Kansas Agricultural Experiment Station Research Reports

Volume 6
Issue 10 *Swine Day*

Article 24

2020

Effect of the Pelleting Process on Diet Formulations with Varying Levels of Crystalline Amino Acids and Reducing Sugars on Digestibility in Growing Pigs

K. M. Dunmire
Kansas State University, karadunmire@k-state.edu

D. A. Lopez
University of Illinois, Champaign, IL

C. J. Fiehler
Kansas State University, cfiehler@k-state.edu

See next page for additional authors

Recommended Citation

Dunmire, K. M.; Lopez, D. A.; Fiehler, C. J.; Jones, C. K.; Li, Y.; Woodworth, J. C.; Goodband, R. D.; Tokach, M. D.; Stark, C. R.; Stein, H. H.; and Paulk, C. B. (2020) "Effect of the Pelleting Process on Diet Formulations with Varying Levels of Crystalline Amino Acids and Reducing Sugars on Digestibility in Growing Pigs," *Kansas Agricultural Experiment Station Research Reports*: Vol. 6: Iss. 10. https://doi.org/10.4148/2378-5977.8005

Effect of the Pelleting Process on Diet Formulations with Varying Levels of Crystalline Amino Acids and Reducing Sugars on Digestibility in Growing Pigs

Abstract

The objective of this study was to determine the effect of thermal processing on the digestibility of amino acids (AA) in diets with or without increased concentrations of free amino acids and reducing sugars (RS). To measure AA digestibility, a total of eight individually housed barrows (initially 69.2 ± 6.8 lb) that had a T-cannula installed in the distal ileum were allotted to a replicated 8 × 8 Latin square design with 8 diets and eight 7-d periods. Thus, each pig was fed each diet in one period and no pig received the same diet more than once. Each period lasted 7 days with the initial 5 days being the adaptation period, and ileal digesta was collected for 9 hours on d 6 and 7. Treatments were arranged in a 2 × 2 × 2 factorial with main effects of crystalline AA concentration (low vs. high), reducing sugars (low vs. high), and diet form (mash vs. pellet). There was no feed form × crystalline AA inclusion × RS inclusion interaction for standardized ileal digestible (SID) AA. There was a feed form × RS interaction ($P < 0.026$) for SID tryptophan. Feeding pelleted high RS diets resulted in decreased SID of tryptophan compared with mash high and low RS diets, and pelleted low RS diets. For the main effects of feed form, the SID of total AA, crude protein (CP), and indispensable AA increased ($P < 0.042$) in pigs fed pelleted diets compared with those fed mash diets. For the main effects of crystalline AA inclusion, pigs fed low or high crystalline AA inclusion had similar SID of total AA and CP. Pigs fed high crystalline AA had increased ($P = 0.007$) SID of tryptophan compared with those fed low crystalline AA diets. The SID of lysine tended to increase ($P = 0.076$) in pigs fed high crystalline AA diets compared with those fed low crystalline AA inclusion diets. Pigs fed high crystalline AA had decreased ($P = 0.050$) SID histidine compared with those fed low crystalline AA diets. The SID of arginine and isoleucine tended to decrease ($P < 0.079$), in pigs fed high crystalline AA. In pigs fed high crystalline AA, the SID of serine and glycine decreased ($P < 0.042$) compared with those fed low crystalline AA. For the main effects of RS diets, pigs fed high RS diets had decreased ($P < 0.05$) SID of total AA, CP, indispensable AA, alanine, aspartic acid, cysteine, glutamic acid, and serine. In conclusion, there was no evidence of interactions between diet types. Therefore, pelleting diets with increased concentration of crystalline AA or RS at the conditions reported herein did not reduce the AA digestibility. However, pelleting diets resulted in improved AA digestibility. Diets formulated with increased concentrations of crystalline AA had increased SID of tryptophan. Formulating diets with 20% DDGS and 15% bakery meal (high RS) resulted in decreased AA digestibility compared with the corn-soybean meal-based diets.

Keywords

crystalline amino acids, reducing sugars, Maillard reaction, pelleting, amino acid digestibility

Creative Commons License

Cover Page Footnote

Appreciation is expressed to the National Pork Board for financial support of this study.

Authors

K. M. Dunmire, D. A. Lopez, C. J. Fiehler, C. K. Jones, Y. Li, J. C. Woodworth, R. D. Goodband, M. D. Tokach, C. R. Stark, H. H. Stein, and C. B. Paulk

Effect of the Pelleting Process on Diet Formulations with Varying Levels of Crystalline Amino Acids and Reducing Sugars on Digestibility in Growing Pigs[1]

Kara M. Dunmire,[2] Diego A. Lopez,[3] Chance J. Fiehler,[2]
Cassandra K. Jones, Yonghui Li,[2] Jason C. Woodworth,
Robert D. Goodband, Mike D. Tokach, Charles R. Stark,[2]
Hans H. Stein,[3] and Chad B. Paulk[2]

Summary

The objective of this study was to determine the effect of thermal processing on the digestibility of amino acids (AA) in diets with or without increased concentrations of free amino acids and reducing sugars (RS). To measure AA digestibility, a total of eight individually housed barrows (initially 69.2 ± 6.8 lb) that had a T-cannula installed in the distal ileum were allotted to a replicated 8 × 8 Latin square design with 8 diets and eight 7-d periods. Thus, each pig was fed each diet in one period and no pig received the same diet more than once. Each period lasted 7 days with the initial 5 days being the adaptation period, and ileal digesta was collected for 9 hours on d 6 and 7. Treatments were arranged in a 2 × 2 × 2 factorial with main effects of crystalline AA concentration (low vs. high), reducing sugars (low vs. high), and diet form (mash vs. pellet). There was no feed form × crystalline AA inclusion × RS inclusion interaction for standardized ileal digestible (SID) AA. There was a feed form × RS interaction ($P < 0.026$) for SID tryptophan. Feeding pelleted high RS diets resulted in decreased SID of tryptophan compared with mash high and low RS diets, and pelleted low RS diets. For the main effects of feed form, the SID of total AA, crude protein (CP), and indispensable AA increased ($P < 0.042$) in pigs fed pelleted diets compared with those fed mash diets. For the main effects of crystalline AA inclusion, pigs fed low or high crystalline AA inclusion had similar SID of total AA and CP. Pigs fed high crystalline AA had increased ($P = 0.007$) SID of tryptophan compared with those fed low crystalline AA diets. The SID of lysine tended to increase ($P = 0.076$) in pigs fed high crystalline AA diets compared with those fed low crystalline AA inclusion diets. Pigs fed high crystalline AA had decreased ($P = 0.050$) SID histidine compared with those fed low crystalline AA diets. The SID of arginine and isoleucine tended to decrease ($P < 0.079$), in pigs fed high crystalline AA. In pigs fed high crystalline AA, the SID of serine and glycine

---

[1] Appreciation is expressed to the National Pork Board for financial support of this study.

[2] Department of Grain Science and Industry, College of Agriculture, Kansas State University, Manhattan, KS.

[3] Department of Animal Science, College of Agriculture University of Illinois, Champaign, IL.

decreased ($P < 0.042$) compared with those fed low crystalline AA. For the main effects of RS diets, pigs fed high RS diets had decreased ($P < 0.05$) SID of total AA, CP, indispensable AA, alanine, aspartic acid, cysteine, glutamic acid, and serine. In conclusion, there was no evidence of interactions between diet types. Therefore, pelleting diets with increased concentration of crystalline AA or RS at the conditions reported herein did not reduce the AA digestibility. However, pelleting diets resulted in improved AA digestibility. Diets formulated with increased concentrations of crystalline AA had increased SID of tryptophan. Formulating diets with 20% DDGS and 15% bakery meal (high RS) resulted in decreased AA digestibility compared with the corn-soybean meal-based diets.

Introduction

Pelleted feed in swine diets is commonly used to improve feed efficiency, feed handling characteristics, and bulk density while decreasing feed wastage. Recent feed safety issues and the importance of pellet quality have led feed manufacture companies to steam condition the grow-finish pig diets at higher temperatures during the pelleting process. In addition, current trends in diet formulation in the swine industry have focused on increasing the use of crystalline amino acids (AA). Another common practice for swine nutritionists is to use byproduct ingredients to reduce feed costs. Common byproducts include distillers dried grains with solubles (DDGS) from the ethanol industry and bakery meal from the food and confectionary industry. Corn and soybean meal commonly used in finishing pig diets contain trace amounts of reducing sugars (RS). The reducing sugars glucose, sucrose, maltose, and fructose typically have concentrations of 0.66, 1.14, 0.23, and 0.4% in corn; 5.03, 4.91, 2.85, and 4.71% in bakery meal; and 1.84%, 0.19%, 2.28%, and 0.74% in DDGS.[4] Soybeans contain glucose ranging from 0.07 to 0.40% (DM-basis), however, glucose is destroyed in the crushing of soybeans to produce soybean meal.[5] The reducing sugars in feed ingredients may pose problems when pelleting diets at increased temperatures. Over-processing can potentially lead to a reduction in amino acid availability due to the Maillard reaction. The Maillard reaction is a non-enzymatic browning reaction between an amino group in amino acids, peptides, or proteins and a carbonyl group of reducing sugars such as glucose, fructose, or lactose. Variables optimizing the Maillard browning reaction include high temperatures and moisture levels, which can occur during feed processing. Thus, pelleting diets containing crystalline amino acids and co-products with reducing sugars may increase the risk for reduced amino acid availability and, consequently, impaired growth performance. Therefore, the objective of this experiment was to test the hypothesis that effects of pelleting swine diets containing free amino acids and reducing sugars at high temperatures will reduce the digestibility of amino acids.

---

[4] Rojas, O. J., Y. Liu, and H. H. Stein. 2013. Phosphorus digestibility and concentration of digestible and metabolizable energy in corn, corn coproducts, and bakery meal fed to growing pigs. J. Anim. Sci. 91:5326-5335.

[5] Grieshop, C. M., C. T. Kadzere, and G. M. Clapper 2003. Chemical and nutritional characteristics of United States soybeans and soybean meals. Journal of Agricultural and Food Chemistry, vol. 51: 26: 7684–7691.

Procedures

The University of Illinois Institutional Animal Care and Use Committee approved the protocol used in this experiment. This study was conducted at the University of Illinois Swine Research Center (Champaign, IL).

A total of eight individually housed growing barrows (initially 69.2 ± 6.8 lb) that had a T-cannula installed in the distal ileum were allotted to an 8 × 8 Latin square design with the 8 diets and eight 7-d periods. Thus, each pig was fed each diet in one period and no pig received the same diet more than once. Pigs were limited to 3 times the maintenance requirement for metabolizable energy (i.e., 90 kcal ME per lb $BW^{0.60}$; NRC[6]). Through the experiment, pigs had free access to water. Pigs were deprived of feed overnight at the end of each experimental period, to be fed with a new diet the following morning. Each period lasted 7 days with the initial 5 days being the adaptation period, and ileal digesta was collected for 9 hours on d 6 and 7. All collected digesta samples were lyophilized and analyzed for crude protein. Amino acid values and standardized ileal digestibility (SID) were calculated as described in Stein et al.[7]

Dietary treatments were arranged in a 2 × 2 × 2 factorial with main effects of crystalline amino acid level (AA; low vs. high); reducing sugars (RS; low vs. high); and diet form (mash vs. pellet; Table 1). For crystalline amino acid treatments, diets were considered low or high based on the inclusion of crystalline AA with high crystalline AA diets having increased concentrations of lysine, threonine, and tryptophan compared with low crystalline AA diets. Valine and isoleucine were included as needed in the high crystalline AA diets. Reducing sugars were naturally occurring in ingredients (corn and soybean meal-based diets; low) or increased by adding DDGS and bakery meal (20 and 15%, respectively; high). All diets contained 0.5% titanium dioxide as an indigestible marker to allow for calculation of AID and SID of AA as described below.

Chemical Analysis

Representative samples of corn, bakery meal, DDGS, soybean meal and treatment diets were analyzed at the University of Missouri Agricultural Experiment Station Chemical Laboratory (Columbia, MO) for dry matter,[8] crude protein,[9] crude fat,[10] crude fiber,[11] ash,[12] complete AA profile,[13] available Lys,[14] and protein solubility in potassium hydroxide (KOH)[15] (Tables 2 and 3). Ileal digesta contents were analyzed for dry

---

[6] National Research Council. 2012. Nutrient Requirements of Swine: Eleventh Revised Edition. Washington, DC: The National Academies Press. https://doi.org/10.17226/13298

[7] H. H. Stein, B. Sève, M. F. Fuller, P. J. Moughan, C. F. M. de Lange, Invited review: Amino acid bioavailability and digestibility in pig feed ingredients: Terminology and application, *Journal of Animal Science*, Volume 85, Issue 1, January 2007, Pages 172–180, https://doi.org/10.2527/jas.2005-742.

[8] AOAC Official Method 934.01, 2006.

[9] AOAC Official Method 990.03, 2006.

[10] AOAC Official Method 920.39 (A).

[11] AOAC Official Method 978.10, 2006.

[12] AOAC Official Method 942.05.

[13] AOAC Official Method 982.30 E(a,b,c), chp. 45.3.05, 2006.

[14] AOAC Official Method 975.44, chp. 45.4.03, 2006.

[15] Protein solubility in potassium hydroxide (KOH) method J. Anim. Sci., 69:2918-2924, 1991.

matter,[8] crude protein,[9] and complete AA profile.[13] Diet and ileal digesta samples were also analyzed for titanium dioxide.[16]

Diet manufacture occurred at the Kansas State University O.H. Kruse Feed Technology and Innovation Center (Manhattan, KS). Whole grain ingredients were ground with a three-high roller mill (RMS Model 924) to an approximate particle size of 600 microns. Feed was mixed in a 1-ton Hayes and Stolz double ribbon mixer. Treatments were pelleted using a 5-ton 100-horsepower pellet mill (Model PM3016-4, California Pellet Mill) equipped with a 5/32 × 1 3/8 in die (L:D = 8.75). The conditioning temperature ranged from 175 to 185°F to achieve a hot pellet temperature of 185 to 190°F and was attained by adjusting the steam addition (Table 4). The pelleted diets were cooled in an experimental counterflow cooler for 15 minutes. To minimize the effect of pellet quality differences, pellets passed through a sifter to remove fines before transport.

A sample of cool pellets was collected, and the fines sifted off by using the corresponding sieve stack.[17] Sifted pellets were split using a riffle divider and 100 grams used for analysis. The 100-g sample was placed into the hopper of the Holmen NHP100 for 60 seconds. The fines were removed as the sample was run. Once completed, the sample was removed from the hopper and weighed. The PDI was calculated by dividing this final sample weight by the 100-g initial sample weight.

Calculations and Statistical Analysis

Values for SID (%) were calculated as indicated below using Stein et al.[6]:

$$1.\ \mathrm{AID}_{\mathrm{AA}}(\%) = \left[1 - \left(\frac{\mathrm{AA}_{\mathrm{diet}}}{\mathrm{AA}_{\mathrm{digesta}}}\right) \times \left(\frac{\mathrm{Ti}_{\mathrm{digesta}}}{\mathrm{Ti}_{\mathrm{diet}}}\right)\right] \times 100,$$

where $\mathrm{AA}_{\mathrm{digesta}}$ and $\mathrm{AA}_{\mathrm{diet}}$ represent the AA concentrations (g/kg) in digesta and diet dry matter (DM), respectively, and $\mathrm{Ti}_{\mathrm{diet}}$ and $\mathrm{Ti}_{\mathrm{digesta}}$ represent the digestible marker concentrations (g/kg) in diet and digesta DM, respectively.

$$2.\ \mathrm{SID}_{\mathrm{AA}}(\%) = \mathrm{AID}_{\mathrm{AA}} + \left[\left(\frac{\mathrm{IAA}_{\mathrm{end}}}{\mathrm{AA}_{\mathrm{diet}}}\right) \times 100\right],$$

where $\mathrm{AID}_{\mathrm{AA}}$ was previously calculated in equation 1, $\mathrm{IAA}_{\mathrm{end}}$ represents basal endogenous losses where average values from digestibility experiments at the University of Illinois were used, and $\mathrm{AA}_{\mathrm{diet}}$ represents the AA concentrations (g/kg) in diet DM.

Data were analyzed as a completely randomized Latin square design using the GLIMMIX procedure of SAS (v. 9.4, SAS Institute, Inc., Cary, NC) with pig as the experimental unit. Fixed effects included feed form, crystalline AA, and RS inclusion; and the interaction between all three, feed form and crystalline AA, feed form and RS, and crystalline AA and RS inclusion. Least square means were calculated for each

---

[16] Journal of Animal Science (2004) 82:179-183.

[17] Schofield, Eileen K, and American Feed Industry Association. Feed Manufacturing Technology V. (pg. 631). American Feed Industry Association, 2005.

independent variable and means were separated using the PDIFF option. Results were considered significant at $P \leq 0.05$.

Results

Chemical analysis of experimental diets indicated that analyzed CP ranged from 13.3 to 19.3% with the expected range of 14.8 to 19.1% for both mash and pelleted diets. The high crystalline AA × low RS diets contained the lowest CP, and the low crystalline AA × high RS diets contained the highest CP (Table 3). The analyzed protein solubility in potassium hydroxide (KOH) values ranged from 48.62% in the low crystalline × high RS mash diet to 81.76% in the low crystalline AA × low RS pelleted diet. Analyzed available lysine content was 0.85% to 1.02%, where the lowest was high crystalline AA × high RS mash diets and highest for the low crystalline AA × low RS mash diet. The Lys:CP expected values ranged from 5.18 to 6.31, where the lowest ratio (5.83) was the high crystalline AA × low RS mash and pelleted diets, and the highest ratio (7.04) was in the low crystalline AA × high RS pellet diet.

The experiment was designed to pellet diets at a conditioning temperature of 190°F. However, at the desired conditioning temperature a consistent pelleting run could not be achieved. Therefore, diets were pelleted to a target hot pellet temperature between 185 and 190°F, which was achieved by pelleting at a conditioning temperature range of 175 to 185°F (Table 4). The PDI for diets containing low RS were improved by more than 10% compared with those containing high RS. These differences in PDI could possibly be explained by increases in added fat in diets containing high RS. Differences in PDI were alleviated by sifting the pellets after post pelleting to remove excessive fines.

There was no feed form × crystalline AA × RS interaction observed for SID of AA. There were no 2-way interactions of feed form × crystalline AA for SID of total AA, indispensable, or dispensable AA (Table 5). There were no 2-way interactions of feed form × RS observed for SID of total AA, CP, or dispensable AA (Table 6). There were no 2-way interactions of feed form × RS observed for SID of indispensable AA, except for tryptophan. Pigs fed pelleted high RS diets resulted in lower SID of tryptophan than mash high RS diets, mash low RS diets, and pelleted low RS diets.

There were no 2-way interactions of crystalline AA × RS observed for SID of total AA, CP, indispensable AA, and dispensable AA (Table 7).

For the main effects of feed form, the SID of total AA, CP, indispensable AA, alanine, aspartic acid, glutamic acid, and serine increased ($P < 0.042$) in the pelleted diets compared with mash diets (Table 8). For the main effects of crystalline AA, pigs fed low or high crystalline AA had SID of total AA and CP that were not different. Pigs fed high crystalline AA had increased ($P = 0.007$) SID of tryptophan compared with those fed low crystalline AA diet. The SID of lysine tended to increase ($P = 0.076$) in pigs fed high crystalline AA diets compared with those fed low crystalline AA diets. Pigs fed high crystalline AA had decreased ($P = 0.050$) SID of histidine compared with those fed low crystalline AA diets. The SID of arginine and isoleucine tended to decrease ($P < 0.079$) in pigs fed high crystalline AA. In pigs fed high crystalline AA the SID of serine and glycine decreased ($P < 0.042$) compared with those fed low crystalline AA. For the main effects of RS diets, pigs fed high RS diets had decreased ($P < 0.05$) SID of total AA, CP, indispensable AA, alanine, aspartic acid, cysteine, glutamic acid, and serine.

Conclusion

This experiment was designed to determine if pelleting different swine diets influence the digestibility of amino acids. Diets were formulated with low or high crystalline AA and low or high reducing sugars provided by co-product ingredients, DDGS, and bakery meal to increase the chances of binding lysine via the Maillard reaction. Diets were pelleted to a target hot pellet temperature between 185 and 190°F. There was no evidence of interactions between diet types, indicating that increasing amounts of crystalline AA and RS did not increase the Maillard reaction or reduce AA digestibility when pelleting diets by using the reported conditions. In addition, pelleting diets resulted in improved AA digestibility. Diets formulated with 20% DDGS and 15% bakery (high RS) resulted in decreased AA digestibility compared with the corn-soybean meal-based diets.

Table 1. Diet composition (as-fed basis)[1,2]

Crystalline AA: Reducing sugars:	Low Low	Low High	High Low	High High
Ingredient, %				
Corn	75.00	44.11	79.68	52.98
Soybean meal	21.00	15.70	16.19	6.85
Dried distiller's grain with solubles	---	20.00	---	20.00
Bakery meal[3]	---	15.00	---	15.00
Soybean oil	1.23	2.70	0.90	2.10
Calcium carbonate	0.70	0.83	0.70	0.85
Monocalcium P, 21%	1.00	0.60	1.10	0.70
Sodium chloride	0.50	0.50	0.50	0.50
L-Lysine-HCl	0.18	0.23	0.33	0.50
DL-Methionine	----	---	0.04	---
L-Threonine	0.09	0.04	0.16	0.16
L-Tryptophan	0.01	0.01	0.04	0.06
L-Valine	---	---	0.07	---
L-Isoleucine	---	---	0.01	0.01
Trace mineral premix[4]	0.15	0.15	0.15	0.15
Vitamin premix[4]	0.15	0.15	0.15	0.15
Titanium dioxide	0.50	0.50	0.50	0.50
Total	100	100	100	100

continued

Table 1. Diet composition (as-fed basis)[1,2]

Crystalline AA:	Low	Low	High	High
Reducing sugars:	Low	High	Low	High
Calculated analysis				
Standardized ileal digestible (SID) AA, %				
Lysine[5,6]	0.83	0.83	0.83	0.83
Isoleucine:lysine	69	76	60	60
Leucine:lysine	156	187	142	162
Methionine:lysine	29	34	30	29
Methionine and cysteine:lysine	57	65	56	55
Threonine:lysine	70	70	70	70
Tryptophan:lysine	21.0	21.0	21.0	21.0
Valine:lysine	77	90	75	72
Histidine:lysine	47	46	42	36
Total lysine, %	0.95	0.99	0.93	0.97
ME, kcal/lb	1,522	1,539	1,517	1,529
NE, kcal/lb	1,179	1,179	1,179	1,179
CP, %	16.4	19.1	14.8	16.0
Ca, %	0.59	0.59	0.59	0.59
P, %	0.56	0.55	0.56	0.53
STTD P, %	0.33	0.33	0.33	0.33

[1] Dietary treatments were arranged in a 2 × 2 × 2 factorial. Main effects consisted of crystalline AA (low vs. high), reducing sugars (low vs. high), and diet form (mash vs. pellet).

[2] Experimental diet was formulated for 50- to 85-lb pigs.

[3] Quincy Farm Products, Quincy, IL.

[4] Provided per lb of premix: 33,300 mg Zn, 33,300 mg Fe, 10,000 mg Mn, 5,000 mg Cu, 90 mg I, 90 mg Se, 750,000 IU vitamin A, 300,000 IU vitamin D, 8,000 IU vitamin E, 600 mg vitamin K, 6 mg vitamin B12, 9,000 mg niacin, 5,000 mg pantothenic acid, and 1,500 mg riboflavin.

[5] To ensure the ability to detect a difference in AA utilization, these diets were formulated to 85% of the recommended SID Lys requirement of pigs.

[6] National Research Council. 2012. Nutrient Requirements of Swine: Eleventh Revised Edition. Washington, DC: The National Academies Press. https://doi.org/10.17226/13298.

[7] AA = amino acids. ME = metabolizable energy. NE = net energy. STTD P = standardized total tract digestible phosphorus.

Table 2. Chemical analysis of individual major ingredients (as-fed basis)[1,2]

Item, %	Corn	Soybean meal	DDGS	Bakery meal
Dry matter	88.10 (88.31)	88.94 (89.98)	90.39 (89.31)	87.28 (86.30)
Crude protein	10.07 (8.24)	45.44 (47.73)	29.77 (28.15)	17.32 (14.30)
Fat	2.25 (3.48)	0.54 (1.52)	5.05 (7.50)	4.03 (5.10)
Crude fiber	1.81 (1.98)	3.73 (3.89)	7.64 (7.28)	8.00
Ash	1.57 (1.30)	6.09 (6.27)	5.00 (4.24)	6.02 (3.22)
Protein solubility[4]	49.95	76.10	26.67	49.71
Available lysine	0.42	2.87	0.92	0.68
Lys:CP	4.27	6.49	3.36	4.33
Total AA	9.67	45.09	27.95	16.29
Indispensable AA				
Arginine	0.51 (0.37)	3.27 (3.45)	1.36 (1.20)	1.04 (0.68)
Histidine	0.29 (0.24)	1.22 (1.28)	0.81 (0.73)	0.43 (0.22)
Isoleucine	0.39 (0.28)	2.23 (2.14)	1.21 (1.05)	0.79 (0.56)
Leucine	1.03 (0.96)	3.52 (3.62)	3.40 (3.23)	1.42 (1.1)
Lysine	0.43 (0.25)	2.95 (2.96)	1.00 (0.79)	0.75 (0.54)
Methionine	0.19 (0.18)	0.63 (0.68)	0.54 (0.57)	0.25 (0.21)
Phenylalanine	0.47 (0.39)	2.36 (2.40)	1.49 (1.38)	0.94 (0.50)
Threonine	0.36 (0.28)	1.77 (1.86)	1.10 (1.02)	0.67 (0.52)
Tryptophan	0.08 (0.06)	0.66 (0.66)	0.21 (0.22)	0.15 (0.18)
Valine	0.48 (0.38)	2.27 (2.23)	1.50 (1.39)	1.04 (0.72)
Dispensable AA				
Alanine	0.64 (0.60)	1.97 (2.06)	2.04 (1.99)	0.95
Aspartic acid	0.76 (0.54)	5.08 (5.41)	1.94 (1.88)	1.33
Cysteine	0.22 (0.19)	0.71 (0.70)	0.60 (0.53)	0.28 (0.18)
Glutamic acid	1.80 (1.48)	8.28 (8.54)	4.45 (4.49)	2.50
Serine	0.44 (0.38)	2.01 (2.36)	1.29 (1.22)	0.71
Tyrosine	0.22 (0.26)	1.66 (1.59)	1.06 (1.07)	1.10 (0.55)
Glycine	0.42 (0.31)	1.91 (1.99)	1.15 (1.07)	0.84
Proline	0.73 (0.71)	2.25 (2.53)	2.35 (2.16)	0.86

[1] Samples were analyzed at the University of Missouri Agricultural Experiment Station Chemical Laboratories in Columbia, MO.

[2] Values in parentheses indicate values used in diet formulation. These values were acquired from the NRC[3] and bakery meal values were provided by supplier. The soybean meal net energy value assigned was 88% of corn.

[3] National Research Council. 2012. Nutrient Requirements of Swine: Eleventh Revised Edition. Washington, DC: The National Academies Press. https://doi.org/10.17226/13298.

[4] Protein solubility in potassium hydroxide (KOH).

AA = amino acids. DDGS = dried distillers grains with solubles.

Table 3. Chemical analysis of experimental diets (as-fed basis)[1,2]

	Mash				Pellets			
Crystalline AA:	Low	Low	High	High	Low	Low	High	High
Reducing sugars:	Low	High	Low	High	Low	High	Low	High
Item, %								
Dry matter	87.37	87.81	87.43	87.88	87.88	87.91	87.83	88.65
Crude protein	15.78	18.71	13.31	15.73	15.61	19.29	14.42	16.99
Fat	1.20	3.69	0.95	2.89	2.13	4.53	2.30	4.40
Fiber	1.60	3.26	1.51	3.04	1.87	3.68	1.78	3.08
Ash	4.19	5.28	4.09	4.84	4.47	5.54	4.31	5.11
Protein solubility[3]	63.45	48.62	62.07	54.66	81.76	57.33	71.73	46.15
Available lysine	1.02	0.96	0.93	0.85	0.98	0.94	0.90	0.98
Total AA	15.04	18.16	13.90	14.88	16.38	19.36	13.95	16.29
Lys:CP	5.90	6.59	5.83	6.15	6.40	7.04	5.83	6.78
Indispensable AA								
Arginine	0.93	1.05	0.81	0.79	1.02	1.15	0.82	0.88
Histidine	0.41	0.49	0.37	0.39	0.44	0.53	0.37	0.43
Isoleucine	0.66	0.80	0.60	0.60	0.72	0.86	0.60	0.67
Leucine	1.36	1.77	1.27	1.51	1.47	1.87	1.28	1.63
Lysine	0.93	1.04	0.92	0.97	1.01	1.11	0.92	1.07
Methionine	0.26	0.32	0.27	0.28	0.28	0.34	0.27	0.29
Phenylalanine	0.75	0.94	0.67	0.74	0.82	1.00	0.68	0.81
Threonine	0.62	0.72	0.63	0.68	0.67	0.78	0.62	0.74
Tryptophan	0.18	0.20	0.20	0.20	0.22	0.22	0.21	0.23
Valine	0.74	0.94	0.72	0.73	0.80	1.01	0.71	0.81
Dispensable AA								
Alanine	0.81	1.08	0.75	0.94	0.87	1.14	0.77	1.02
Aspartic acid	1.43	1.60	1.24	1.14	1.57	1.72	1.24	1.26
Cysteine	0.28	0.34	0.26	0.29	0.31	0.37	0.25	0.31
Glutamic acid	2.70	3.12	2.43	2.44	2.93	3.30	2.44	2.68
Serine	0.65	0.77	0.58	0.61	0.71	0.84	0.59	0.70
Tyrosine	0.53	0.71	0.49	0.61	0.57	0.75	0.48	0.66
Glycine	0.63	0.79	0.56	0.62	0.69	0.84	0.57	0.70
Proline	0.93	1.23	0.89	1.07	1.01	1.26	0.88	1.14

[1] Dietary treatments were arranged in a 2 × 2 × 2 factorial with main effects of crystalline amino acids (AA) (low vs. high), reducing sugar (low vs. high), and diet form (mash vs. pellet).

[2] Samples were analyzed at the University of Missouri Agricultural Experiment Station Chemical Laboratories in Columbia, MO.

[3] Protein solubility in potassium hydroxide (KOH).

Table 4. Feed processing and pellet quality of pelleted diets[1,2]

Crystalline amino acids:	Low	Low	High	High
Reducing sugars:	Low	High	Low	High
Item				
Production rate, ton/h	4.2	4.0	4.1	3.8
Conditioning temperature, °F	185.2	182.4	181.4	175.5
Hot pellet temperature, °F	192.8	189.3	189.6	185.0
Pellet durability index (PDI), %[3]	71.5	53.7	72.15	59.6

[1] Treatments were pelleted using a 5-ton 100-horsepower pellet mill (Model PM3016-4, California Pellet Mill) equipped with a 5/32 × 1 3/8 in die (L:D = 8.75).

[2] Pellets were sifted to remove fines to ensure no effect of pellet quality on pig performance.

[3] Holmen NHP100 for 60 seconds.

Table 5. Standardized ileal digestibility of crude protein (CP) and amino acids (AA) as a 2-way interaction of feed form × crystalline AA[1,2]

Form:	Mash		Pellet			
Crystalline AA:	Low	High	Low	High	SEM	*P*-value[3]
SID, %						
Total AA	81.71	79.84	84.36	84.83	1.066	0.263
Crude protein	78.51	75.24	81.84	82.84	1.559	0.194
Indispensable AA						
Arginine	92.52	90.67	96.51	95.64	0.787	0.513
Histidine	81.83	79.64	84.36	82.95	0.924	0.663
Isoleucine	81.41	77.85	84.64	84.06	1.102	0.170
Leucine	81.35	79.93	85.19	85.44	1.068	0.425
Lysine	85.24	86.28	86.56	89.01	0.992	0.470
Methionine	86.81	86.01	90.89	90.85	1.100	0.721
Phenylalanine	81.73	79.38	85.09	85.14	1.061	0.247
Threonine	75.23	76.09	77.16	80.33	1.283	0.357
Tryptophan	86.64	88.69	87.88	92.07	1.141	0.337
Valine	77.37	74.36	80.72	80.52	1.266	0.257
Dispensable AA						
Alanine	79.58	77.91	83.85	84.82	1.246	0.281
Aspartic acid	76.80	74.52	79.09	78.62	0.998	0.354
Cysteine	69.75	66.75	71.31	70.02	1.277	0.495
Glutamic acid	82.26	82.02	84.10	85.73	0.931	0.304
Serine	82.02	77.98	85.83	84.89	1.228	0.199
Tyrosine	85.89	84.05	88.75	89.34	0.821	0.133
Glycine	66.04	58.46	66.38	64.51	2.293	0.205
Proline	104.11	98.59	106.28	105.27	5.160	0.653

[1] A total of eight individually housed growing barrows (initially 69.2 ± 6.8 lb) that had a T-cannula installed in the distal ileum were allotted to a replicated 8 × 8 Latin square design with the 8 diets and eight 7-d periods.

[2] Dietary treatments were arranged in a 2 × 2 × 2 factorial with main effects of crystalline AA (low vs. high), reducing sugar (low vs. high), and diet form (mash vs. pellet). This table represents the 2 × 2 factorial of crystalline AA (low vs. high) and diet form (mash vs. pellet).

[3] Probability, $P <$ of a 2-way interaction of feed form and crystalline AA.

Table 6. Standardized ileal digestibility of crude protein (CP) and amino acids (AA) as a 2-way interaction of feed form × reducing sugar (RS) fed to pigs[1,2]

Form:	Mash		Pellet			
RS:	Low	High	Low	High	SEM	*P*-value[3]
SID, %						
Total AA	82.98	78.57	87.31	81.87	1.066	0.618
Crude protein	78.86	74.89	85.10	79.29	1.559	0.545
Indispensable AA						
Arginine	93.84	89.36	98.43	93.72	0.787	0.885
Histidine	84.12	77.35	87.79	79.52	0.924	0.404
Isoleucine	82.54	76.71	87.72	80.97	1.100	0.670
Leucine	82.74	78.54	87.60	83.02	1.068	0.854
Lysine	88.18	83.34	91.46	84.11	0.992	0.198
Methionine	89.51	83.30	94.74	87.01	1.100	0.478
Phenylalanine	82.44	78.66	87.39	82.84	1.061	0.710
Threonine	78.14	73.18	82.66	74.83	1.283	0.256
Tryptophan	87.53	87.80	92.38	87.58	1.141	0.026
Valine	78.92	72.81	84.68	76.56	1.266	0.416
Dispensable AA						
Alanine	80.24	77.25	86.89	81.79	1.246	0.385
Aspartic acid	79.46	71.86	83.34	74.37	0.998	0.484
Cysteine	71.56	64.94	75.11	66.21	1.277	0.361
Glutamic acid	84.66	79.62	86.53	83.30	0.931	0.321
Serine	83.31	76.70	89.27	81.46	1.228	0.619
Tyrosine	84.82	85.12	89.30	88.79	0.821	0.611
Glycine	63.02	61.48	67.60	63.29	2.293	0.537
Proline	100.10	102.60	104.3	107.26	5.160	0.964

[1] A total of eight individually housed growing barrows (initially 69.2 ± 6.8 lb) that had a T-cannula installed in the distal ileum were allotted to a replicated 8 × 8 Latin square design with the 8 diets and eight 7-d periods.

[2] Dietary treatments were arranged in a 2 × 2 × 2 factorial with main effects of crystalline AA (low vs. high), reducing sugar (low vs. high), and diet form (mash vs. pellet). This table represents the 2 × 2 factorial of RS (low vs. high) and diet form (mash vs. pellet).

[3] Probability, $P <$ of a 2-way interaction of feed form and reducing sugars.

Table 7. Standardized ileal digestibility (SID) of crude protein (CP) and amino acids (AA) as a 2-way interaction of crystalline AA inclusion × reducing sugar (RS)[1,2]

Crystalline AA:	Low		High			
RS:	Low	High	Low	High	SEM	*P*-value[3]
SID, %						
Total AA	85.17	80.91	85.13	79.54	1.066	0.520
Crude protein	82.32	78.03	81.63	76.15	1.559	0.699
Indispensable AA						
Arginine	96.62	92.42	95.65	90.66	0.787	0.605
Histidine	86.44	79.75	85.47	77.12	0.924	0.358
Isoleucine	85.55	80.49	84.71	77.19	1.101	0.255
Leucine	85.15	81.39	85.19	80.18	1.068	0.555
Lysine	89.23	82.57	90.41	84.88	0.992	0.557
Methionine	91.29	86.41	92.96	83.91	1.100	0.056
Phenylalanine	85.10	81.72	84.74	79.78	1.060	0.443
Threonine	79.62	72.77	81.17	75.24	1.283	0.711
Tryptophan	88.90	85.62	91.01	89.75	1.141	0.364
Valine	81.58	76.51	82.03	72.86	1.266	0.102
Dispensable AA						
Alanine	83.281	80.15	83.84	78.89	1.246	0.456
Aspartic acid	81.35	74.55	81.45	71.68	0.998	0.131
Cysteine	74.07	66.99	72.61	64.16	1.277	0.578
Glutamic acid	84.66	81.70	86.53	81.22	0.931	0.199
Serine	87.02	80.84	85.56	77.31	1.228	0.389
Tyrosine	87.66	86.98	86.47	86.93	0.821	0.478
Glycine	67.75	64.67	62.97	60.10	2.293	0.945
Proline	104.05	106.34	100.35	103.51	5.160	0.931

[1] A total of eight individually housed growing barrows (initially 69.2 ± 6.8 lb) that had a T-cannula installed in the distal ileum were allotted to a replicated 8 × 8 Latin square design with the 8 diets and eight 7-d periods.

[2] Dietary treatments were arranged in a 2 × 2 × 2 factorial with main effects of crystalline AA (low vs. high), reducing sugar (low vs. high), and diet form (mash vs. pellet). This table represents the 2 × 2 factorial of crystalline AA (low vs. high) and RS (low vs. high).

[3] Probability, $P <$ of a 2-way interaction of crystalline AA and reducing sugar.

Table 8. Standardized ileal digestibility (SID) of crude protein (CP) and amino acids (AA) main effects of feed form, crystalline AA, and reducing sugar (RS)[1,2]

	Form		Crystalline AA		RS			*P*-value[3]		
SID, %	Mash	Pellet	Low	High	Low	High	SEM	Form	AA	RS
Total AA	80.78	84.60	83.04	82.33	85.15	80.22	0.737	0.001	0.500	0.001
Crude protein	76.88	82.20	80.18	78.89	81.98	77.09	1.078	0.001	0.340	0.002
Indispensable AA										
Arginine	91.60	96.08	94.52	93.15	96.14	91.54	0.544	0.001	0.079	0.001
Histidine	80.74	83.66	83.10	81.30	85.96	78.44	0.639	0.002	0.050	0.001
Isoleucine	79.63	84.34	83.02	80.95	85.13	78.84	0.762	0.001	0.059	0.001
Leucine	80.64	85.31	83.27	82.67	85.78	80.78	0.739	0.001	0.577	0.001
Lysine	85.76	87.79	85.90	87.65	89.82	83.72	0.686	0.041	0.076	0.001
Methionine	86.41	90.87	88.85	88.43	92.13	85.16	0.759	0.001	0.698	0.001
Phenylalanine	80.55	85.12	83.41	82.26	84.75	80.75	0.733	0.001	0.269	0.001
Threonine	75.66	78.74	76.20	78.21	80.40	74.01	0.888	0.017	0.113	0.001
Tryptophan	87.66	89.98	87.26	90.38	89.95	87.69	0.789	0.042	0.007	0.046
Valine	75.87	80.62	79.04	77.44	81.80	74.68	0.875	0.001	0.200	0.001
Dispensable AA										
Alanine	78.75	84.34	81.71	81.37	83.56	79.52	0.862	0.001	0.776	0.002
Aspartic acid	75.66	78.85	77.95	76.57	81.40	73.11	0.690	0.002	0.160	0.001
Cysteine	68.25	70.66	70.53	68.38	73.34	65.57	0.883	0.058	0.090	0.001
Glutamic acid	84.14	84.92	83.18	83.89	85.60	81.46	0.644	0.004	0.442	0.001
Serine	80.00	85.36	83.93	81.43	86.29	79.08	0.849	0.001	0.042	0.001
Tyrosine	84.97	89.05	87.32	86.70	87.06	86.96	0.568	0.001	0.436	0.897
Glycine	62.25	65.44	66.21	61.48	65.31	62.39	1.586	0.157	0.039	0.194
Proline	101.35	105.78	105.19	101.93	102.2	104.93	3.568	0.380	0.517	0.587

[1] A total of eight individually housed growing barrows (initially 69.2 ± 6.8 lb) that had a T-cannula installed in the distal ileum were allotted to a replicated 8 × 8 Latin square design with the 8 diets and eight 7-d periods.

[2] Dietary treatments were arranged in a 2 × 2 × 2 factorial with main effects of crystalline AA (low vs. high), reducing sugar (low vs. high), and diet form (mash vs. pellet).

[3] Probability, $P <$ for the main effects of form, crystalline AA, or reducing sugar.