8 and 32.9%, respectively ($P < 0.001$). However, the feed preference was unaffected by the additional S. In an 84-d feeding experiment (Exp. 4), 120 growing barrows (34.2 ± 2.25 kg BW) were used. The treatment structure and the experimental design were the same as in Exp. 2 except that 30% of DDGS was used and there were 2 phases. Pigs fed the control diet gained more weight (1,021 vs. 912 and 907 g/d; $P < 0.05$) and had greater G:F (0.335 vs. 0.316 and 0.307; $P < 0.05$) compared with the other 2 treatment groups and greater ADFI (3,054 vs. 2,887; $P < 0.05$) than the DDGS group. The carcass weight was heavier (87.9 vs. 80.7 or 80.9 kg; $P < 0.05$) in the pigs fed the control diet than in those fed the DDGS diet or the DDGS + S diet and heavier liver (1,860 vs. 1,661 g; $P < 0.05$) and kidneys (372 vs. 331 g; $P < 0.05$) than those fed the DDGS diet. The redness (a*) of the loin muscle was greater in the control group (8.62 vs. 7.39 than in the DDGS + S group. Overall, inclusion of 20 to 30% of DDGS in swine diets decreased the palatability and negatively affected the growth performance. But, the S concentration up to 0.34% in diets did not have detrimental effects on feed palatability, growth performance, carcass characteristics, or pork quality.

Key words: distillers dried grains with solubles, feed preference, growth performance, pigs, sulfur

3. Introduction

The distillers dried grains with solubles (**DDGS**) is a co-product from the corn ethanol production. The annual production of DDGS in the U.S. has been dramatically increased, and the production is expected to increase to more than 30 million metric tons within the next decade. The DDGS may be used in swine diets where it can replace corn, soybean meal, and dicalcium phosphate. The digestibility of energy, phosphorus, and amino acids in DDGS by pigs has been determined (Fastinger and Mahan, 2006; Stein et al., 2007; Petersen et al., 2007). In production experiments, DDGS has been used in diets fed to weanling and growing pigs, and the inclusion of 20 to 30% DDGS in diets fed to growing pigs has resulted in excellent pig performance in some experiments (Whitney et al., 2004; DeDecker et al., 2005; Cook et al., 2005; Spencer et al., 2007). However, reduced feed intake of diets containing DDGS, and therefore also reduced pig performance, has been reported from some experiments (Fu et al., 2004; Linneen et al., 2006; Whitney et al., 2006; Hinson et al., 2007). It was also reported that sometimes pigs prefer to eat diets containing no DDGS rather than diets containing DDGS (Hastad et al., 2005). It is, however, not known why feed intake is reduced under certain situations, but not under others. It has been suggested that this may be related to the concentration of S in DDGS. In fact, there is very limited knowledge about the consequences of high concentrations of S in diets fed to pigs.

Sulfur is an essential non-metallic element for animals and plants. Most of the S in diets fed to monogastric animals is included in the form of S-containing AA (methionine, cysteine, and taurine), but inorganic forms of S are also present in the inorganic calcium and phosphorus sources that are often added to diets. Water, grain, and other feed ingredients may also supply S. Sulfur is intrinsic in DDGS because the corn kernel contains about 0.1% S and it is usually concentrated by a factor of 3 in DDGS. Yeast also creates some sulfites during fermentation. Historically, sulfuric acid was used in the dry grind ethanol production for pH adjustment. A few studies have reported that the level of S in DDGS varied greatly, which may be a consequence of variations in the amount of sulfuric acid used in the production of DDGS (Dr. R. Mass, personal communication). Excessive S may impair animal performance by reducing the availability and absorption of other minerals. It is well known that a high S level in cattle feed can lead to polioencephalomalacia. The NRC (1996) recommends a maximum tolerable level of 0.4% S of the dry matter in rations fed to cattle, but there are no recommendations on the concentration of S that is tolerable in diets fed to pigs. Some sources of DDGS may contain up to 0.74% S (Spiehs et al., 2002), and if these sources are used in swine diets at concentrations of 30%, the total concentration of S in the diet will be between 0.4 and 0.5%. If S is also present in the drinking water, the daily intake of S may be relatively high.

4. Stated objectives from original proposal

The first objective of this research is to determine the concentration of total S and the different forms of S (i.e., amino acid bound S, sulfates, and sulfides) in DDGS. The second objective is to add increasing concentrations of S to diets fed to weanling and growing pigs to investigate the influence of S on palatability of feed and on pig performance.

The overall objective of this project is to evaluate the extent of variation in S concentration in DDGS and to provide data on how elevated S levels in swine diets impact the performance of weanling and growing-finishing pigs.

5. Materials and methods

Four experiments were conducted in environmentally controlled rooms at the University of Illinois at Urbana-Champaign. The protocol for the experiments was reviewed and approved by the Institutional Animal Care and Use Committee at the University of Illinois. All pigs used in the experiment were Landrace (3/4) by Large White (1/4) cross-bred barrows (Genetiporc, Alexandria, MN).

Experiment 1 – Feed Preference of Weanling Pigs

In a 10-d feed preference experiment, 48 weanling barrows with an average initial BW of 20.1 kg (SD = 2.16) were used. Pigs were grouped into 8 blocks by initial BW and randomly allotted to 3 groups in a randomized complete block design using Experimental Animal Allotment Program (Kim and Lindemann, 2007). Two pigs were housed in each concrete slatted floor 1.1 × 1.9 m pen equipped with 2 stainless feeders and a nipple drinker. Pigs had free access to feed and water during the entire experimental period.

Three diets were formulated (Table 1). The control diet consisted primarily on ground corn and dehulled soybean meal supplemented with minerals and vitamins. The DDGS diet included 20% of DDGS containing 0.30% of S, and the energy and nutrients concentration of this diet was similar to the control diets (Table 2). The last diet, the DDGS + S diet, also contained 20% DDGS (0.30% S) and included 0.74% of calcium sulfate (21.9% Ca and 16.2% S) to mimic the DDGS with high S concentration (0.90%). The S concentration in DDGS samples from 35 ethanol plants in the United States were analyzed at the National Corn-to-Ethanol Research Center (Edwardsville, IL), and the range of S concentration was from 0.3 to 0.9%. The concentration of Ca and available P was equalized in diets 2 and 3 by changing the inclusion level of dicalcium phosphate and limestone.

In the first group, one feeder contained the control diet and the other feeder contained the DDGS diet; in the second group, the control diet and the DDGS + S diet; in the last group, the DDGS diet and the DDGS + S diet. Thus, all possible combinations from the 3 diets were made. The positions of the 2 feeders within the pen were switched daily to minimize positional preference. Individual BW was recorded at the beginning of the experiment and at the end of the experiment. Feed allotments and feed disappearance were recorded daily.

Experiment 2 – Growth Performance of Weanling Pigs

In a 28-d feeding experiment, a total of 90 weanling barrows with an average initial BW of 10.3 kg (SD = 1.44) were allotted to 3 dietary treatments, 10 blocks based on BW, and 3 pigs per pen in a randomized complete block design. Three pigs were housed in a 1.0 × 1.0 m fully slatted, plastic-coated metal floor pen equipped with a stainless feeder and a nipple drinker. Pigs had free access to feed and water.

The same diets as in Exp. 1 were used in this experiment (Table 1 and 2). Dietary treatments included the control diet, the DDGS diet, and the DDGS + S diet. Individual BW and feed intake were measured on d 0, 14, and 28.

Experiment 3 – Feed Preference of Growing Pigs

In a 10-d feed preference experiment, 30 growing barrows with an average initial BW of 49.6 kg (SD = 2.32) were used. Pigs were grouped into 10 blocks by initial BW and randomly allotted to 3 groups in a randomized complete block design using Experimental Animal Allotment Program (Kim and Lindemann, 2007). Pigs were individually housed in each concrete slatted floor 2.6 × 3.7 m pen equipped with 2 stainless feeders and 2 nipple drinkers. Pigs had free access to feed and water.

Three grower diets were formulated (Table 3). The control diet consisted primarily on ground corn and dehulled soybean meal supplemented with minerals and vitamins. The DDGS diet included 30% of DDGS containing 0.30% of S, and the energy and nutrients concentration of this diet was similar to the control diets (Table 4). The last diet, the DDGS + S diet, also contained 30% DDGS (0.30% S) and included 1.10% of calcium sulfate (21.9% Ca and 16.2% S) to mimic the DDGS with high S concentration (0.90%). The concentration of Ca and available P was equalized in diets 2 and 3 by changing the inclusion level of dicalcium phosphate and limestone.

The grower diets were used in the feed preference experiment. In the first group, one feeder contained the control diet and the other feeder contained the DDGS diet; in the second group, the control diet and the DDGS + S diet; in the last group, the DDGS diet and the DDGS + S diet. Thus, all possible combinations from the 3 diets were made. The positions of the 2 feeders within the pen were switched daily to minimize positional preference. Individual BW was recorded at the beginning of the experiment, on d 5, and at the end of the 10-d experiment. Feed allotments and feed disappearance were recorded daily.

Experiment 4 – Growth Performance and Carcass Traits of Grow-finishing Pigs

In an 84-d feeding experiment consisting of 2 phases of 42 d, a total of 120 growing barrows with an average initial BW of 34.2 kg (SD = 2.25) were allotted to 3 dietary treatments, 10 replicated pens, and 4 pigs per pen in a randomized complete block design based on BW. Four pigs were housed in each concrete slatted floor 1.9 × 2.6 m pen equipped with a stainless feeder and a nipple drinker. Pigs had free access to feed and water.

Dietary treatments included the control diet, the DDGS diet, and the DDGS + S diet. Phase 1 diets were provided during the first 42 d and phase 2 diets during the following 42 d. Individual pig BW and feed intake were measured on d 0, 42 and 84.

At the end of the feeding experiment, a pig representing the mean BW of each pen was killed to determine carcass characteristics, organ weights, and pork quality.

Chemical Analysis

All diet samples were gound through a 1-mm screen in a Wiley mill (model 4; Thomas Scientific, Swedesboro, NJ) and analyzed for GE using an adiabatic bomb calorimeter (Model 6300, Parr Instruments, Moline, IL). The test for total sulfur content in diet samples was performed at NCERC (see the section from NCERC for analytical method)

Calculation and Statistical Analysis

All data were analyzed using SAS (SAS Inst. Inc., Cary, NC). In the feed preference experiments (Exp 1 and 3), ADG, ADFI, G:F, and feed:gain were calculated. In Exp. 3, two outliers were detected by UNIVARIATE procedures based on the ADG during the overall period and removed from the data. The ADG of these outliers deviated by 1.9 and 2.9 times interquartile ranges, respectively, from the mean of the treatment group while ADG of other pigs were within the 1.5 times interquartile range of the treatment group mean. The model for MIXED procedures included treatment as the fixed variable and block as the random variable. Least squares means of treatment groups are compared in a pair-wise manner using PDIFF option of MIXED procedures. The differences were converted to letter groupings using the PDMIX800 macro in SAS (Saxton, 1998). Each animal was considered as an experimental unit. An alpha level of 0.05 was used for determination of statistical significance.

Feed preference was calculated as: Preference, % = intake of the individual diet, kg ÷ (intake from the both diets in the pen, kg) × 100. The preference data were analyzed using the paired *t*-test.

The analysis procedures for the data from the growth performance experiments (Exp 2 and 4) were the same as the performance analysis in Exp 1 and 3. In Exp. 2, three pigs were removed from the experiment due to the growth retardation which was unrelated to the dietary treatment. The feed intake of the remaining pigs in the same pen was estimated using the model developed by Lindemann and Kim (2007). In Exp. 4, one pig died on d 59.

6. Results

Experiment 1 – Feed Preference of Weanling Pigs

Growth performance data are summarized in Table 5. Growth performance was unaffected by the dietary treatments ($P > 0.20$).

Feed intake data are summarized in Table 6. The feed intakes for 2 diets are compared on the daily and cumulative bases. Pigs provided with a choice of the control diet and the DDGS diet consumed less ($P < 0.05$) from the DDGS diet for 4 d in the 10-d experiment. Similarly, when the control diet and the DDGS + S diet were provided, pigs consumed less ($P < 0.05$) from the DDGS + S diet for 4 d. In a choice of the DDGS diet and the DDGS + S diet, pigs consumed more DDGS diet than the DDGS + S diet on d 1, but after that we failed to find the difference of intake between these 2 diets.

On a cumulative basis, the less consumption for the DDGS diet over the control diet was significant ($P < 0.05$) on d 4, 9, and 10, and the less consumption for the DDGS + S diet over the control diet was significant ($P < 0.05$) on d 10. However, the feed consumption did not differ between the DDGS diet and the DDGS + S diet when these diets are provided in the same pen except on d 1.

Feed preference based on the feed intake is summarized in Table 7. On a daily basis, the lower preference ($P < 0.05$) for the DDGS diet and the DDGS + S diet compared with the control diet was observed for 4 and 5 d, respectively, out of 10 d. Although pigs consumed less ($P < 0.05$) from the DDGS + S diet than the DDGS diet on d 1, no preference difference was observed between these diets on the other days.

On a cumulative basis, the lower feed preference for the DDGS diet over the control diet was significant ($P < 0.05$) on d 4, 9, and 10, and the lower feed preference for the DDGS + S diet over the control diet was significant ($P < 0.05$) on d 9, and 10. During the overall period (10 d), the feed preference for the DDGS diet and the DDGS + S diet compared with the control diet was 35.2 and 32.6%, respectively ($P < 0.05$). However, the feed consumption was not different between the DDGS diet and the DDGS + S diet.

Experiment 2 – Growth Performance of Weanling Pigs

During d 0 to 14 of the growth performance experiment (Table 8), pigs fed the control diet gained more weight (390 vs. 296 or 292 g/d; $P < 0.05$) and had greater G:F (0.550 vs. 0.444 or 0.408; $P < 0.05$) compared with those fed the DDGS diet or the DDGS + S diet. During d 14 to 28, the control group had greater ADG (603 vs. 541 g/d; $P < 0.05$) than the DDGS group and had greater G:F (0.535 vs. 0.486 and 0.484; $P < 0.05$) than the DDGS group and the DDGS + S group. During the overall period, pigs fed the control diet gained more weight (497 vs. 423 and 416 g/d; $P < 0.05$) and had greater G:F (0.540 vs. 0.471 and 0.455; $P < 0.05$) compared with the other two treatment groups.

Experiment 3 – Feed Preference of Growing Pigs

Growth performance data from the preference study are summarized in Table 9. Pigs provided with the control diet and the DDGS + S diet consumed more feed (2.99 vs. 2.69 g/d; $P = 0.024$) than those with the control diet and the DDGS diet during d 5 to 10. Other than this, growth performance was unaffected by the dietary treatments ($P > 0.14$).

Daily and cumulative feed intake data are summarized in Table 10. Pigs provided with a choice of the control diet and the DDGS diet consumed less ($P < 0.05$) from the DDGS diet for 7 d in the 10-d experiment. Similarly, when the control diet and the DDGS + S diet were provided, pigs consumed less ($P < 0.05$) from the DDGS + S diet for 7 d. In a choice of the DDGS diet and the DDGS + S diet, we failed to find the difference of intake between these 2 diets.

On a cumulative basis, the less consumption for the DDGS diet or the DDGS + S diet over the control diet became significant ($P < 0.05$) on d 2 and lasted for the rest of the experiment. However, the feed consumption did not differ between the DDGS diet and the DDGS + S diet when these diets are provided in the same pen.

Feed preference based on the feed intake is summarized in Table 11. On a daily basis, the lower preference ($P < 0.05$) for the DDGS diet and the DDGS + S diet compared with the control diet was observed for 7 and 8 d, respectively, out of 10 d. Although pigs consumed less ($P < 0.05$) from the DDGS + S diet than the DDGS diet on d 3, no preference difference was observed between these diets on the other days.

On a cumulative basis, the lower feed preference for the DDGS diet or the DDGS + S diet over the control diet became significant ($P < 0.05$) on d 2 and lasted for the rest of the experiment. During the overall period (10 d), the feed preference for the DDGS diet and the DDGS + S diet compared with the control diet was 29.8 and 32.9%, respectively ($P < 0.001$). However, the feed consumption was not different between the DDGS diet and the DDGS + S diet.

Experiment 4 – Growth Performance and Carcass Traits of Grow-finishing Pigs

During d 0 to 42 of the growth performance experiment (Table 12), pigs fed the control diet gained more weight (1,025 vs. 915 or 910 g/d; $P < 0.05$) than those fed the DDGS diet or the DDGS + S diet. The ADFI of the control group was greater (2,722 vs. 2,553; $P < 0.05$) compared with the DDGS group, and G:F of the control group was greater (0.377 vs. 0.352; $P < 0.05$) than the DDGS + S group. During d 42 to 84, the control group had greater ADG (1,017 vs. 904 g/d; $P < 0.05$) and G:F (0.300 vs. 0.272; $P < 0.05$) than the DDGS + S group. During the overall period, pigs fed the control diet gained more weight (1,021 vs. 912 and 907 g/d; $P < 0.05$) and had greater G:F (0.335 vs. 0.316 and 0.307; $P < 0.05$) compared with the other 2 treatment groups and greater ADFI (3,054 vs. 2,887; $P < 0.05$) than the DDGS group.

The pigs fed the control diet had heavier carcass weight (87.9 vs. 80.7 or 80.9 kg; $P < 0.05$) than those fed the DDGS diet or the DDGS + S diet and heavier liver (1,860 vs. 1661 g; $P < 0.05$) and kidneys (372 vs. 331 g; $P < 0.05$) than those fed the DDGS diet (Table 13). However, there were no difference in carcass traits between the DDGS group and the DDGS + S group. Loin muscle qualities were unaffected by the dietary treatments except that the redness (a*) was greater in the control group (8.62 vs. 7.39 than in the DDGS + S group (Table 14).

7. Discussion

Feed Preference

The response in feed preference was more apparent and instant in growing pigs than in weanling pigs. The less responsiveness of feed preference in weanling pigs may be associated with the lower inclusion level of DDGS (20 vs. 30%). The other possible reason is the number of pigs in a pen. In the experiment with growing pigs, only 1 pig was housed in each pen, but in the experiment with weanling pigs, there were 2 pigs in each pen. Although we assumed that a feeder space was sufficient for 2 weanling pigs, a competition for a diet, and thus an associated error, was not completely eliminated. In other studies with 1 pig per pen (Seabolt, 2008; Solà-Oriol et al., 2009), the difference in feed preference was detectible after 1 or 2 d.

When a corn-soybean meal-based diet and a diet containing DDGS were provided, the feed preference was for the corn-soybean meal-based diet in both weanling and growing pigs. Previously, a linear reduction of preference was reported with increasing the inclusion of DDGS from 0 to 30% in the diet (Seabolt, 2008). The potential reasons for the reduced feed preference for the DDGS diet include 1) the fiber content, 2) mycotoxin, and 3) the S content in DDGS.

In a recent study by Solà-Oriol et al. (2009), pigs had a low preference for oats (8.5% crude fiber) compared with other cereal grains, but the preference was improved when the husk was removed from the oats resulting in 1.0% crude fiber. The DDGS generally contains over 25% of NDF that is at 3 times greater than corn (NRC, 1998). Thus, the high fiber contents in DDGS may impair the palatability of the diet.

Pigs are highly sensitive to vomitoxin and the diet containing 2 to 3 ppm of vomitoxin may reduce feed intake and weight gain (van Heugten, 2001). Seabolt (2008) reported that a source of DDGS contained 4 ppm of vomitoxin. Although it was not analyzed in the present experiment, mycotoxin may also be a reason for the reduced feed palatability.

The S content in the diet may also be reason for the reduced feed preference because S causes rotten-eggs smell. It was one of our objectives to investigate the influence of S on feed palatability. Thus, S as calcium sulfate was added to the DDGS diet to mimic a DDGS source containing 0.9% of S. The feed preference was decreased when DDGS was included to the corn-soybean meal-based diet containing a similar S concentration. However, feed preference was not further impaired by adding S to the DDGS diet. This shows that the S concentration up to 0.9% in DDGS may not be a direct reason for the reduced palatability of the DDGS diet.

Therefore, the inclusion of DDGS (20 and 30% for weanling and growing pigs, respectively) in swine diets reduced the palatability, and 0.9% of S in DDGS is tolerable to pigs in terms of the feed palatability.

Growth performance

In the present study, the feed intake was reduced by approximately 6% (2,722 vs. 2,553 g/d) when 30% of DDGS was included in the diet fed to growing pigs. Other than this, however, the feed intake was unaffected by the dietary DDGS. The difference in feed palatability measured in a 2-choice feed preference test may not be necessarily reflected in feed intake in growth performance experiments where pigs have only 1 choice of diet in each pen perhaps due to the lack of choice for diets and the adaptation to the less palatable diet. However, the reduced feed intake in a growth performance experiment may be explained by the feed palatability.

Weight gain and feed efficiency were clearly reduced by the inclusion of DDGS to the diet both in weanling and grow-finishing pigs. Based on a recent review by Stein and Shurson (2009), ADG was not affected by the inclusion of DDGS in 18 experiments, but reduced in 6 experiments. It was suggested that the reduced growth performance may be associated with the relatively poorer quality of the DDGS used in some experiments. In the present experiment, we intended to formulate the diets to provide very similar concentrations of ME, CP, Lys based on standardized ileal digestibility, Ca, and available P. In the DDGS, the CP concentration was analyzed to be 29.2% (NCERC), and the AA concentrations were estimated using the CP:AA ratio for general corn DDGS sources (Stein, 2007). The standardized ileal digestibility values were also from Stein (2007). The concentration of Ca and P in DDGS was analyzed by the DDGS provider and 77% bioavailability of P was assumed based on NRC (1998).

The concentration of Lys in the DDGS was calculated to be 0.83% and was used for the diet formulation. However, analyzed Lys in the DDGS was 0.70% (U of MO) and the CP in the DDGS was 26.3% (UIUC). Thus, the impaired ADG and G:F in pigs fed diets including DDGS may be due to the AA deficiency or imbalance in the diets containing DDGS.

Carcass Traits

The carcass weight was heavier and carcass length was longer in the pigs fed the control diet than in those fed the DDGS diet or the DDGS + S diet. These differences were mainly due to the greater slaughter weight in the control group. However, the dressing percentage, 10th-rib fat depth, and LM area were not different among the treatment groups. Based on the review by Stein and Shurson (2009), dietary DDGS reduced dressing percentages in 8 experiments, but did not affect dressing percentages in 10 experiments. The reduced dressing percentage in pigs fed the diets containing DDGS is explained by the increased gut fill and increased intestinal weight (Kass et al., 1980). The DDGS in the present experiment contained 26.9% of NDF which is typical in corn DDGS. It is unclear why the dressing percentage was unaffected by the dietary DDGS.

The weight of liver and kidney was heavier in the control group compared with the DDGS group. This may also be associated with the slaughter weight. The quality of pork was largely unaffected by the inclusion of DDGS to the diets.

Taken together, inclusion of 20 to 30% of DDGS in swine diets decreased the palatability and negatively affected the growth performance. But, the S concentration up to 0.34% in diets did not have detrimental effects on feed palatability, growth performance, carcass characteristics, or pork quality.

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9. Tables

Table 1. Ingredient and chemical composition of experimental diets for weanling pigs, Exp. 1 and 2

Itiem	Control	DDGS[1]	DDGS + S
Ingredient, %			
Corn	73.52	62.46	62.17
Soybean meal, 48% CP	23.00	14.00	14.00
DDGS	-	20.00	20.00
L-Lys·HCl	0.33	0.54	0.54
DL-Met	0.08	0.05	0.05
L-Thr	0.10	0.11	0.11
L-Trp	0.02	0.05	0.05
Dicalcium phosphate	1.40	0.80	0.80
Limestone	0.85	1.29	0.84
Calcium sulfate	-	-	0.74
Salt	0.40	0.40	0.40
Vitamin-mineral mixture[2]	0.30	0.30	0.30
Total	100.00	100.00	100.00

[1]DDGS represents distillers dried grains with solubles.

[2]Provides the following quantities of vitamins and micro minerals per kilogram of complete diet: vitamin A, 11,128 IU; vitamin D_3, 2,204 IU; vitamin E, 66 IU; vitamin K, 1.42 mg; thiamin, 0.24 mg; riboflavin, 6.58 mg; pyridoxine, 0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid, 23.5 mg; niacin, 44 mg; folic acid, 1.58 mg; biotin, 0.44 mg; Cu, 10 mg as copper sulfate; Fe, 125 mg as iron sulfate; I, 1.26 mg as potassium iodate; Mn, 60 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; and Zn, 100 mg as zinc oxide.

Table 2. Chemical composition of experimental diets for weanling pigs, Exp. 1 and 2

Itiem	Control	DDGS[1]	DDGS + S
Calculated composition			
ME, cal/g	3,292	3,308	3,298
CP, %	17.47	18.33	18.31
SID[2] Lys, %	1.03	1.03	1.03
SID M+C, %	0.59	0.59	0.59
SID Thr, %	0.64	0.64	0.64
SID Trp, %	0.19	0.19	0.19
Thr:Lys	0.62	0.62	0.62
Trp:Lys	0.19	0.19	0.19
S, %	0.226	0.221	0.341
Ca, %	0.71	0.71	0.71
P, %	0.62	0.59	0.59
Available P, %	0.32	0.32	0.32
Analyzed composition			
CP, %	16.4	16.9	16.9
Lys, %	1.11	1.11	1.16
Ether extract, %	2.31	3.44	3.64

[1]DDGS represents distillers dried grains with solubles.

[2]Standardized ileal digestible AA.

Table 3. Ingredient composition of experimental diets for grow-finishing pigs, Exp. 3 and 4

	Growing period (Exp. 3 and 4)			Finishing period (Exp. 4)		
Itiem	Control	DDGS[1]	DDGS + S	Control	DDGS	DDGS + S
Ingredient, %						
Corn	74.65	61.33	60.90	81.90	67.65	67.22
Soybean meal, 48% CP	23.00	6.00	6.00	16.00	-	-
DDGS	-	30.00	30.00	-	30.00	30.00
L-Lys·HCl	-	0.43	0.43	-	0.40	0.40
L-Thr	-	0.03	0.03	-	-	-
L-Trp	-	0.04	0.04	-	0.05	0.05
Dicalcium phosphate	0.85	-	-	0.90	-	-
Limestone	0.80	1.47	0.80	0.50	1.20	0.53
Calcium sulfate	-	-	1.10	-	-	1.10
Salt	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin-mineral mixture[2]	0.30	0.30	0.30	0.30	0.30	0.30
Total	100.00	100.00	100.00	100.00	100.00	100.00

[1]DDGS represents distillers dried grains with solubles.

[2]Provides the following quantities of vitamins and micro minerals per kilogram of complete diet: vitamin A, 11,128 IU; vitamin D_3, 2,204 IU; vitamin E, 66 IU; vitamin K, 1.42 mg; thiamin, 0.24 mg; riboflavin, 6.58 mg; pyridoxine, 0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid, 23.5 mg; niacin, 44 mg; folic acid, 1.58 mg; biotin, 0.44 mg; Cu, 10 mg as copper sulfate; Fe, 125 mg as iron sulfate; I, 1.26 mg as potassium iodate; Mn, 60 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; and Zn, 100 mg as zinc oxide.

Table 4. Chemical composition of experimental diets for grow-finishing pigs, Exp. 3 and 4

	Grower 1 (Exp. 3 and 4)			Grower 2 (Exp. 4)		
Itiem	Control	DDGS[1]	DDGS + S	Control	DDGS	DDGS + S
Calculated composition						
ME, cal/g	3,330	3,348	3,333	3,342	3,361	3,347
CP, %	17.12	17.16	17.12	14.40	14.79	14.76
SID[2] Lys, %	0.78	0.78	0.78	0.60	0.60	0.60
SID M+C, %	0.52	0.54	0.54	0.46	0.48	0.48
SID Thr, %	0.55	0.51	0.51	0.45	0.40	0.40
SID Trp, %	0.17	0.15	0.15	0.13	0.13	0.13
Thr:Lys	0.71	0.66	0.66	0.75	0.66	0.66
Trp:Lys	0.22	0.20	0.20	0.22	0.22	0.22
S, %	0.206	0.198	0.375	0.185	0.179	0.356
Ca, %	0.58	0.58	0.58	0.46	0.46	0.46
P, %	0.53	0.47	0.46	0.51	0.44	0.44
Available P, %	0.22	0.23	0.23	0.22	0.22	0.22
Analyzed composition						
GE, kcal/kg	3,769	3,997	3,784	3,784	4,024	4,007
CP, %	17.0	16.2	16.4	13.4	14.0	13.9
Lys, %	0.92	0.89	0.83	0.70	0.61	0.75
Ether extract, %	2.34	4.18	4.43	2.46	4.01	4.58

[1]DDGS represents distillers dried grains with solubles.

[2]Standardized ileal digestible AA.

Table 5. Growth performance of weanling pigs fed experimental diets[1], Exp. 1

Diets[2]:	Control and DDGS	Control and DDGS + S	DDGS and DDSG + S	SEM	*P*-value
BW, kg					
D 0	20.1	20.1	20.1	0.77	0.818
D 10	25.7	26.2	25.5	1.05	0.361
D 0 to 10					
ADG, g/d	567	603	537	41.1	0.340
ADFI, g/d	1,082	1,193	1,101	63.6	0.348
G:F	0.520	0.504	0.486	0.0151	0.253
Feed:gain	1.94	1.99	2.07	0.058	0.230

[a,b]Means without a common superscript within a raw differ ($P < 0.05$).

[1]Each least squares mean represents 8 pens (2 pigs per pen).

[2]Two different diets were provided in 2 feeders for each pen, and the positions of the 2 feeders within the pen were switched daily. DDGS represents distillers dried grains with solubles.

Table 6. Daily and cumulative feed intake of weanling pigs[1], Exp. 1

	Group 1				Group 2				Group 3			
Diet[2]:	Control	DDGS	SEM	*P*-value	Control	DDGS + S	SEM	*P*-value	DDGS	DDGS + S	SEM	*P*-value
Daily feed intake, kg/d												
D 1	0.46	0.63	0.236	0.641	0.56	0.69	0.234	0.703	0.78	0.42	0.091	0.027
D 2	1.18	1.01	0.250	0.647	1.24	1.30	0.284	0.881	1.11	1.07	0.163	0.875
D 3	1.18	0.62	0.174	0.061	1.27	0.73	0.412	0.382	1.07	0.84	0.220	0.494
D 4	1.63	0.46	0.166	0.002	1.34	0.74	0.291	0.184	1.39	0.84	0.275	0.205
D 5	1.28	0.96	0.386	0.585	1.49	0.56	0.257	0.038	1.08	0.93	0.365	0.771
D 6	1.71	0.86	0.358	0.140	1.99	0.67	0.274	0.011	1.61	1.05	0.449	0.405
D 7	1.38	0.84	0.397	0.365	1.48	1.03	0.355	0.400	1.09	1.00	0.439	0.892
D 8	1.70	0.83	0.255	0.046	2.11	1.02	0.414	0.106	1.58	1.19	0.505	0.610
D 9	1.79	0.71	0.228	0.012	1.89	0.73	0.173	0.002	1.48	1.12	0.380	0.522
D 10	1.69	0.72	0.284	0.047	2.49	0.54	0.160	<0.001	1.43	1.03	0.394	0.496
Cumulative feed intake, kg												
D 1	0.46	0.63	0.236	0.641	0.56	0.69	0.234	0.703	0.78	0.42	0.091	0.027
D 2	1.64	1.64	0.409	0.992	1.79	1.99	0.389	0.735	1.88	1.49	0.202	0.210
D 3	2.82	2.26	0.446	0.407	3.06	2.71	0.715	0.739	2.95	2.33	0.286	0.169
D 4	4.45	2.73	0.467	0.035	4.41	3.45	0.901	0.477	4.34	3.18	0.497	0.142
D 5	5.73	3.69	0.767	0.102	5.89	4.01	0.975	0.215	5.42	4.10	0.812	0.288
D 6	7.43	4.55	0.921	0.063	7.88	4.68	1.140	0.088	7.03	5.15	1.221	0.312
D 7	8.81	5.39	1.255	0.095	9.36	5.71	1.362	0.100	8.12	6.15	1.627	0.421
D 8	10.51	6.21	1.370	0.062	11.47	6.73	1.665	0.084	9.69	7.34	2.074	0.449
D 9	12.31	6.92	1.546	0.043	13.36	7.46	1.800	0.054	11.18	8.46	2.377	0.446
D 10	13.99	7.64	1.710	0.034	15.86	8.01	1.736	0.015	12.60	9.49	2.743	0.449

[1]Each least squares mean represents 8 observations.

[2]Two different diets were provided in 2 feeders for each pig, and the positions of the 2 feeders within the pen were switched daily. DDGS represents distillers dried grains with solubles.

Table 7. Daily and cumulative feed preference of weanling pigs[1], Exp. 1

	Group 1				Group 2				Group 3			
Diet[2]:	Control	DDGS	SEM	*P*-value	Control	DDGS + S	SEM	*P*-value	DDGS	DDGS + S	SEM	*P*-value
Feed preference based on daily feed intake, %												
D 1	50.3	49.7	22.33	0.985	49.5	50.5	18.21	0.969	71.0	29.0	11.33	0.035
D 2	55.2	44.8	10.20	0.494	49.8	50.2	10.20	0.974	50.2	49.8	7.80	0.975
D 3	64.5	35.5	9.81	0.075	69.6	30.4	16.92	0.146	63.2	36.8	17.54	0.323
D 4	78.7	21.3	6.72	0.001	64.9	35.1	13.67	0.167	61.4	38.6	10.71	0.175
D 5	57.5	42.5	16.34	0.537	70.7	29.3	11.18	0.035	49.9	50.1	17.49	0.994
D 6	63.0	37.0	12.02	0.171	75.7	24.3	10.78	0.012	59.1	40.9	15.73	0.439
D 7	60.3	39.7	16.93	0.420	62.0	38.0	15.21	0.303	45.6	54.4	21.44	0.779
D 8	70.9	29.1	11.20	0.034	71.2	28.8	13.48	0.062	56.9	43.1	18.16	0.609
D 9	72.5	27.5	8.58	0.008	74.1	25.9	7.84	0.003	54.8	45.2	16.18	0.687
D 10	73.9	26.1	11.04	0.018	82.0	18.0	4.61	<0.001	55.7	44.3	17.01	0.652
Feed preference based on cumulative feed intake, %												
D 1	50.3	49.7	22.33	0.985	49.5	50.5	18.21	0.969	71.0	29.0	11.33	0.035
D 2	52.0	48.0	11.99	0.818	48.4	51.6	10.36	0.834	55.9	44.1	6.37	0.233
D 3	55.5	44.5	8.64	0.400	54.4	45.6	11.55	0.604	56.7	43.3	5.97	0.154
D 4	61.8	38.2	6.33	0.033	57.4	42.6	10.30	0.345	58.5	41.5	6.79	0.120
D 5	60.6	39.4	7.98	0.102	60.3	39.7	8.91	0.145	57.0	43.0	8.34	0.272
D 6	61.4	38.6	7.27	0.062	63.4	36.6	8.28	0.056	57.2	42.8	9.45	0.319
D 7	61.1	38.9	8.28	0.099	62.8	37.2	8.51	0.071	55.8	44.2	10.82	0.475
D 8	62.5	37.5	7.59	0.053	64.0	36.0	8.87	0.061	55.8	44.2	11.74	0.508
D 9	63.8	36.2	7.53	0.036	65.1	34.9	8.43	0.039	55.5	44.5	11.86	0.533
D 10	64.8	35.2	7.57	0.028	67.4	32.6	7.31	0.012	55.5	44.5	12.20	0.542

[1]Each least squares mean represents 8 observations.

[2]Two different diets were provided in 2 feeders for each pig, and the positions of the 2 feeders within the pen were switched daily. DDGS represents distillers dried grains with solubles.

Table 8. Growth performance of weanling pigs fed experimental diets[1], Exp. 2

Diets[2]:	Control	DDGS	DDSG + S	SEM	*P*-value
BW, kg					
D 0	10.4	10.4	10.4	0.45	0.466
D 14	15.8[a]	14.6[b]	14.5[b]	0.56	<0.001
D 28	24.3[a]	22.3[b]	22.0[b]	0.77	0.001
D 0 to 14					
ADG, g/d	390[a]	296[b]	292[b]	14.2	<0.001
ADFI, g/d	713	668	719	28.2	0.349
G:F	0.550[a]	0.444[b]	0.408[b]	0.0150	<0.001
Feed:gain	1.83[b]	2.27[a]	2.49[a]	0.076	<0.001
D 14 to 28					
ADG, g/d	603[a]	549[ab]	541[b]	22.6	0.039
ADFI, g/d	1134	1132	1122	43.4	0.967
G:F	0.535[a]	0.486[b]	0.484[b]	0.0131	0.018
Feed:gain	1.89[b]	2.07[ab]	2.08[a]	0.053	0.027
Overall					
ADG, g/d	497[a]	423[b]	416[b]	15.7	<0.001
ADFI, g/d	924	901	920	32.9	0.818
G:F	0.540[a]	0.471[b]	0.455[b]	0.0122	<0.001
Feed:gain	1.86[b]	2.14[a]	2.21[a]	0.053	<0.001

[a,b]Means without a common superscript within a raw differ ($P < 0.05$).

[1]Each least squares mean represents 10 pens of 3 pigs per pen.

[2]DDGS represents distillers dried grains with solubles.

Table 9. Growth performance of growing pigs fed experimental diets[1], Exp. 3

Diets[2]:	Control and DDGS	Control and DDGS + S	DDGS and DDSG + S	SEM	*P*-value
BW, kg					
D 0	49.7	49.4	49.6	0.78	0.727
D 5	53.8	53.4	52.9	1.08	0.477
D 10	60.7	60.3	59.7	1.20	0.505
D 0 to 5					
ADG, g/d	828	796	695	97.8	0.548
ADFI, g/d	2,565	2,622	2,491	119.2	0.615
G:F	0.318	0.304	0.279	0.0316	0.665
Feed:gain	3.76	3.63	3.75	0.565	0.985
D 5 to 10					
ADG, g/d	1,384	1,388	1,353	71.1	0.923
ADFI, g/d	2,688[b]	2,987[a]	2,742[ab]	106.1	0.024
G:F	0.519	0.467	0.492	0.0261	0.305
Feed:gain	1.99	2.18	2.06	0.112	0.408
Overall					
ADG, g/d	1,106	1,092	1,020	53.8	0.384
ADFI, g/d	2,627	2,805	2,615	105.5	0.152
G:F	0.422	0.390	0.391	0.0138	0.140
Feed:gain	2.40	2.58	2.57	82.1	0.174

[a,b]Means without a common superscript within a raw differ ($P < 0.05$).

[1]Each least squares mean represents 10 individually penned pigs.

[2]Two different diets were provided in 2 feeders for each pig, and the positions of the 2 feeders within the pen were switched daily. DDGS represents distillers dried grains with solubles.

Table 10. Daily and cumulative feed intake of growing pigs[1], Exp. 3

	Group 1				Group 2				Group 3			
Diet[2]:	Control	DDGS	SEM	*P*-value	Control	DDGS + S	SEM	*P*-value	DDGS	DDGS + S	SEM	*P*-value
Daily feed intake, kg/d												
D 1	1.52	0.83	0.230	0.065	1.43	0.86	0.214	0.091	1.31	0.93	0.328	0.446
D 2	1.60	1.18	0.172	0.115	1.88	0.97	0.189	0.008	0.99	1.78	0.307	0.111
D 3	2.13	0.55	0.153	<0.001	1.81	1.08	0.214	0.039	1.64	0.98	0.231	0.085
D 4	1.64	0.77	0.242	0.032	1.62	0.83	0.176	0.011	0.95	1.58	0.371	0.273
D 5	1.87	0.76	0.168	0.001	1.51	1.15	0.326	0.455	1.33	1.09	0.333	0.638
D 6	1.63	0.73	0.174	0.005	1.89	0.63	0.259	0.008	1.03	1.44	0.417	0.507
D 7	1.90	0.87	0.281	0.029	2.03	0.93	0.315	0.036	1.20	1.69	0.346	0.352
D 8	1.98	0.70	0.329	0.023	2.15	1.05	0.312	0.035	0.77	1.61	0.360	0.142
D 9	1.60	0.91	0.308	0.148	2.08	0.90	0.373	0.052	1.36	1.56	0.508	0.795
D 10	2.41	0.72	0.400	0.015	2.41	0.89	0.320	0.009	1.63	1.50	0.385	0.817
Cumulative feed intake, kg												
D 1	1.52	0.83	0.230	0.065	1.43	0.86	0.214	0.091	1.31	0.93	0.328	0.446
D 2	3.12	2.01	0.323	0.038	3.31	1.83	0.330	0.011	2.29	2.71	0.539	0.600
D 3	5.24	2.55	0.256	<0.001	5.12	2.91	0.465	0.008	3.93	3.69	0.644	0.802
D 4	6.88	3.32	0.343	<0.001	6.73	3.73	0.491	0.002	4.88	5.27	0.804	0.743
D 5	8.75	4.08	0.427	<0.001	8.24	4.88	0.640	0.005	6.21	6.36	1.091	0.922
D 6	10.38	4.80	0.462	<0.001	10.12	5.51	0.811	0.003	7.23	7.80	1.305	0.767
D 7	12.28	5.67	0.661	<0.001	12.15	6.43	0.978	0.003	8.43	9.49	1.420	0.615
D 8	14.26	6.38	0.823	<0.001	14.29	7.48	1.166	0.003	9.20	11.10	1.571	0.421
D 9	15.86	7.29	1.067	<0.001	16.37	8.38	1.462	0.004	10.56	12.66	1.708	0.415
D 10	18.26	8.01	1.329	<0.001	18.78	9.27	1.619	0.002	12.19	14.16	1.998	0.510

[1]Each least squares mean represents 10 observations.

[2]Two different diets were provided in 2 feeders for each pig, and the positions of the 2 feeders within the pen were switched daily. DDGS represents distillers dried grains with solubles.

Table 11. Daily and cumulative feed preference of growing pigs[1], Exp. 3

	Group 1				Group 2				Group 3			
Diet[2]:	Control	DDGS	SEM	*P*-value	Control	DDGS + S	SEM	*P*-value	DDGS	DDGS + S	SEM	*P*-value
Feed preference based on daily feed intake, %												
D 1	63.7	36.3	9.21	0.065	64.5	35.5	9.71	0.064	58.9	41.1	14.82	0.423
D 2	58.8	41.2	6.49	0.087	66.6	33.4	7.46	0.012	37.0	63.0	11.25	0.146
D 3	79.5	20.5	4.40	<0.001	63.0	37.0	7.18	0.031	63.7	36.3	8.50	0.057
D 4	69.1	30.9	10.68	0.032	65.0	35.0	6.26	0.008	36.0	64.0	14.73	0.220
D 5	71.6	28.4	6.38	0.001	56.7	43.3	12.99	0.486	53.0	47.0	14.09	0.771
D 6	70.0	30.0	7.72	0.005	75.6	24.4	10.31	0.007	44.2	55.8	17.84	0.660
D 7	69.9	30.1	10.79	0.029	68.6	31.4	10.84	0.039	39.1	60.9	11.41	0.218
D 8	71.5	28.5	11.65	0.029	67.7	32.3	9.93	0.032	32.4	67.6	16.35	0.172
D 9	65.5	34.5	12.57	0.114	70.7	29.3	12.51	0.044	47.1	52.9	18.19	0.825
D 10	77.6	22.4	12.71	0.013	71.2	28.8	8.52	0.007	52.2	47.8	13.64	0.828
Feed preference based on cumulative feed intake, %												
D 1	63.7	36.3	9.21	0.065	64.5	35.5	9.71	0.064	58.9	41.1	14.82	0.423
D 2	61.5	38.5	6.69	0.038	65.2	34.8	7.00	0.014	46.7	53.3	10.64	0.675
D 3	67.9	32.1	4.02	<0.001	64.3	35.7	6.11	0.009	52.2	47.8	8.41	0.719
D 4	68.3	31.7	4.36	<0.001	64.5	35.5	4.60	0.002	48.3	51.7	8.21	0.777
D 5	69.1	30.9	4.31	<0.001	62.9	37.1	4.84	0.004	49.4	50.6	8.76	0.922
D 6	69.1	30.9	3.94	<0.001	64.9	35.1	5.18	0.003	48.1	51.9	8.74	0.772
D 7	69.2	30.8	4.57	<0.001	65.6	34.4	5.36	0.003	47.1	52.9	7.99	0.619
D 8	69.7	30.3	4.69	<0.001	66.0	34.0	5.49	0.003	45.3	54.7	7.69	0.414
D 9	69.2	30.8	5.28	<0.001	66.5	33.5	6.04	0.004	45.4	54.6	7.52	0.420
D 10	70.2	29.8	5.79	<0.001	67.1	32.9	5.80	0.002	46.3	53.7	7.90	0.525

[1]Each least squares mean represents 10 observations.

[2]Two different diets were provided in 2 feeders for each pig, and the positions of the 2 feeders within the pen were switched daily. DDGS represents distillers dried grains with solubles.

Table 12. Growth performance of growth-finishing pigs fed experimental diets[1], Exp. 4

Diets[2]:	Control	DDGS	DDSG + S	SEM	*P*-value
BW, kg					
D 0	34.2	34.2	34.2	0.74	0.252
D 42	77.3[a]	72.6[b]	72.4[b]	1.34	<0.001
D 84	120.0[a]	110.8[b]	110.4[b]	2.12	<0.001
D 0 to 42					
ADG, g/d	1,025[a]	915[b]	910[b]	19.6	<0.001
ADFI, g/d	2,722[a]	2,553[b]	2,586[ab]	62.1	0.024
G:F	0.377[a]	0.360[ab]	0.352[b]	0.0071	0.014
Feed:gain	2.66[b]	2.79[ab]	2.85[a]	0.054	0.014
D 42 to 84					
ADG, g/d	1,017[a]	909[ab]	904[b]	32.9	0.032
ADFI, g/d	3,385	3,221	3,317	67.0	0.211
G:F	0.300[a]	0.282[ab]	0.272[b]	0.0064	0.012
Feed:gain	3.35[b]	3.55[ab]	3.71[a]	0.081	0.013
Overall					
ADG, g/d	1,021[a]	912[b]	907[b]	20.4	<0.001
ADFI, g/d	3,054[a]	2,887[b]	2,951[ab]	54.0	0.044
G:F	0.335[a]	0.316[b]	0.307[b]	0.0043	<0.001
Feed:gain	2.99[b]	3.17[a]	3.26[a]	0.043	<0.001

[a,b]Means without a common superscript within a raw differ ($P < 0.05$).

[1]Each least squares mean represents 10 pens of 4 pigs per pen.

[2]DDGS represents distillers dried grains with solubles.

Table 13. Carcass characteristics and organ weights of pigs fed experimental diets[1], Exp. 4

Diets[2]:	Control	DDGS	DDSG + S	SEM	*P*-value
Carcass characteristics					
Slaughter wt, kg	116.8[a]	107.8[b]	108.6[b]	2.00	0.002
Hot carcass wt, kg	87.9[a]	80.7[b]	80.9[b]	1.71	0.004
Dressing percentage, %	75.2	74.8	74.5	0.36	0.312
Carcass length, cm	85.5[a]	82.8[b]	83.0[ab]	0.77	<0.001
10th-rib fat depth, cm	28.7	30.2	26.7	1.60	0.304
LM area, cm^2	38.9	36.4	37.8	0.86	0.138
Organ wt, g					
Liver	1860[a]	1661[b]	1765[ab]	61.8	0.046
Kidney	372[a]	331[b]	352[ab]	11.4	0.025
Heart	466	428	451	16.2	0.257
Spleen	216	191	201	9.4	0.165

[a,b]Means without a common superscript within a raw differ ($P < 0.05$).

[1]Each least squares mean represents 10 pigs.

[2]DDGS represents distillers dried grains with solubles.

Table 14. Loin muscle quality of pigs fed experimental diets[1], Exp. 4

Diets[2]:	Control	DDGS	DDSG + S	SEM	*P*-value
24-h pH	5.48	5.49	5.53	0.023	0.367
Drip loss, %	4.74	5.41	3.39	0.800	0.208
Minolta color score					
Lightness (L*)	51.29	51.82	49.31	1.096	0.252
Redness (a*)	8.62[a]	7.51[ab]	7.39[b]	0.372	0.037
Yellowness (b*)	5.53	5.17	4.72	0.373	0.317
Subjective score[3]					
Color	2.40	2.70	2.70	0.179	0.402
Marbling	1.70	2.30	2.50	0.263	0.101
Firmness	2.10	2.40	2.90	0.274	0.132

[a,b]Means without a common superscript within a raw differ ($P < 0.05$).

[1]Each least squares mean represents 10 pigs.

[2]DDGS represents distillers dried grains with solubles.

[3]Color (1 = pale pinkish gray to white; 6 = dark purplish red); marbling (1 = 1.0% intramuscular fat; 10 = 10% intramuscular fat); firmness (1 = soft; 6 = very firm).