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J ANIM SCI 2012, 90:1255-1261.
doi: 10.2527/jas.2010-3691 originally published online November 7, 2011

Amino acid digestibility of corn distillers dried grains with solubles, liquid condensed solubles, pulse dried thin stillage, and syrup balls fed to growing pigs[1]

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ABSTRACT: Distillers dried grains with solubles (DDGS) has low and variable AA digestibility. The variability is often attributed to damage during the heating process, and it has been suggested that the damage happens to the soluble components of DDGS such as reducing sugars. Combining solubles and grains sometimes produces syrup balls (SB); their digestibility is unknown. The objective of this experiment was to identify potential sources of poor and variable AA digestibility in DDGS. Specifically, our objective was to determine whether the problems are associated with the solubles component or with SB. The ingredients evaluated were DDGS, intact SB, ground SB, liquid condensed solubles (LCS), and pulse dried thin stillage (PDTS) obtained from the same ethanol plant. The LCS is produced by evaporation of thin stillage. Each ingredient was used as the only source of AA in an experimental diet. In a duplicate 6 × 6 Latin square design with 7-d adaptation and collection periods, the 6 treatments consisted of an N-free diet and the 5 test ingredients. Pigs had 5 d of adaptation to each diet, and on d 6 and 7 ileal digesta were collected from an ileal cannula for 8 h each day. Both SB treatments had apparent ileal digestibility (AID) and standardized ileal digestibility (SID) of AA that were similar or greater ($P < 0.05$) than those of DDGS. The AID and SID values of Lys and a few other AA were similar in LCS (SID Lys: 63.1%) and DDGS (SID Lys: 61.5%), but the digestibility values of most AA in LCS were less than in DDGS ($P < 0.05$). The low digestibility of AA in LCS was most pronounced for Met (SID: LCS, 41.9% vs. DDGS, 82.8%). The LCS had less ($P < 0.05$) AID and SID of CP (SID: 67.8%) than intact SB (SID: 85.2%) and ground SB (SID: 85.9%) as well as all AA. The PDTS generally had the least AID and SID and had less ($P < 0.05$) CP (SID: 55.3%) and several AA, including Lys, compared with LCS. In conclusion, the presence of SB does not decrease AA digestibility of DDGS, and the LCS evaluated has less indispensible AA digestibility than DDGS. The LCS has low digestibility of AA that seems to not be caused by heat damage.

Key words: amino acid digestibility, corn distillers coproducts, growing pig

J. Anim. Sci. 2012. 90:1255–1261
http://dx.doi.org/10.2527/jas.2010-3691

INTRODUCTION

Distillers dried grains with solubles (**DDGS**), a coproduct from the production of ethanol from grains, has generally low and variable AA digestibility compared with the grain that it originates from (Stein and Shurson, 2009). It is generally accepted that heating is partially responsible for the low and variable digestibility, but it is not clear whether the problem is primarily associated with the wet grains or solubles portion of DDGS. To summarize the process, the grain is received and ground by the ethanol plant; after simultaneous sacharification and fermentation and then distillation, the result is whole stillage and ethanol. Whole stillage goes through a centrifuge and the results are wet grains and thin stillage (**TS**), which has about 4 to 8% DM (Rausch and Belyea, 2006). The TS goes through an evaporator, resulting in liquid condensed soluble (**LCS**) with about 30 to 40% DM. Condensed soluble is generally mixed with wet grains and then dried to produce DDGS. Pahm et al. (2008a) found greater digestibility in distillers dried grains than in DDGS, indicating that much of the problem may lie in the solubles component. Optimization of the process for coproduct

[1]Funding from the National Pork Board and the Nutrition Efficiency Consortium, Des Moines, Iowa, is appreciated.
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Received November 11, 2010.
Accepted October 26, 2011.

quality requires knowledge of whether the problem derives primarily from the grains or the soluble, and, if from the solubles, whether it is inherent in the TS or is produced in the conversion to LCS. This information would also be important in the direct use of the liquid coproducts in liquid feeding systems.

Some batches of DDGS contain substantial amounts of hard agglomerations called syrup balls (**SB**) that are difficult to dissolve when intact and therefore may contribute to low nutrient digestibility. Preliminary results from our laboratory indicate that the amount of SB in 7 samples of DDGS previously analyzed for AA bioavailability in chicks (Pahm et al., 2009) ranged from 0 to 20%. In general, samples with increased amounts of SB had poor Lys availability in chicks. We are aware of no measurements of AA digestibility of SB in pigs or the effect of grinding the SB on digestibility. The objective of this experiment was to identify potential sources of poor and variable AA digestibility in DDGS. Specifically, our objective was to determine whether the problems are associated with the solubles component or with SB, in which the composition is similar to that of DDGS but the particle size is variable.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocol for the experiment.

Animals, Experimental Design, and Diets

Twelve growing barrows (initial BW = 36.4 ± 2.5 kg) originating from the mating of Line 337 boars to C 22 females (Pig Improvement Company, Hendersonville, TN) were used in the experiment. Pigs were allotted to a replicated 6 × 6 Latin square design with 6 pigs in each square and six 1-wk periods. Pigs were placed individually in pens (1.2 × 1.5 m) that each had fully slatted T-bar floors, a 1-hole feeder, and a nipple drinker.

The DDGS, LCS, TS, and SB were obtained from the National Corn to Ethanol Research Center (Edwardsville, IL). The products obtained were DDGS, DDGS with SB (extra LCS was added intentionally to produce an extra amount of SB), LCS, and TS (Table 1). Each product was obtained from a different run at the ethanol pilot plant. The evaporator operated at a temperature of 63°C and a pressure of 20 kPa. The evaporator required a residence time of approximately 2.5 to 3 d. For drying the final product, the dryer outlet temperature varied from 100 to 180°C; this temperature range was not specific for the treatment but rather was the one reported by the company that processed the product.

The TS was sent to a commercial company (Pulse Combustion Systems, Payson, AZ) to be pulse dried because the original material was too dilute to allow consumption of enough AA to support accurate estimation of digestibility. The pulse-drying system is able

Table 1. Analyzed concentration of DM and nutrients in ingredients[1] (%; as-fed basis)

Item	DDGS	ISB	GSB	LCS	PDTS
DM	87.89	80.23	79.42	34.95	94.79
CP	29.19	22.83	23.55	15.51	21.55
ADF	13.10	8.23	7.89	0.00	0.17
NDF	35.46	25.70	24.83	0.00	0.10
Ca	0.03	0.04	0.04	0.07	0.10
P	0.70	0.87	0.89	1.72	2.38
Indispensable AA					
Arg	1.29	1.05	1.03	0.72	0.92
His	0.73	0.58	0.57	0.43	0.52
Ile	1.09	0.80	0.77	0.40	0.57
Leu	3.46	2.43	2.35	0.75	1.06
Lys	1.01	0.87	0.84	0.77	0.80
Met	0.64	0.48	0.45	0.17	0.21
Phe	1.45	1.07	1.03	0.43	0.56
Thr	1.07	0.88	0.84	0.53	0.69
Trp	0.21	0.19	0.19	0.13	0.18
Val	1.43	1.08	1.05	0.63	0.92
Dispensable AA					
Ala	2.02	1.51	1.47	0.80	1.16
Asp	1.83	1.51	1.38	0.90	1.26
Cys	0.53	0.43	0.40	0.22	0.33
Glu	4.20	2.92	2.81	1.20	2.15
Gly	1.07	0.87	0.85	0.69	0.99
Pro	2.16	1.58	1.59	0.92	1.21
Ser	1.28	1.04	1.01	0.59	0.69
Tyr	1.13	0.85	0.82	0.35	0.41

[1]DDGS = distillers dried grains with solubles; ISB = intact syrup balls; GSB = ground syrup balls; LCS = liquid condensed solubles; PDTS = pulse dried thin stillage.

to process raw materials with unusually high moisture content. It is a continuous and fast process and requires less than 1 s to dry and about 1 min to recover the product. The sonic shock created by the pulse combustor, operating at a high speed (250 cycles/s), increases the surface area of the particulate and makes evaporation very efficient.

The DDGS with SB was sieved through a seed cleaner (Western model 30 Gyrating Cleaner, Union Iron Works, Decatur, IL). Two screens with an area of 1.62 m^2 each were used. The screen size was determined after sifting DDGS in different meshes to assess which sieve would be able to capture the SB. The screens (McNichols Co., Tampa, FL) had mesh sizes of 10 and 14 openings per 2.5 cm^2. The SB were collected from the second screen. One-half of the SB were ground through a hammer mill (Jacobson Universal No. 4, Jacobson Machine Works, Minneapolis, MN) at 14,747 × *g* with a 1.27-cm screen. The other one-half was fed as ISB.

Six diets were formulated (Tables 2 and 3). Chromic oxide (0.4%, as-fed basis) was included in the diets as an inert marker. Each ingredient tested was the only source of AA in the diet.

Surgery, Feeding, and Sample Collections

A T-cannula was inserted in the distal ileum of each pig as described by Stein et al. (1998) after feed withdrawal for 18 h. Feed was provided to at least 3 times the estimated maintenance requirement (106 kcal of ME/kg of $BW^{0.75}$; NRC, 1998). The 6 diets were as follows: N-free diet (used to measure endogenous losses), ISB diet, GSB diet, pulse dried TS (**PDTS**) diet, DDGS diet, and a separately prepared dry supplement that was fed in combination with the LCS to avoid the imprecision that would have occurred from mixing the viscous liquid with dry materials. The ME density was calculated as 3,790 kcal/kg for the N-free diet, 3,866 kcal/kg for the intact and ground SB diets, 3,547 kcal/kg for the PDTS diet, 3,822 kcal/kg for the DDGS diet, 3,445 kcal/kg for the dry supplement that was fed on the top of the LCS, and 1,380 kcal/kg for the LCS as fed. For the calculations, it was assumed that ME values of SB were identical to the ME in DDGS (3,989 kcal/kg of DM; Stein, 2007). Even though one may argue that the composition of SB and DDGS are not the same, this assumption needed to be made because of the lack of available data regarding SB composition. The ME values for LCS and PDTS were calculated assuming a DE value of 4,107 kcal/kg of DM (Stein and de Lange, 2007), the DM values measured in this experiment, and ME equal to 96% of DE.

Pigs had ad libitum access to water throughout the experiment. They were fed at 0700 and 1630 h. Each 7-d period consisted of a 5-d adaptation and 2-d collection. On collection days, caps were removed from cannulas and a 237-mL plastic bag (baby bottle bag that fits Playtex, Gerber, or Evenflow nursers or holders, Walgreen Co., Deerfield, IL) was attached to the outer part of the cannula with a cable zip tie. Immediately after the bags were full, or at least once every 30 min, bags were removed and the collected digesta was frozen at −20°C.

Table 2. Ingredient composition of experimental diets[1] (%; as-fed basis)

Item	N free	DDGS	ISB	GSB	Dry supplement[2]	PDTS
Corn starch	79.35	17.55	16.55	16.55	—	14.30
Sugar	10.00	20.00	20.00	20.00	92.48	20.00
Soybean oil	3.00	—	1.00	1.00	1.00	—
Limestone	0.80	1.35	1.35	1.35	3.37	1.60
Dicalcium phosphate	1.25	—	—	—	—	—
Solka-Floc[3]	4.00	—	—	—	2.00	3.00
Vitamins and mineral mix[4]	0.30	0.30	0.30	0.30	0.75	0.30
Salt	0.40	0.40	0.40	0.40	0.40	0.40
Potassium carbonate	0.40	—	—	—	—	—
Magnesium oxide	0.10	—	—	—	—	—
Chromic oxide[5]	0.40	0.40	0.40	0.40	0.00	0.40
DDGS	—	60.00	—	—	—	—
Intact syrup ball	—	—	60.00	—	—	—
Ground syrup balls	—	—	—	60.00	—	—
Thin stillage	—	—	—	—	—	60.00

[1]DDGS = distillers dried grains with solubles; ISB = intact syrup balls; GSB = ground syrup balls; PDTS = pulse dried thin stillage.

[2]Dry supplement added to the feeder on top of the liquid condensed solubles (LCS). Fed at a ratio of 40 parts supplement and 60 parts LCS by weight. This supplement did not contained chromic oxide, which was added to only the LCS.

[3]International Fiber Corp. (North Tonawanda, NY).

[4]The vitamin–micromineral premix provided the following 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; thiamine, 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; Zn, 100 mg as zinc oxide.

[5]Diets contained 0.40% of chromic oxide as an indigestible marker.

Table 3. Analyzed concentration of DM and nutrients in experimental diets[1] (%; as-fed basis)

Item	N free	DDGS	ISB	GSB	Dry supplement[2]	PDTS
CP	0.33	16.16	12.80	12.47	0.07	12.61
DM	92.33	91.28	86.96	87.12	99.75	91.28
Indispensable AA						
Arg	0.01	0.78	0.62	0.59	0.00	0.56
His	0.00	0.43	0.35	0.33	0.00	0.29
Ile	0.01	0.65	0.48	0.47	0.00	0.33
Leu	0.02	2.02	1.46	1.44	0.00	0.65
Lys	0.01	0.59	0.50	0.48	0.00	0.45
Met	0.00	0.39	0.28	0.27	0.00	0.15
Phe	0.01	0.86	0.63	0.62	0.00	0.34
Thr	0.01	0.65	0.50	0.49	0.00	0.43
Trp	<0.04	0.13	0.10	0.10	<0.04	0.08
Val	0.01	0.85	0.65	0.62	0.00	0.52
Dispensable AA						
Ala	0.01	1.23	0.94	0.92	0.00	0.71
Asp	0.02	1.14	0.83	0.87	0.00	0.77
Cys	0.00	0.24	0.25	0.24	0.00	0.22
Glu	0.00	1.96	1.97	1.96	0.00	1.37
Gly	0.01	0.51	0.53	0.51	0.00	0.57
Pro	0.01	1.28	0.99	0.98	0.00	0.81
Ser	0.01	0.76	0.60	0.59	0.00	0.46
Tyr	0.01	0.47	0.48	0.47	0.00	0.46

[1]DDGS = distillers dried grains with solubles; ISB = intact syrup balls; GSB = ground syrup balls; PDTS = pulse dried thin stillage.

[2]Dry supplement added to the feeder on top of the liquid condensed solubles (LCS). Fed at a ratio of 40 parts supplement and 60 parts LCS by weight.

Sample Analysis

All analyses except AA were performed in duplicate and samples were reanalyzed if differences between duplicates exceeded 5%. Ileal samples were thawed and mixed within animal and period and a subsample was collected, lyophilized, and ground. Samples of all test materials were collected at the time of mixing. The DM of ingredients, diets, and digesta were determined by oven drying at 135°C for 2 h (method 930.15; AOAC International, 2007).

Digesta samples were freeze dried before analysis. Digesta, diets, and ingredients were ground and analyzed for AA (amino acid analyzer, model L8800, Hitachi High Technologies America Inc., Pleasanton, CA) using ninhydrin for postcolumn derivatization and norleucine as the internal standard. Before analysis, samples were hydrolyzed with 6 *N* HCl for 24 h at 110°C [method 982.30 E(a); AOAC International, 2007]. Methionine and Cys were determined as Met sulfone and cysteic acid after cold performic acid oxidation overnight before hydrolysis [method 982.30 E(b); AOAC International, 2007]. Tryptophan was determined after NaOH hydrolysis for 22 h at 110°C [method 982.30 E(c); AOAC International, 2007].

The concentration of N was measured using the combustion method (procedure 990.03; AOAC International, 2007) with a rapid N-cube protein/nitrogen apparatus (Elementar Americas Inc., Mt. Laurel, NJ). Aspartic acid was used as a calibration standard, and CP was calculated as N × 6.25.

The chromium concentration was determined using inductively coupled plasma atomic emission spectrometry (method 990.08; AOAC International, 2007). Samples were prepared using nitric acid–perchloric acid (method 968.088D; AOAC International, 2007).

The Ca and total P were measured by inductively coupled plasma spectroscopy (method 985.01; AOAC International, 2007) after wet ash sample preparation (method 975.03; AOAC International, 2007). Standard methods were used for measurement of ADF (method 973.18; AOAC International, 2007) and NDF (Holst, 1973).

Calculations

Apparent ileal digestibility (**AID**) values for AA were calculated as described by Stein et al. (2007):

$$\text{AID } (\%) = \{1 - [(\text{AA}_{\text{digesta}}/\text{AA}_{\text{diet}}) \times (\text{Cr}_{\text{diet}}/\text{Cr}_{\text{digesta}})]\} \times 100,$$

where $\text{AA}_{\text{digesta}}$ is the AA concentration in the ileal digesta DM (g/kg), AA_{diet} is the AA concentration in the diet DM (g/kg), Cr_{diet} is the chromium concentration in the diet DM (g/kg), and $\text{Cr}_{\text{digesta}}$ is the chromium concentration in the ileal digesta DM (g/kg).

The endogenous loss/kg of DMI (IAA_{end}) of each AA was determined from pigs fed the N-free diet based on the following equation:

$$\text{IAA}_{\text{end}} = [\text{AA}_{\text{digesta}} \times (\text{Cr}_{\text{diet}}/\text{Cr}_{\text{digesta}})],$$

Table 4. Apparent ileal digestibilities of CP and AA in the diet ingredients[1,2] (%)

	Ingredient						
Item	DDGS	ISB	GSB	LCS	PDTS	SEM	*P*-value
CP	55.2^{x}	64.3^{w}	64.5^{w}	41.7^{y}	32.8^{z}	3.8	<0.01
Indispensable AA							
Arg	76.5^{x}	78.6^{x}	74.9^{x}	65.0^{y}	60.9^{y}	3.4	<0.01
His	74.4^{y}	78.6^{x}	77.9^{x}	71.5^{y}	59.3^{z}	1.7	<0.01
Ile	75.0^{x}	77.1^{x}	77.1^{x}	58.7^{y}	54.7^{z}	2.0	<0.01
Leu	81.8^{x}	83.7^{x}	84.0^{x}	57.8^{y}	57.6^{y}	1.8	<0.01
Lys	59.8^{y}	69.9^{x}	68.8^{x}	61.0^{y}	39.1^{z}	3.1	<0.01
Met	82.3^{x}	81.2^{x}	81.7^{x}	40.1^{z}	46.9^{y}	2.0	<0.01
Phe	80.1^{x}	81.8^{x}	82.3^{x}	60.4^{y}	58.0^{y}	1.8	<0.01
Thr	64.2^{x}	65.0^{x}	65.8^{x}	40.8^{y}	36.2^{z}	2.4	<0.01
Trp	69.3^{x}	67.6^{x}	70.3^{x}	57.9^{y}	48.1^{z}	2.0	<0.01
Val	71.9^{x}	75.2^{x}	74.7^{x}	58.8^{y}	49.2^{z}	2.0	<0.01
Mean	73.5^{x}	75.9^{x}	75.7^{x}	57.2^{y}	51.3^{z}	2.0	<0.01
Dispensable AA							
Ala	73.2^{y}	76.8^{x}	75.2^{x}	52.8^{y}	50.4^{y}	2.7	<0.01
Asp	62.5^{x}	64.6^{x}	64.8^{x}	36.5^{y}	33.6^{y}	2.5	<0.01
Cys	68.0^{x}	70.4^{x}	70.2^{x}	47.5^{y}	46.4^{y}	2.7	<0.01
Glu	76.3^{x}	79.2^{x}	79.2^{x}	47.0^{z}	52.7^{y}	2.2	<0.01
Gly	31.3^{x}	40.2^{x}	33.7^{x}	8.2^{y}	0.6^{y}	8.1	<0.01
Pro	5.6^{x}	9.6^{x}	−5.9^{x}	−94.2^{y}	−80.5^{y}	25.9	<0.01
Ser	72.7^{x}	73.7^{x}	74.2^{x}	50.6^{y}	41.2^{z}	2.1	<0.01
Tyr	80.3^{x}	82.2^{x}	82.6^{x}	58.4^{y}	58.2^{y}	1.9	<0.01
Mean	58.7^{x}	62.1^{x}	59.3^{x}	25.8^{y}	25.3^{y}	5.3	<0.01

$^{w–z}$Values within a row without a common superscript are different ($P < 0.05$).

[1]DDGS = distillers dried grains with solubles; ISB = intact syrup balls; GSB = ground syrup balls; LCS = liquid condensed solubles; PDTS = pulse dried thin stillage.

[2]Values are means of 12 observations/treatment.

where IAA_{end} is the basal endogenous loss of an AA (g/kg of DMI), $AA_{digesta}$ is the concentration of that AA in the digesta, and Cr_{diet} and $Cr_{digesta}$ are the chromium concentration in diet and digesta, respectively (g/kg of DM). The average IAA_{end} for the 12 pigs was used to calculate the standardized ileal digestibility (**SID**) of AA in all diets.

The SID was calculated by the following equation:

$$SID\ (\%) = AID + [(IAA_{end}/AA_{diet}) \times 100].$$

Statistical Analysis

Data were analyzed using PROC MIXED (SAS Inst. Inc., Cary, NC). Pig was the experimental unit. An α value of 0.05 was used to determine differences among means. Pig, period, and diet were used as class variables. Pig and period were considered random effects. An ANOVA was conducted.

RESULTS

The DDGS was analyzed for AA, CP, ADF, NDF, Ca, and P (Table 1); these values agreed with published values (Stein and Shurson, 2009). In general, the patterns of treatment effects were similar for AID and SID measurements (Tables 4 and 5).

In both SB treatments, the AID and SID of most AA were similar to that of DDGS, and AID of CP, Lys, and His and AID of Ala were actually greater than that of DDGS ($P < 0.05$). The LCS had less ($P < 0.05$) AID and SID of CP and all AA than did ISB and GSB. The digestibility values of Lys and a few other AA were similar in LCS and DDGS, but digestibility of most AA was less ($P < 0.05$) in LCS than in DDGS. The low digestibility of AA in LCS was most pronounced for Met and Pro. The PDTS generally had the least or similar AID and SID ($P < 0.05$) for several AA, including Lys, compared with LCS. However, digestibility of Met was greater in PDTS than in LCS.

DISCUSSION

The presence of SB does not seem to be a problem because AID and SID of AA of ISB and GSB were not less than the digestibility in DDGS. The similarity of the present digestibility values for DDGS to those reported by Stein and Shurson (2009) lends confidence in the measurements. The present observation is important in that many samples of DDGS contain SB, as observed in a preliminary study conducted at the University of Illinois. Those preliminary results have shown the hardness of those balls and their insolubility in different solutions; however, this was not a problem because the animals could digest and absorb AA in both ISB and GSB. In producing the test ingredients, an unusually large amount of SB was created by increasing the ratio of solubles to grains during the final

Table 5. Standardized ileal digestibilities of CP and AA in the ingredients[1,2] (%)

	Ingredient						
Item	DDGS	ISB	GSB	LCS	PDTS	SEM	*P*-value
CP	73.9^{x}	85.2^{w}	85.9^{w}	67.8^{y}	55.3^{z}	3.8	<0.01
Indispensable AA							
Arg	89.2^{xy}	95.2^{x}	92.3^{xy}	86.6^{y}	80.4^{z}	3.4	<0.01
His	75.2^{y}	79.7^{x}	79.1^{x}	72.9^{y}	60.8^{z}	1.7	<0.01
Ile	76.1^{x}	78.5^{x}	78.6^{x}	61.3^{y}	56.9^{z}	2.0	<0.01
Leu	82.3^{x}	84.5^{x}	84.8^{x}	60.1^{y}	59.4^{y}	1.8	<0.01
Lys	61.5^{y}	72.0^{x}	71.0^{x}	63.1^{y}	41.6^{z}	3.1	<0.01
Met	82.8^{x}	81.9^{x}	82.5^{x}	41.9^{z}	48.3^{y}	2.0	<0.01
Phe	80.9^{x}	82.9^{x}	83.4^{x}	62.8^{y}	60.2^{y}	1.8	<0.01
Thr	66.0^{x}	67.5^{x}	68.3^{x}	44.3^{y}	39.2^{z}	2.4	<0.01
Trp	71.1^{x}	70.1^{x}	72.9^{x}	60.9^{y}	51.5^{z}	2.0	<0.01
Val	73.2^{x}	76.8^{x}	76.4^{x}	61.4^{y}	54.9^{z}	2.0	<0.01
Mean	75.8^{x}	78.9^{x}	78.9^{x}	60.0^{y}	55.3^{z}	2.0	<0.01
Dispensable AA							
Ala	74.4^{x}	78.5^{x}	76.9^{x}	55.7^{y}	52.7^{y}	2.6	<0.01
Asp	64.0^{x}	66.6^{x}	66.9^{x}	39.4^{y}	36.0^{y}	2.5	<0.01
Cys	69.2^{x}	71.9^{x}	71.7^{x}	50.1^{y}	48.2^{y}	2.7	<0.01
Glu	77.2^{x}	80.3^{x}	80.4^{x}	54.6^{y}	50.0^{z}	2.2	<0.01
Gly	37.4^{x}	48.0^{x}	41.8^{x}	17.3^{y}	8.3^{y}	8.1	<0.01
Pro	17.1^{x}	24.9^{x}	9.5^{x}	−69.2^{y}	−60.7^{y}	25.6	<0.01
Ser	74.2^{x}	75.7^{x}	76.3^{x}	53.7^{y}	44.3^{z}	2.1	<0.01
Tyr	81.1^{x}	83.4^{x}	83.8^{x}	61.0^{y}	60.4^{y}	1.9	<0.01
Mean	61.8^{x}	66.2^{x}	63.4^{x}	30.0^{y}	30.4^{y}	5.3	<0.01

$^{w–z}$Values within a row without a common superscript are different ($P < 0.05$).

[1]DDGS = distillers dried grains with solubles; ISB = intact syrup balls; GSB = ground syrup balls; LCS = liquid condensed solubles; PDTS = pulse dried thin stillage.

[2]Values are means of 12 observations/treatment.

drying process. This deviation from the normal process produced more SB than usual, but we have no reason to suspect that it changed the digestibility of those SB. The fact that DDGS had less and variable digestibility compared with corn may be explained by factors such as application of severe and variable heat, greater concentration of dietary fiber, decreased Lys concentration, and others (Stein and Shurson, 2009), but not by the presence of variable amounts of SB.

Pahm et al. (2008a) reported greater SID of CP and AA in distillers dried grains than in DDGS and suggested that this may reflect more extensive Maillard reaction when LCS and grains are dried together than when the grains are dried alone. If so, the more extensive Maillard reaction may be attributable to the presence of reducing sugars in LCS, or to the greater heat required for drying the wet grains plus LCS, or both. However, our results indicated that a separate limit exists on digestibility of AA in LCS that is not due to the drying process for 2 reasons. First, our low values for LCS were measured on a product that was subjected to an evaporation process to convert TS to LCS, as is usually done in ethanol plants, but not to the more intense final drying process in combination with the grains. Second, when intact proteins are heated in the presence of reducing substances, Lys is usually damaged more extensively than other AA because its free amino group is available to participate in the Maillard reaction (Pahm et al., 2008b). Most measurements of AA digestibility in DDGS show digestibility of Lys to be less and more variable than that of other AA (Stein, 2007). However, in the present data, the digestibility of Met in LCS was substantially less than that of Lys, indicating that the low digestibility of AA in LCS can result from a cause other than heat damage. It is possible that the proteins in LCS are more complex and less digestible than other corn proteins, but this hypothesis has not been experimentally verified.

The obvious heat damage of TS during pulse drying in the present study prevented our planned determination of whether the low AA digestibility of LCS is a property of the original TS emerging from the fermentation or whether it results from heat damage during the condensation step that removes much of the moisture to form LCS. The temperature and conditions used in pulse drying the TS were established from results of a test run, with the temperature kept as low as possible to avoid reduction in nutritional value. The product temperature did not exceed 315°C throughout the process, and the exhaust air temperature was 558°C. The residence time averaged 12 h. Product was not recycled in the pulse dryer. However, the pulse-drying procedure used was apparently so severe that it markedly reduced the AA digestibility. In conclusion, the presence of SB in DDGS did not seem to reduce AA digestibility, but LCS had low digestibility of AA that did not seem to be caused by heat damage.

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