*Journal of Animal Science*, 2023, **101**, 1–10
https://doi.org/10.1093/jas/skad208
Advance access publication 21 June 2023
**Non ruminant nutrition**

# Standardized ileal digestibility of amino acids differs among sources of bakery meal when fed to growing pigs

**Hans H. Stein,[†,1] Olayiwola Adeola,[‡] Samuel K. Baidoo,[||] Merlin D. Lindemann,[$] Sunday A. Adedokun,[$] and North Central Coordinating Committee on Swine Nutrition (NCCC-42)[#]**

[†]Division of Nutritional Sciences, University of Illinois, Urbana-Champaign, IL, USA
[‡] Department of Animal Sciences, Purdue University, West Lafayette, IN, USA
[||]Department of Animal Sciences, University of Minnesota, Waseca, MN, USA
[$]Department of Animal Sciences, University of Kentucky, Lexington, KY, USA
[#]Other members of the NCCC-42 committee at the time this work is listed above Literature Cited section.
[1]Corresponding author: hstein@illinois.edu

## Abstract

A multistate experiment involving universities in IL, IN, KY, and MN was conducted as a part of the research efforts by the North-Central Coordinating Committee-42 on swine nutrition. The null hypothesis that there are no differences in the standardized ileal digestibility (**SID**) of amino acids (**AA**) among different sources of bakery meal was tested. Eleven sources of bakery meal were procured from swine-producing states in the United States and each source was included in one diet as the sole source of AA. A N-free diet was prepared as well. Diets were prepared in one batch and divided into four sub-batches that were subsequently distributed to the four participating universities. At each university, diets were fed to 12 pigs that had a T- cannula installed in the distal ileum. Pigs were allotted to incomplete Latin square designs with 12 pigs and 4, 5, or 6 periods for a total of 21 replicate pigs per diet. Each period lasted 7 d with ileal digesta being collected from the cannulas on days 6 and 7. Samples were analyzed for AA and the SID of each AA was calculated. Results indicated that there were differences ($P < 0.001$) in the SID of all AA except Pro among the 11 sources of bakery meal. The differences in SID of AA observed in this experiment were greater than what is usually observed among sources of the same ingredient, indicating that there is more variability among sources of bakery meal than among different sources of other ingredients. This is likely a consequence of different raw materials being used in the production of different sources of bakery meal. Regardless of source of bakery meal, the AA with the least SID was Lys indicating that some of the raw materials in the product streams used to generate the bakery meals may have been overheated. Additionally, the Lys:crude protein ratio in each source of bakery meal was not a good predictor of the SID of Lys, which likely reflects the different raw materials being included in the different meals. In conclusion, the SID of AA varies among different sources of bakery meal and the SID of Lys is less than the SID of all other indispensable AA.

## Lay Summary

Eleven sources of bakery meal were used in a regional experiment to determine digestibility of amino acids. Diets containing each source of bakery meal were prepared at one university and distributed to three other universities. Diets were fed to pigs that had a cannula installed in the distal ileum and ileal digesta were collected from pigs for 2 d following 5 d of adaptation. Results indicated that there is considerable variation in the digestibility of all amino acids among sources of bakery meal, which is likely a reflection of differences in raw material use among different producers of bakery meal. Results also demonstrated that the digestibility of Lys is less than the digestibility of all other amino acids, indicating that some of the raw materials used in the production of bakery meal may have been heat damaged. It may, therefore, be necessary to add additional Lys to diets containing bakery meal.

**Key words:** amino acids, bakery meal, digestibility, lysine, pigs

**Abbreviations:** AA, amino acids; AID, apparent ileal digestibility; NCCC, North Central Coordinating Committee; SID, standardized ileal digestibility

## Introduction

Human foods that cannot be used for their intended purposes may be included in diets for pigs (Jinno et al., 2018; Tretola et al., 2019a; Luciano et al., 2022). On a global basis, if all nonusable food items are used in feed for animals, these items may contribute up to 15% of total feed usage for livestock (Sandström et al., 2022). There are, however, considerable challenges associated with collection, cleaning, preparation, and incorporation of nonusable food items into practical diets for animals (Tretola et al., 2017). There is also a risk of contamination with harmful microbes and viruses associated with the use of these ingredients (Tretola et al., 2019b; Shurson, 2020). Additionally, the chemical composition and nutritional values of collected food products vary greatly (Fung et al., 2019a, 2019b) and for many food items, a drying procedure is needed to stabilize the ingredients. There are, therefore, only a limited number of nonusable food items that are used in diets for commercially fed pigs. In North America, nonusable food items used in

Received April 19, 2023 Accepted June 16, 2023.

**Table 1.** Nutrient composition of the 11 sources of bakery meal[1]

| Item, % | Bakery meal source | | | | | | | | | | | Average | CV |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G | H | I | J | K | | |
| Dry matter | 89.90 | 90.06 | 88.99 | 90.11 | 88.67 | 88.49 | 88.43 | 89.25 | 84.88 | 86.47 | 90.18 | 88.68 | 1.9 |
| Crude protein | 11.13 | 12.00 | 9.03 | 11.91 | 13.34 | 13.91 | 11.32 | 12.32 | 12.87 | 8.03 | 12.26 | 11.65 | 15.9 |
| Lys to crude protein ratio, × 10 | 3.59 | 2.83 | 3.55 | 3.86 | 3.82 | 2.95 | 3.27 | 3.09 | 3.73 | 3.24 | 4.73 | 3.51 | 15.2 |
| Indispensable amino acids | | | | | | | | | | | | | |
| Arg | 0.53 | 0.58 | 0.47 | 0.63 | 0.67 | 0.60 | 0.60 | 0.50 | 0.73 | 0.35 | 0.67 | 0.57 | 18.7 |
| His | 0.24 | 0.26 | 0.20 | 0.27 | 0.30 | 0.26 | 0.27 | 0.27 | 0.32 | 0.15 | 0.29 | 0.26 | 18.2 |
| Ile | 0.45 | 0.44 | 0.35 | 0.45 | 0.55 | 0.45 | 0.45 | 0.49 | 0.57 | 0.39 | 0.53 | 0.46 | 14.3 |
| Leu | 0.82 | 0.80 | 0.63 | 0.86 | 1.03 | 0.84 | 0.82 | 0.92 | 1.06 | 0.66 | 0.96 | 0.85 | 15.7 |
| Lys | 0.40 | 0.34 | 0.32 | 0.46 | 0.51 | 0.41 | 0.37 | 0.38 | 0.48 | 0.26 | 0.58 | 0.41 | 21.9 |
| Met | 0.17 | 0.19 | 0.15 | 0.19 | 0.19 | 0.19 | 0.18 | 0.21 | 0.20 | 0.11 | 0.20 | 0.18 | 15.5 |
| Phe | 0.52 | 0.51 | 0.42 | 0.52 | 0.61 | 0.54 | 0.53 | 0.58 | 0.67 | 0.46 | 0.60 | 0.54 | 13.3 |
| Thr | 0.34 | 0.35 | 0.27 | 0.37 | 0.43 | 0.36 | 0.36 | 0.36 | 0.47 | 0.27 | 0.44 | 0.37 | 16.9 |
| Trp | 0.12 | 0.15 | 0.10 | 0.13 | 0.13 | 0.11 | 0.17 | 0.13 | 0.15 | 0.10 | 0.16 | 0.13 | 17.4 |
| Val | 0.53 | 0.54 | 0.42 | 0.56 | 0.63 | 0.53 | 0.54 | 0.55 | 0.74 | 0.43 | 0.60 | 0.55 | 16.0 |
| Dispensable amino acids | | | | | | | | | | | | | |
| Ala | 0.47 | 0.48 | 0.39 | 0.54 | 0.63 | 0.48 | 0.48 | 0.46 | 0.73 | 0.38 | 0.56 | 0.51 | 20.0 |
| Asp | 0.75 | 0.70 | 0.61 | 0.79 | 1.01 | 0.80 | 0.72 | 0.68 | 0.92 | 0.56 | 1.06 | 0.78 | 20.3 |
| Cys | 0.23 | 0.27 | 0.19 | 0.23 | 0.25 | 0.25 | 0.27 | 0.27 | 0.23 | 0.15 | 0.21 | 0.23 | 15.8 |
| Glu | 2.54 | 2.83 | 1.99 | 2.46 | 2.61 | 2.62 | 3.03 | 3.32 | 1.88 | 1.23 | 2.56 | 2.46 | 23.5 |
| Gly | 0.46 | 0.52 | 0.40 | 0.51 | 0.58 | 0.49 | 0.53 | 0.45 | 0.65 | 0.34 | 0.53 | 0.49 | 17.2 |
| Pro | 0.85 | 0.93 | 0.64 | 0.83 | 0.86 | 0.83 | 0.99 | 1.16 | 0.65 | 0.40 | 0.81 | 0.81 | 24.5 |
| Ser | 0.44 | 0.44 | 0.34 | 0.45 | 0.50 | 0.46 | 0.47 | 0.49 | 0.51 | 0.30 | 0.51 | 0.44 | 15.6 |
| Tyr | 0.33 | 0.33 | 0.28 | 0.33 | 0.41 | 0.35 | 0.35 | 0.38 | 0.80 | 0.84 | 0.37 | 0.43 | 44.8 |
| Total amino acids | 10.4 | 10.9 | 8.4 | 10.8 | 12.1 | 10.8 | 11.3 | 11.9 | 12.0 | 7.6 | 11.9 | 10.7 | 13.8 |

[1]All values except dry matter were adjusted to 88% dry matter.

animal feeding are marketed under the common name "bakery meal" because they primarily consist of products from the bakery and confectionary industries and include dated or otherwise unusable breakfast cereals, breads, cakes, cookies, and other bakery products (Slominski et al., 2004; Liu et al., 2018). Following collection from production facilities, supermarkets, or restaurants, ingredients are unpacked, ground, and mixed. Nonfood ingredients such a cereal co-products or soybean meal are sometimes mixed with the collected food items to ensure that the final product meets nutritional specifications. Indeed, a recent survey (Liu et al., 2018) of the chemical composition of 46 sources of bakery meal from the United States indicated that there was surprisingly little variation in chemical composition among different sources of bakery meal regardless of the geographical area in which the ingredients were produced. It, therefore, appears that the bakery meal industry is able to blend different product streams in such a way that a final product with a relatively constant chemical composition is produced. However, the nutritional value of a feed ingredient depends not only on the chemical composition, but also on the digestibility of energy and nutrients. As a consequence, there is a need to determine the digestibility of nutrients in bakery meal and also to determine if differences exist among sources of bakery meal. Therefore, the objective of this research was to test the null hypothesis that amino acid (**AA**) digestibility in bakery meal is not different among sources.

## Materials and methods

The experiment was part of the research efforts of the North Central Coordinating Committee on Swine Nutrition (NCCC-42) and four universities participated in the animal work of the experiment (i.e., University of Illinois, Purdue University, , University of Kentucky, and University of Minnesota). The protocol for the experiment was reviewed and approved by the Institutional Animal Care and Use Committee at each participating university. Pigs used at the four universities were the offspring of PIC Line 359 males mated to Camborough females (PIC, Hendersonville, TN, USA; University of Illinois, Urbana, IL, USA); Duroc males mated to Yorkshire × Landrace females (Purdue University, Lafayette, IN, USA); Compart Duroc males mated to Topigs 20 females (Topigs Norsvin, Burnsville, MN, USA; University of Minnesota, St. Paul, USA); and Chester White males mated to Yorkshire × Landrace females (University of Kentucky, Lexington, KY, USA). Twelve male pigs were used at each university and the average initial body weight of pigs was 35.2 ± 9.4 kg.

### Animals, housing, diets, feeding, and sample collection

Eleven sources of bakery meal were collected from feed mills located in the swine-producing states of the United States. Each source was shipped to the University of Illinois where subsamples were collected for analysis (Table 1). Each source of bakery meal was mixed into one diet as the only source of AA and an N-free diet was prepared as well. Thus, a total of 12 diets were formulated (Tables 2 and 3). Vitamins and minerals were included in all diets to meet or exceed current requirement estimates (NRC, 2012) and all diets also contained 0.40% titanium dioxide as an indigestible marker. Each diet was mixed in one batch at the University of Illinois, bagged, and distributed to the four participating universities.

Each university fed diets to 12 growing pigs that had a T-cannula installed in the distal ileum. Pigs were allotted to incomplete Latin square designs with six periods at the University of IL and Purdue University, five periods at the University of KY, and four periods at the University of MN for a total of 21 possible observations per diet. Pigs were housed individually and water was available at all times. Pigs were provided their respective diets at 3.3 times the maintenance requirement for metabolizable energy (i.e., 197 kcal metabolizable energy (ME)/kg × body weight $(BW)^{0.60}$; NRC, 2012). The calculated metabolizable energy in the bakery meal diets and the N-free diet was 3,320 kcal/kg (as-fed) and 3,790 kcal/kg (as-fed), respectively.

Each experimental period lasted 7 d. The initial 5 d of each period were considered an adaptation period and ileal digesta were collected on days 6 and 7 for 9 h using standard procedures with digesta collection starting immediately after feeding the morning meal. No acid was added to collection bags because this does not influence AA digestibility (Lee et al., 2021).

Cannulas were opened and a 225-mL plastic bag was attached to the opened cannula barrel and digesta flowing into the bag were collected. Bags were removed whenever they were full or every 30 min and replaced with a new bag. All samples were stored at −20 °C as soon as collected. At the conclusion of each period, ileal digesta samples were thawed, mixed within animal and diet, and sub-samples were collected. Digesta samples were lyophilized and shipped overnight to the University of Illinois where they were finely ground using a coffee grinder before analysis.

### Sample analysis

All analyses were conducted in duplicates. Dry matter in the 11 sources of bakery meal, all diets, and freeze-dried ileal digesta samples was determined by placing 1 g of sample

**Table 2.** Ingredient composition of experimental diets, as-fed basis

| Item | Bakery meal[1] | N-free |
|---|---|---|
| Bakery meal | 97.85 | — |
| Soybean oil | — | 4.00 |
| Ground limestone | 0.30 | 0.30 |
| Dicalcium phosphate | 0.90 | 1.75 |
| Sucrose | — | 20.00 |
| Corn starch | — | 68.50 |
| Solka floc[2] | — | 4.00 |
| Magnesium oxide | — | 0.10 |
| Potassium carbonate | — | 0.40 |
| Sodium chloride | 0.40 | 0.40 |
| Titanium dioxide | 0.40 | 0.40 |
| Vitamin–mineral premix[3] | 0.15 | 0.15 |

[1]A total of 11 diets were formulated using 11 sources of bakery meal.
[2]Fiber Sales and Development Corp., Urbana, OH.
[3]The vitamin–micromineral premix provided the following quantities of vitamins and micro minerals per kilogram of complete diet: vitamin A as retinyl acetate, 11,150 IU; vitamin $D_3$ as cholecalciferol, 2,210 IU; vitamin E as DL alpha tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.42 mg; thiamin as thiamine mononitrate, 1.10 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 1.00 mg; vitamin $B_{12}$, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.6 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 125 mg as iron sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese hydroxychloride; Se, 0.30 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc hydroxychloride.

**Table 3.** Analyzed nutrient composition of experimental diets, as-fed basis

| Item, % | Bakery meal diet | | | | | | | | | | | N-free diet |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G | H | I | J | K | |
| Dry matter | 89.98 | 90.23 | 89.44 | 90.49 | 88.58 | 87.99 | 87.99 | 89.06 | 85.94 | 86.77 | 90.38 | 92.77 |
| Crude protein | 11.08 | 12.07 | 9.21 | 11.92 | 13.51 | 11.23 | 13.81 | 12.39 | 12.31 | 8.21 | 13.00 | 0.53 |
| Indispensable amino acids | | | | | | | | | | | | |
| Arg | 0.50 | 0.56 | 0.44 | 0.63 | 0.65 | 0.54 | 0.66 | 0.49 | 0.64 | 0.35 | 0.66 | 0.01 |
| His | 0.24 | 0.27 | 0.19 | 0.28 | 0.30 | 0.24 | 0.30 | 0.27 | 0.29 | 0.16 | 0.29 | 0.00 |
| Ile | 0.42 | 0.43 | 0.33 | 0.43 | 0.52 | 0.41 | 0.48 | 0.46 | 0.51 | 0.40 | 0.51 | 0.01 |
| Leu | 0.80 | 0.79 | 0.62 | 0.86 | 1.02 | 0.79 | 0.93 | 0.89 | 0.96 | 0.68 | 0.95 | 0.02 |
| Lys | 0.38 | 0.35 | 0.28 | 0.45 | 0.50 | 0.38 | 0.41 | 0.37 | 0.43 | 0.27 | 0.57 | 0.01 |
| Met | 0.17 | 0.18 | 0.15 | 0.19 | 0.21 | 0.16 | 0.21 | 0.20 | 0.18 | 0.11 | 0.20 | 0.01 |
| Phe | 0.51 | 0.52 | 0.40 | 0.54 | 0.61 | 0.49 | 0.61 | 0.58 | 0.62 | 0.48 | 0.58 | 0.01 |
| Thr | 0.35 | 0.36 | 0.28 | 0.39 | 0.44 | 0.34 | 0.40 | 0.37 | 0.45 | 0.29 | 0.44 | 0.01 |
| Trp | 0.12 | 0.15 | 0.07 | 0.13 | 0.11 | 0.10 | 0.14 | 0.13 | 0.11 | 0.09 | 0.13 | $< 0.02$ |
| Val | 0.52 | 0.54 | 0.42 | 0.57 | 0.63 | 0.51 | 0.59 | 0.55 | 0.69 | 0.47 | 0.60 | 0.01 |
| Dispensable amino acids | | | | | | | | | | | | |
| Ala | 0.46 | 0.48 | 0.37 | 0.54 | 0.61 | 0.46 | 0.54 | 0.45 | 0.64 | 0.40 | 0.56 | 0.01 |
| Asp | 0.76 | 0.71 | 0.62 | 0.83 | 1.03 | 0.74 | 0.83 | 0.68 | 0.86 | 0.57 | 1.05 | 0.02 |
| Cys | 0.22 | 0.26 | 0.20 | 0.25 | 0.26 | 0.23 | 0.27 | 0.25 | 0.20 | 0.15 | 0.22 | 0.01 |
| Glu | 2.47 | 2.86 | 2.03 | 2.49 | 2.68 | 2.47 | 3.21 | 3.31 | 1.76 | 1.25 | 2.54 | 0.02 |
| Gly | 0.44 | 0.51 | 0.37 | 0.51 | 0.55 | 0.44 | 0.55 | 0.44 | 0.56 | 0.35 | 0.50 | 0.01 |
| Pro | 0.87 | 0.98 | 0.66 | 0.88 | 0.91 | 0.80 | 1.08 | 1.15 | 0.65 | 0.45 | 0.83 | 0.05 |
| Ser | 0.42 | 0.43 | 0.34 | 0.45 | 0.51 | 0.43 | 0.50 | 0.48 | 0.46 | 0.29 | 0.47 | 0.01 |
| Tyr | 0.28 | 0.29 | 0.21 | 0.33 | 0.37 | 0.26 | 0.35 | 0.34 | 0.80 | 0.86 | 0.33 | 0.01 |
| Total amino acids | 10.19 | 10.89 | 8.19 | 11.00 | 12.17 | 9.99 | 12.27 | 11.68 | 11.01 | 7.81 | 11.69 | 0.41 |

in a drying oven for 2 h at 135 °C (method 930.15; AOAC Int., 2007). Crude protein in ingredient and diet samples was calculated as N × 6.25 and N was measured using the combustion procedure (method 990.03; AOAC Int., 2007) on a LECO FP628 (LECO Corp., Saint Joseph, MI). Amino acids in bakery meals, diets, and ileal digesta samples were analyzed on a Hitachi Amino Acid Analyzer (Model No. L8800; Hitachi High Technologies America, Inc.; Pleasanton, CA) using ninhydrin for postcolumn derivatization and norleucine as the internal standard. Prior to analysis, samples were hydrolyzed with 6*N* HCl for 24 h at 110 °C [method 982.30 E(a); AOAC Int., 2007]. Methionine and Cys were determined as Met sulfone and cysteic acid after an overnight cold performic acid oxidation before hydrolysis [method 982.30 E(b); AOAC Int., 2007]. Tryptophan was determined after BaOH hydrolysis for 22 h at 110 °C [method 982.30 E(c); AOAC Int., 2007]. The concentration of titanium in diet and ileal digesta samples was analyzed following the procedure of Myers et al. (2004).

### Calculations and statistical analysis

Following analysis, the apparent ileal digestibility (**AID**), basal endogenous losses, and the standardized ileal digestibility (**SID**) were calculated for crude protein and AA in the 11 diets containing bakery meal (Stein et al., 2007). Because bakery meal was the only source of AA in each diet, the AID and SID of AA in diets also represented the AID and SID of AA in bakery meal.

Data were analyzed using PROC MIXED in SAS (SAS Institute Inc., Cary, NC). Homogeneity of the variances was confirmed. The model included dietary treatment as the fixed effect and station as well as the interaction between dietary treatment and station as random effects. Pig was the experimental unit. Least square means were calculated and separated using the pdiff option with Tukey's adjustment. Differences were considered significant at $P \leq 0.05$ and a trend at $P \leq 0.10$. Correlation coefficients ($r$) between Lys:CP and digestibility of Lys or digestible Lys (% of diet) were determined using the CORR procedure of SAS.

## Results

The AID of all indispensable AA in the 11 sources of bakery meal ranged from 50.5% to 74.2% (Table 4). The AID ranged from 31.1% to 58.7% for Lys; from 54.9% to 80.4% for Met; from 38.4% to 64.6% for Thr; from 42.7% to 66.7% for Trp; and from 47.4% to 71.7% for Val. The AID of dispensable AA in the 11 sources of bakery meal ranged from 42.7% to 66.7%. The endogenous losses of CP and AA varied somewhat among research stations with station A having the greatest ($P < 0.05$) value for most AA (Table 5).

The SID of all indispensable AA in the 11 sources of bakery meal ranged from 61.5% to 81.8% (Table 6). The SID ranged from 43.2% to 67.2% for Lys; from 62.3% to 84.3% for Met; from 53.1% to 77.5% for Thr; from 53.7% to 86.5% for Trp; and from 56.7% to 79.6% for Val. The SID of all dispensable AA in the 11 sources of bakery meal ranged from 64.4 to 88.6%.

The correlation coefficients between the Lys to crude protein ratio and the apparent or standardized ileal digestibility of Lys were not significant (Table 7). However, there were correlations ($P < 0.05$) between the Lys to crude protein ratio and the concentrations (%) of apparent ileal digestible Lys or standardized ileal digestible Lys in the bakery meals.

## Discussion

The average dry matter (88.68%) in the 11 sources of bakery meal used in this experiment was in agreement with values (86.99 and 89.39) reported by Almeida et al. (2011) and Casas et al., (2015). In contrast, greater dry matter (91.82) was analyzed by Casas et al. (2018) and by Liu et al. (2018) who reported an average dry matter of 91.84% in 46 sources of bakery meal. These differences are likely a result of different drying intensities of the products included in the production of the bakery meals.

The average concentration of crude protein in the bakery meals used in this experiment (11.60%, as-fed basis) was in agreement with the average crude protein (12.20%, as-fed basis) reported by Liu et al (2018) and values (11.30% and 11.09%) reported by Almeida et al. (2011) and by Casas et al. (2018). Likewise, the average concentrations of Lys, Met, Thr, Trp, and Val (0.41%, 0.18%, 0.37%, 0.13%, and 0.55%, respectively, as-fed basis) analyzed in the 11 sources of bakery meal used in this experiment were close to values (i.e., 0.35%, 0.19%, 0.38%, 0.13%, and 0.55%, respectively, as-fed basis) reported by Liu et al. (2018). These values are also in agreement with Casas et al. (2018) who analyzed 0.38%, 0.17%, 0.38%, 0.12%, and 0.51% for Lys, Met, Thr, Trp, and Val, respectively, as-fed basis, whereas Almeida et al. (2011) reported a lower concentration of Lys (0.27%, as-fed basis), but values for Met (0. 18%, as-fed basis), Thr (0.36%, as-fed basis), Trp (0.10%, as-fed basis), and Val (0.52%, as-fed basis) that were in agreement with values obtained in this experiment. Slightly greater concentrations of Lys, Met, Thr, Trp, and Val (0.41%, 0.20%, 0.44%, 0.16%, and 0.62%, respectively, as-fed basis) have also been reported (Casas et al., 2015). However, it appears that concentrations of dry matter, crude protein, and AA in the 11 sources of bakery meal used in this experiment generally were within the range of values typically observed in commercial sources of bakery meal from the United States.

The SEM for the AID and SID of AA in the 11 sources of bakery meal that were used was close to the SEM usually obtained in AA digestibility experiments where 6 to 10 replications are used. The SEM is usually lower when more replications are included in an experiment, but that was not the case in this experiment, which is likely a result of additional variability being introduced by using four different universities to determine the digestibility of AA. An effort to minimize variability was made by mixing diets in only one batch and then distributing sub-batches to participating universities. Because twice as many replications as usually used in digestibility experiments were used in this experiment, it was possible to maintain an acceptable SEM for the AID and SID of AA despite conducting the experiment at four different universities.

Values for the SID of AA in bakery meal produced in the United States have been reported from three experiments (Almeida et al., 2011; Casas et al., 2015; 2018). However, in each of these experiments, only one source of bakery meal was included and to the best of our knowledge, this is the first time SID of AA in multiple sources of bakery meal is being reported. The average SID of indispensable AA (73.7%) that was observed in the current experiment represents a range

**Table 4.** Apparent ileal digestibility of crude protein and amino acids (AA) in 11 sources of bakery meal

| Item | Bakery meal | | | | | | | | | | | Mean | SD | Diet[1] | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G | H | I | J | K | | | SEM | *P*-value |
| Observation, *n* | 18 | 20 | 20 | 19 | 18 | 17 | 17 | 21 | 19 | 19 | 21 | — | — | — | — |
| Crude protein | 49.6$^{de}$ | 63.6$^{ab}$ | 56.7$^{bcd}$ | 51.8$^{cd}$ | 61.1$^{abc}$ | 52.3$^{cd}$ | 67.9$^{a}$ | 66.7$^{a}$ | 40.6$^{ef}$ | 38.0$^{f}$ | 62.6$^{ab}$ | 55.56 | 10.08 | 3.61 | <0.001 |
| Indispensable AA | | | | | | | | | | | | | | | |
| Arg | 63.0$^{d}$ | 74.2$^{ab}$ | 68.0$^{bcd}$ | 72.6$^{abc}$ | 75.5$^{ab}$ | 65.3$^{cd}$ | 76.6$^{a}$ | 71.9$^{abc}$ | 64.6$^{cd}$ | 52.5$^{e}$ | 75.3$^{ab}$ | 69.05 | 7.28 | 2.62 | <0.001 |
| His | 64.1$^{de}$ | 75.8$^{ab}$ | 68.0$^{cd}$ | 70.4$^{bcd}$ | 73.6$^{abc}$ | 66.4$^{d}$ | 77.5$^{a}$ | 76.4$^{ab}$ | 57.9$^{ef}$ | 56.2$^{f}$ | 75.0$^{ab}$ | 69.22 | 7.43 | 1.73 | <0.001 |
| Ile | 59.9$^{de}$ | 73.8$^{ab}$ | 67.3$^{bcd}$ | 64.0$^{cd}$ | 69.4$^{abc}$ | 64.3$^{cd}$ | 75.9$^{a}$ | 74.8$^{ab}$ | 52.1$^{f}$ | 53.3$^{ef}$ | 71.0$^{abc}$ | 65.97 | 8.20 | 1.83 | <0.001 |
| Leu | 66.1$^{d}$ | 77.4$^{ab}$ | 71.3$^{bcd}$ | 70.2$^{cd}$ | 75.0$^{abc}$ | 69.5$^{cd}$ | 80.3$^{a}$ | 79.4$^{a}$ | 56.5$^{e}$ | 54.4$^{e}$ | 75.5$^{abc}$ | 70.50 | 8.63 | 1.88 | <0.001 |
| Lys | 35.5$^{cde}$ | 39.4$^{bcde}$ | 46.5$^{abc}$ | 43.1$^{bcde}$ | 51.6$^{ab}$ | 45.6$^{abcd}$ | 50.4$^{ab}$ | 50.3$^{ab}$ | 32.5$^{de}$ | 31.1$^{e}$ | 58.7$^{a}$ | 44.07 | 8.71 | 3.43 | <0.001 |
| Met | 70.3$^{cd}$ | 77.3$^{ab}$ | 72.6$^{bcd}$ | 72.6$^{bcd}$ | 76.4$^{abc}$ | 68.7$^{d}$ | 80.4$^{a}$ | 79.8$^{a}$ | 59.8$^{e}$ | 54.9$^{e}$ | 77.8$^{ab}$ | 71.88 | 8.16 | 1.31 | <0.001 |
| Phe | 67.2$^{d}$ | 78.6$^{ab}$ | 72.8$^{bcd}$ | 71.2$^{cd}$ | 74.8$^{abc}$ | 69.9$^{cd}$ | 81.2$^{a}$ | 80.6$^{a}$ | 60.6$^{e}$ | 60.7$^{e}$ | 75.6$^{abc}$ | 72.11 | 7.15 | 1.63 | <0.001 |
| Thr | 44.1$^{efg}$ | 61.5$^{abc}$ | 53.1$^{bcde}$ | 50.5$^{cdef}$ | 60.1$^{abcd}$ | 49.3$^{defg}$ | 64.6$^{a}$ | 62.8$^{ab}$ | 41.8$^{fg}$ | 38.4$^{g}$ | 63.7$^{ab}$ | 53.64 | 9.49 | 3.42 | <0.001 |
| Trp | 65.2$^{bc}$ | 77.7$^{a}$ | 57.8$^{c}$ | 65.6$^{bc}$ | 64.3$^{bc}$ | 63.2$^{bc}$ | 76.7$^{a}$ | 78.0$^{a}$ | 43.9$^{d}$ | 54.8$^{c}$ | 71.0$^{ab}$ | 65.30 | 10.51 | 4.34 | <0.001 |
| Val | 56.4$^{de}$ | 69.6$^{ab}$ | 63.5$^{abcd}$ | 61.3$^{bcd}$ | 66.5$^{abc}$ | 60.1$^{cd}$ | 71.7$^{a}$ | 70.7$^{a}$ | 50.1$^{e}$ | 47.4$^{e}$ | 68.2$^{abc}$ | 62.32 | 8.22 | 2.76 | <0.001 |
| Mean | 58.8$^{de}$ | 71.0$^{ab}$ | 65.6$^{bcd}$ | 64.5$^{bcd}$ | 69.5$^{abc}$ | 62.8$^{cd}$ | 74.2$^{a}$ | 73.0$^{a}$ | 53.2$^{ef}$ | 50.5$^{f}$ | 71.1$^{ab}$ | 64.92 | 7.96 | 1.93 | <0.001 |
| Dispensable AA | | | | | | | | | | | | | | | |
| Ala | 47.3$^{de}$ | 60.6$^{abc}$ | 54.3$^{bcd}$ | 55.7$^{abcd}$ | 62.1$^{abc}$ | 51.6$^{cd}$ | 65.6$^{a}$ | 62.3$^{ab}$ | 46.5$^{de}$ | 40.6$^{e}$ | 63.8$^{ab}$ | 55.49 | 8.22 | 2.39 | <0.001 |
| Asp | 49.3$^{de}$ | 62.0$^{abc}$ | 58.6$^{abc}$ | 56.2$^{bcd}$ | 64.1$^{ab}$ | 53.6$^{cd}$ | 66.3$^{a}$ | 61.8$^{abc}$ | 41.7$^{e}$ | 43.6$^{e}$ | 65.9$^{a}$ | 56.63 | 8.67 | 2.55 | <0.001 |
| Cys | 58.7$^{c}$ | 71.5$^{ab}$ | 61.2$^{bc}$ | 63.0$^{abc}$ | 65.2$^{abc}$ | 63.1$^{abc}$ | 73.6$^{a}$ | 72.1$^{a}$ | 34.8$^{d}$ | 41.4$^{d}$ | 61.9$^{bc}$ | 60.59 | 12.23 | 2.95 | <0.001 |
| Glu | 78.8$^{c}$ | 86.8$^{ab}$ | 82.2$^{bc}$ | 80.6$^{c}$ | 80.9$^{c}$ | 80.4$^{c}$ | 88.0$^{a}$ | 88.4$^{a}$ | 63.4$^{d}$ | 67.5$^{d}$ | 81.3$^{c}$ | 79.85 | 7.90 | 1.23 | <0.001 |
| Gly | 22.1$^{cd}$ | 44.0$^{ab}$ | 29.6$^{abc}$ | 26.8$^{bc}$ | 45.5$^{ab}$ | 18.3$^{cd}$ | 48.1$^{a}$ | 44.2$^{ab}$ | 13.5$^{cd}$ | 4.8$^{d}$ | 41.5$^{ab}$ | 30.77 | 14.85 | 7.03 | <0.001 |
| Pro | 13.1$^{abc}$ | 37.5$^{ab}$ | 2.4$^{abc}$ | 4.7$^{abc}$ | 39.1$^{ab}$ | -19.0$^{bc}$ | 38.6$^{ab}$ | 49.0$^{a}$ | -33.3$^{cd}$ | -83.0$^{d}$ | 19.3$^{abc}$ | 6.22 | 39.15 | 21.18 | <0.001 |
| Ser | 57.0$^{d}$ | 71.0$^{ab}$ | 63.8$^{bcd}$ | 61.3$^{cd}$ | 68.2$^{abc}$ | 63.3$^{bcd}$ | 74.0$^{a}$ | 73.7$^{a}$ | 48.3$^{e}$ | 43.8$^{e}$ | 67.0$^{abc}$ | 62.85 | 9.85 | 2.16 | <0.001 |
| Tyr | 57.1$^{d}$ | 71.2$^{b}$ | 59.8$^{cd}$ | 64.1$^{c}$ | 71.2$^{b}$ | 56.8$^{d}$ | 75.7$^{b}$ | 75.6$^{b}$ | 83.1$^{a}$ | 88.4$^{a}$ | 71.7$^{b}$ | 70.43 | 10.28 | 2.02 | <0.001 |
| Mean | 55.5$^{cd}$ | 69.0$^{ab}$ | 58.8$^{bcd}$ | 57.3$^{cd}$ | 66.7$^{abc}$ | 53.4$^{de}$ | 71.5$^{a}$ | 72.8$^{a}$ | 43.8$^{e}$ | 42.7$^{e}$ | 64.2$^{abcd}$ | 59.60 | 10.35 | 3.99 | <0.001 |
| Mean, all AA | 56.9$^{c}$ | 69.4$^{a}$ | 61.3$^{bc}$ | 60.1$^{bc}$ | 67.4$^{ab}$ | 57.1$^{c}$ | 72.2$^{a}$ | 72.6$^{a}$ | 47.8$^{d}$ | 46.3$^{d}$ | 67.0$^{ab}$ | 61.65 | 9.10 | 2.81 | <0.001 |

[1]Effect of source of bakery meal.
[a,b,c,d,e,f]Means within a row lacking a common superscript letter are different ($P < 0.05$).

**Table 5.** Basal endogenous losses (gram per kilogram dry matter intake) of amino acids from pigs fed the N-free diet at four universities[1]

| Item | Universities | | | | Mean | SD | Station | |
|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | | | SEM | *P*-value |
| Observation, *n* | 6 | 5 | 5 | 5 | — | — | — | — |
| Crude protein | 30.23 | 26.36 | 26.23 | 16.31 | 24.78 | 5.94 | 5.88 | 0.404 |
| Indispensable amino acids | | | | | | | | |
| Arg | 1.23 | 1.22 | 0.39 | 0.59 | 0.86 | 0.43 | 0.33 | 0.191 |
| His | 0.24 | 0.19 | 0.15 | 0.18 | 0.19 | 0.04 | 0.02 | 0.075 |
| Ile | 0.43[a] | 0.33[ab] | 0.30[b] | 0.30[b] | 0.34 | 0.06 | 0.03 | 0.024 |
| Leu | 0.73[a] | 0.49[b] | 0.47[b] | 0.51[b] | 0.55 | 0.12 | 0.05 | 0.003 |
| Lys | 0.50 | 0.69 | 0.58 | 0.38 | 0.54 | 0.13 | 0.11 | 0.302 |
| Met | 0.11 | 0.08 | 0.09 | 0.09 | 0.09 | 0.01 | 0.01 | 0.166 |
| Phe | 0.43[a] | 0.28[b] | 0.28[b] | 0.30[b] | 0.32 | 0.07 | 0.03 | 0.007 |
| Thr | 0.72 | 0.58 | 0.55 | 0.51 | 0.59 | 0.09 | 0.06 | 0.082 |
| Trp | 0.18[a] | 0.11[b] | 0.10[b] | 0.11[b] | 0.13 | 0.04 | 0.01 | < 0.001 |
| Val | 0.74[a] | 0.46[b] | 0.42[b] | 0.51[b] | 0.53 | 0.14 | 0.04 | < 0.001 |
| Total, indispensable amino acids | 5.31 | 4.43 | 3.32 | 3.48 | 4.13 | 0.92 | 0.56 | 0.069 |
| Dispensable AA | | | | | | | | |
| Ala | 1.00 | 0.85 | 0.54 | 0.58 | 0.74 | 0.22 | 0.18 | 0.251 |
| Asp | 1.10[a] | 0.83[ab] | 0.66[b] | 0.77[b] | 0.84 | 0.19 | 0.08 | 0.007 |
| Cys | 0.23[a] | 0.16[b] | 0.18[ab] | 0.19[ab] | 0.19 | 0.03 | 0.02 | 0.033 |
| Glu | 1.31[a] | 0.98[ab] | 0.82[b] | 0.91[ab] | 1.01 | 0.21 | 0.11 | 0.026 |
| Gly | 3.05 | 2.74 | 0.97 | 1.68 | 2.11 | 0.96 | 0.59 | 0.081 |
| Pro | 12.35 | 12.95 | 2.58 | 6.01 | 8.47 | 5.03 | 3.59 | 0.161 |
| Ser | 0.69[a] | 0.59[ab] | 0.42[b] | 0.46[ab] | 0.54 | 0.12 | 0.06 | 0.032 |
| Tyr | 0.39[a] | 0.26[b] | 0.25[b] | 0.26[b] | 0.29 | 0.07 | 0.02 | 0.002 |
| Total dispensable amino acids | 20.11 | 19.37 | 6.42 | 10.86 | 14.19 | 6.67 | 4.52 | 0.127 |
| Total, all amino acids | 25.80 | 24.13 | 10.39 | 14.62 | 18.74 | 7.43 | 5.02 | 0.123 |

[1]A = University of Illinois; B = Purdue University; C = University of Minnesota; and D = University of Kentucky.
[a,b]Means within a row lacking a common superscript letter are different ($P < 0.05$).

from 60.4% to 81.8%. This range overlaps with the average SID of indispensable AA (78.5% and 69.1%) reported by Almeida et al. (2011) and Casas et al. (2018), whereas Casas et al. (2015) reported an average SID for indispensable AA of 86.8%. This relatively large range among values for the SID of indispensable AA in bakery meal indicates that it may be better to use an average value for SID of AA for bakery meal rather than using values from individual sources, unless the digestibility of the particular source used is known. The range for the average SID of indispensable AA in bakery meal obtained in this experiment is also much greater than what has been observed for other ingredients where the SID of AA in at least 10 sources of the same ingredient was determined [i.e., distillers dried grains with solubles (Stein et al., 2006; Kim et al., 2012); 00-rapeseed meal (Maison and Stein, 2014); soybean meal (Sotak-Peper et al., 2017); and wheat middlings (Casas and Stein, 2017)]. Likewise, the range among the 11 sources of bakery meal in SID for most of the individual AA was approximately 20 percentage units, which is also a greater range than what has been observed for other ingredients. These variations indicate that whereas producers of bakery meal appear to be efficient in blending different product streams to produce final products that have fairly constant chemical composition, the digestibility of AA is not constant among sources, which likely reflects different raw materials used in the blends. It is, however, also possible that differences in processing procedures, either by the producers of the bakery meal or the producers of the raw materials going into the bakery meal, may contribute to the differences in SID of AA that were observed.

For individual AA, the lowest SID was observed for Lys in all sources of bakery meal, which is in agreement with reported data (Almeida et al., 2011; Casas et al, 2015; 2018). This observation reflects that many of the ingredients used in bakery meal are heat processed in preparation for their primary use, which may have produced damage that reduced the digestibility of Lys, because overheating of an ingredient results in reduced digestibility of Lys (Almeida et al., 2013). Indeed, the digestibility of Lys in breakfast cereals is extremely low (Rutherfurd et al., 2015; Fanelli et al., 2021), and if breakfast cereals were included in some of the bakery meals used in the experiment, this may explain the low digestibility of Lys.

With the exception of one source of bakery meal, Thr had the second lowest SID value in all sources of bakery meal (after Lys). It is expected that Thr always has the lowest SID among indispensable AA due to the large concentration of Thr in mucin proteins, which make up the largest part of the endogenous AA. Indeed, pigs fed diets that result in increased losses of mucin, such as high fiber diets or diets that induce an immune system stimulation, have increased needs for Thr to compensate for the losses of Thr in mucin (Mathai et al.,

**Table 6.** Standardized ileal digestibility of crude protein and amino acids (AA) in 11 sources of bakery meal[1]

| Item | Bakery meal | | | | | | | | | | | Mean | SD | Diet[2] | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G | H | I | J | K | | | SEM | *P*-value |
| Observation, *n* | 18 | 20 | 20 | 19 | 18 | 17 | 17 | 21 | 19 | 19 | 21 | — | — | — | — |
| Crude protein | $69.7^{cd}$ | $82.1^{a}$ | $80.8^{ab}$ | $70.6^{cd}$ | $77.4^{abc}$ | $71.7^{bcd}$ | $83.7^{a}$ | $84.5^{a}$ | $57.9^{e}$ | $64.2^{de}$ | $79.9^{ab}$ | 74.79 | 8.63 | 3.47 | <0.001 |
| Indispensable AA | | | | | | | | | | | | | | | |
| Arg | $78.7^{cd}$ | $88.1^{a}$ | $85.6^{abc}$ | $84.8^{abc}$ | $87.0^{ab}$ | $79.3^{bcd}$ | $88.0^{a}$ | $87.6^{a}$ | $76.0^{d}$ | $74.4^{d}$ | $87.0^{ab}$ | 83.32 | 5.17 | 2.64 | <0.001 |
| His | $71.1^{de}$ | $82.1^{ab}$ | $76.8^{abcd}$ | $76.5^{bcd}$ | $79.1^{abc}$ | $73.3^{cd}$ | $83.0^{a}$ | $82.6^{ab}$ | $63.5^{f}$ | $66.5^{ef}$ | $80.9^{ab}$ | 75.95 | 6.66 | 1.44 | <0.001 |
| Ile | $67.2^{cd}$ | $81.0^{a}$ | $76.6^{ab}$ | $71.2^{bc}$ | $75.2^{ab}$ | $71.6^{bc}$ | $82.1^{a}$ | $81.3^{a}$ | $57.8^{e}$ | $60.7^{de}$ | $77.0^{ab}$ | 72.87 | 8.19 | 1.59 | <0.001 |
| Leu | $72.2^{c}$ | $83.6^{a}$ | $79.2^{abc}$ | $76.0^{bc}$ | $79.7^{ab}$ | $75.6^{bc}$ | $85.5^{a}$ | $84.8^{a}$ | $61.4^{d}$ | $61.3^{d}$ | $80.7^{ab}$ | 76.38 | 8.44 | 1.52 | <0.001 |
| Lys | $48.2^{cde}$ | $53.2^{bcde}$ | $63.5^{ab}$ | $53.9^{bcde}$ | $61.1^{abcd}$ | $58.0^{abcd}$ | $61.9^{abc}$ | $63.3^{ab}$ | $43.2^{e}$ | $48.2^{de}$ | $67.2^{a}$ | 56.53 | 7.70 | 4.25 | <0.001 |
| Met | $75.2^{de}$ | $82.0^{abc}$ | $78.2^{bcde}$ | $77.1^{cde}$ | $80.3^{abcd}$ | $73.8^{e}$ | $84.3^{a}$ | $83.9^{ab}$ | $64.2^{f}$ | $62.3^{f}$ | $82.0^{abc}$ | 76.66 | 7.45 | 1.25 | <0.001 |
| Phe | $72.9^{cd}$ | $84.2^{a}$ | $80.1^{ab}$ | $76.6^{bc}$ | $79.4^{ab}$ | $75.7^{bc}$ | $85.9^{a}$ | $85.6^{a}$ | $65.1^{e}$ | $66.5^{de}$ | $80.6^{ab}$ | 77.51 | 7.08 | 1.34 | <0.001 |
| Thr | $59.3^{cd}$ | $76.3^{a}$ | $72.0^{ab}$ | $64.2^{bcd}$ | $72.0^{ab}$ | $64.6^{bc}$ | $77.5^{a}$ | $76.9^{a}$ | $53.1^{d}$ | $56.0^{cd}$ | $75.8^{a}$ | 67.97 | 8.94 | 2.74 | <0.001 |
| Trp | $74.7^{bcd}$ | $85.2^{a}$ | $73.9^{cd}$ | $74.4^{bcd}$ | $74.4^{bcd}$ | $74.2^{bcd}$ | $84.6^{ab}$ | $86.5^{a}$ | $53.7^{e}$ | $66.9^{d}$ | $79.7^{abc}$ | 75.30 | 9.33 | 3.12 | <0.001 |
| Val | $65.6^{cd}$ | $78.5^{ab}$ | $74.9^{abc}$ | $69.7^{bc}$ | $73.9^{abc}$ | $69.2^{bc}$ | $79.6^{a}$ | $79.3^{a}$ | $56.7^{d}$ | $57.3^{d}$ | $76.2^{ab}$ | 70.99 | 8.22 | 2.05 | <0.001 |
| Mean | $68.1^{de}$ | $80.0^{ab}$ | $77.3^{abc}$ | $72.9^{bcd}$ | $76.8^{abc}$ | $72.0^{cd}$ | $81.8^{a}$ | $81.5^{a}$ | $60.4^{f}$ | $61.5^{ef}$ | $78.7^{abc}$ | 73.72 | 7.58 | 1.60 | <0.001 |
| Dispensable AA | | | | | | | | | | | | | | | |
| Ala | $62.1^{cd}$ | $74.8^{ab}$ | $72.5^{ab}$ | $68.3^{abc}$ | $73.0^{ab}$ | $66.1^{bcd}$ | $77.7^{a}$ | $77.2^{a}$ | $56.5^{d}$ | $56.9^{d}$ | $75.9^{ab}$ | 69.19 | 7.82 | 2.14 | <0.001 |
| Asp | $59.2^{d}$ | $72.7^{ab}$ | $70.7^{abc}$ | $65.3^{bcd}$ | $71.2^{abc}$ | $63.5^{cd}$ | $75.1^{a}$ | $72.8^{ab}$ | $50.0^{e}$ | $56.4^{de}$ | $73.1^{ab}$ | 66.36 | 8.20 | 1.93 | <0.001 |
| Cys | $66.4^{b}$ | $78.0^{a}$ | $69.7^{ab}$ | $69.8^{ab}$ | $71.6^{ab}$ | $70.3^{ab}$ | $79.7^{a}$ | $78.8^{a}$ | $42.9^{c}$ | $52.3^{c}$ | $69.7^{ab}$ | 68.11 | 11.24 | 2.56 | <0.001 |
| Glu | $82.5^{b}$ | $90.0^{a}$ | $86.6^{ab}$ | $84.3^{b}$ | $84.2^{b}$ | $83.9^{b}$ | $90.8^{a}$ | $91.1^{a}$ | $68.3^{d}$ | $74.5^{c}$ | $84.9^{b}$ | 83.73 | 6.91 | 0.99 | <0.001 |
| Gly | $65.7^{bcd}$ | $81.3^{ab}$ | $81.3^{ab}$ | $64.2^{bcde}$ | $79.1^{abc}$ | $61.0^{cde}$ | $81.7^{ab}$ | $87.2^{a}$ | $45.6^{e}$ | $58.3^{de}$ | $79.7^{abc}$ | 71.37 | 13.08 | 6.19 | <0.001 |
| Pro | $100.7^{a}$ | $114.3^{a}$ | $118.8^{a}$ | $91.7^{a}$ | $120.8^{a}$ | $74.8^{a}$ | $106.7^{a}$ | $112.8^{a}$ | $81.2^{a}$ | $87.7^{a}$ | $111.9^{a}$ | 101.94 | 15.83 | 19.41 | 0.155 |
| Ser | $68.6^{c}$ | $82.4^{a}$ | $78.0^{ab}$ | $72.2^{bc}$ | $77.5^{ab}$ | $74.3^{bc}$ | $83.5^{a}$ | $83.7^{a}$ | $58.4^{d}$ | $60.0^{d}$ | $77.3^{ab}$ | 74.16 | 8.75 | 1.70 | <0.001 |
| Tyr | $66.4^{e}$ | $80.2^{bc}$ | $72.2^{de}$ | $72.0^{de}$ | $78.0^{cd}$ | $66.7^{e}$ | $83.0^{bc}$ | $83.2^{bc}$ | $86.1^{ab}$ | $91.2^{a}$ | $79.6^{c}$ | 78.05 | 7.96 | 1.45 | <0.001 |
| Mean | $77.2^{bcd}$ | $88.6^{a}$ | $85.5^{abc}$ | $77.8^{bcd}$ | $84.7^{abc}$ | $75.0^{cde}$ | $88.4^{ab}$ | $90.5^{a}$ | $64.4^{e}$ | $72.0^{de}$ | $83.9^{abc}$ | 80.74 | 8.14 | 3.24 | <0.001 |
| Mean, all AA | $73.6^{de}$ | $85.0^{a}$ | $82.0^{ab}$ | $75.6^{bcd}$ | $80.9^{abcd}$ | $73.7^{cde}$ | $85.6^{a}$ | $86.9^{a}$ | $62.4^{f}$ | $67.5^{ef}$ | $81.4^{abc}$ | 77.70 | 7.86 | 2.25 | <0.001 |

[1]Values for standardized ileal digestibility were calculated by correcting the values for apparent ileal digestibility with corresponding values for the basal ileal endogenous losses that were determined at each experiment station.
[2]Effect of source of bakery meal.
[a,b,c,d,e,f]Means within a row lacking a common superscript letter are different ($P < 0.05$).

**Table 7.** Correlation coefficients (*r*) between Lys to crude protein ratio and ileal digestibility of Lys or ileal digestible Lys in bakery meal fed to growing pigs (*n* = 11)

| Item | Lys to crude protein ratio | *P*-value |
|---|---|---|
| Apparent ileal digestibility (%) of Lys | 0.397 | 0.227 |
| Apparent ileal digestible Lys, % of diet | 0.720 | 0.012 |
| Standardized ileal digestibility (%) of Lys | 0.237 | 0.483 |
| Standardized ileal digestible Lys, % of diet | 0.727 | 0.011 |

2016; Wellington et al., 2018, 2019). The observation that the SID of Lys in all sources of bakery meal used in this experiment was less than the SID of Thr further indicates that the SID of Lys was reduced in these products, possibly due to heat damage.

The observation that there were differences among experiment stations for endogenous losses of some of the indispensable AA is in agreement with previous data (Stein et al., 2007). Whereas the reasons for the differences among experiments in basal endogenous losses of AA remain to be elucidated, the current data support the recommendation that basal endogenous losses should be determined in each experiment in which SID of AA is determined (Stein et al., 2007; NRC, 2012).

Calculation of the Lys to crude protein ratio is often used as an indication of heat damage in a feed ingredient because a lower ratio is an indication of overheating and damage to Lys (González-Vega et al., 2011). The Lys to crude protein ratios that were calculated for the 11 sources of bakery meal used in this experiment varied from 2.83 to 4.17. However, the lack of a correlation between the Lys to crude protein ratio and the SID of Lys indicates that this ratio cannot be used to indicate heat damage in bakery meal, which is likely because different raw materials with different Lys to crude protein ratios were used in the different meals. As an example, if soybean-based ingredients, which have high concentrations of Lys relative to crude protein, are included in the blend, the concentration of Lys in the resulting bakery meal will be high and the Lys to crude protein ratio will be high as well. However, if other ingredients are used in the product stream of bakery meal, a different Lys to crude protein ratio will be expected. As a consequence, the Lys to crude protein ratio in bakery meal cannot be used as an indicator of heat damage as is the case for homogenous ingredients.

## Conclusions

The SID of AA in 11 sources of bakery meal collected in swine-producing states in the United States indicated that Lys has the lowest SID of all AA, which is most likely due to heat damage in some of the ingredients used to manufacture the bakery meals. It was further demonstrated that there is much more variability in the SID of individual AA in bakery meal than what is commonly observed for other ingredients, which is likely due to different raw materials being used in the production of the different sources of bakery meal. It, therefore, appears that although manufacturers of bakery meal are effective in producing products with constant chemical compositions, they are less effective in producing final products with constant AA digestibility. The relatively large variations in the SID of AA among sources of bakery meal and the low SID of Lys indicates that users of bakery meals may want to limit the inclusion rate of bakery meal in diets fed to pigs. Additionally, it is important that diets are balanced for digestible AA and that the low digestibility of Lys in bakery meal is compensated by inclusion of other sources of Lys in the diets.

## Acknowledgments

Donation of the 11 sources of bakery meal from the vendors of the products is greatly appreciated. Project management and statistical analysis by Dr. Su A Lee (University of Illinois, Urbana-Champaign, IL, USA) are also greatly appreciated.

## Conflict of Interest Statement

The authors have no conflicts of interest.

## Other members of the NCCC-42 committee

M. J. Azain, University of Georgia, Athens, GA, USA; S. D. Carter, Oklahoma State University, Stillwater, OK, USA; T. D. Crenshaw, University of Wisconsin, Madison, WI, USA; R. Dilger, University of Illinois, Urbana-Champaign, IL, USA; G. M. Hill, Michigan State University, East Lansing, MI, USA; R. Jha, University of Hawaii at Manoa, Honolulu, HI, USA; B. J. Kerr, ARS-USDA, Ames, IA, USA; S. W. Kim, North Carolina State University, Raleigh, NC, USA; S. Liao, Mississippi State University Starkville, MS, USA; Y. Liu, University of California, Davis, CA, USA; P. S. Miller, University Nebraska, Lincoln, NE, USA; J. L. Nelssen, Kansas State University, Manhattan, KS, USA; J. F. Patience, Iowa State University, Ames, IA, USA; M. S. Shannon, University of Missouri, Columbus, MO, USA; T. Woyengo, South Dakota State University, Brookings, SD, USA. Administrative Advisor: D. Beitz, Iowa State University, Ames, IA, USA.

M. J. Azain, University of Georgia, Athens, GA, USA; S. D. Carter, Oklahoma State University, Stillwater, OK, USA; T. D. Crenshaw, University of Wisconsin, Madison, WI, USA; R. Dilger, University of Illinois, Urbana-Champaign, IL, USA; G. M. Hill, Michigan State University, East Lansing, MI, USA; R. Jha, University of Hawaii at Manoa, Honolulu, HI, USA; B. J. Kerr, ARS-USDA, Ames, IA, USA; S. W. Kim, North Carolina State University, Raleigh, NC, USA; S. Liao, Mississippi State University Starkville, MS, USA; Y. Liu, University of California, Davis, CA, USA; P. S. Miller, University Nebraska, Lincoln, NE, USA; J. L. Nelssen, Kansas State University, Manhattan, KS, USA; J. F. Patience, Iowa State University, Ames, IA, USA; M. S. Shannon, University of Missouri, Columbus, MO, USA; T. Woyengo, South Dakota State University, Brookings, SD, USA. Administrative Advisor: D. Beitz, Iowa State University, Ames, IA, USA.

## Literature Cited

Almeida, F. N., G. I. Petersen, and H. H. Stein. 2011. Digestibility of amino acids in corn, corn co-products and bakery meal fed to growing pigs. *J. Anim. Sci.* 89:4109–4115. doi:10.2527/jas.2011-4143.

Almeida, F. N., J. K. Htoo, J. Thomson, and H. H. Stein. 2013. Amino acid digestibility of heat damaged distillers dried grains with solubles fed to pigs. *J. Anim. Sci. Biotechnol.* 4:44. doi:10.1186/2049-1891-4-44.

AOAC Int. 2007. *Official methods of analysis of AOAC Int*. 18th ed. Rev. 2nd ed.Gaithersburg, MD: AOAC Int.

Casas, G. A., and H. H. Stein. 2017. The ileal digestibility of most amino acids is greater in red dog than in wheat middlings when fed to growing pigs. *J. Anim. Sci*. 95:2718–2725. doi:10.2527/jas.2017.1515.

Casas, G. A., J. A. S. Almeida, and H. H. Stein. 2015. Amino acid digestibility in rice co-products fed to growing pigs. *Anim. Feed Sci. Technol*. 207:150–158. doi:10.1016/j.anifeedsci.2015.05.024.

Casas, G. A., N. W. Jaworski, J. K. Htoo, and H. H. Stein. 2018. Ileal digestibility of amino acids in selected feed ingredients fed to young growing pigs. *J. Anim. Sci*. 96:2361–2370. doi:10.1093/jas/sky114.

Fanelli, N. S., H. M. Bailey, and H. H. Stein. 2021. Values for digestible indispensable amino acid score (DIAAS) determined in pigs are greater for milk than for breakfast cereals, but DIAAS values for individual ingredients are additive in combined meals including both breakfast cereals and milk. *J. Nutr*. 151:540–547. doi:10.1093/jn/nxaa398.

Fung, L., P. E. Urriola, L. Baker, and G. C. Shurson. 2019a. Estimated energy and nutrient composition of different sources of food waste and their potential for use in sustainable swine feeding programs. *Transl. Anim. Sci*. 3:143–152. doi:10.1093/tas/txy099.

Fung, L., P. E. Urriola, L. Baker, and G. C. Shurson. 2019b. Energy, amino acid, and phosphorus digestibility and energy prediction of thermally processed food waste sources for swine. *Transl. Anim. Sci*. 3:676–691. doi:10.1093/tas/txz028.

González-Vega, J. C., B. G. Kim, J. K. Htoo, A. Lemme, and H. H. Stein. 2011. Amino acid digestibility in heated soybean meal fed to growing pigs. *J. Anim. Sci*. 89:3617–3625. doi:10.2527/jas.2010-3465.

Jinno, C., Y. He, D. Morash, E. McNamara, S. Zicari, A. King, H. H. Stein, and Y. Liu. 2018. Enzymatic digestion turns food waste into feed for growing pigs. *Anim. Feed Sci. Technol*. 242:48–58. doi:10.1016/j.anifeedsci.2018.05.006.

Kim, B. G., D. Y. Kil, Y. Zhang, and H. H. Stein. 2012. Concentrations of analyzed or reactive lysine, but not crude protein, may predict the concentration of digestible lysine in distillers dried grains with solubles fed to pigs. *J. Anim. Sci*. 90:3798–3808. doi:10.2527/jas.2011-4692.

Lee, S. A., L. Blavi, D. M. D. L. Navarro, and H. H. Stein. 2021. Addition of hydrogen chloride to collection bags or collection containers did not change basal endogenous losses or ileal digestibility of amino acid in corn, soybean meal, or wheat middlings fed to growing pigs. *Anim. Biosci*. 34:1632–1642. doi:10.5713/ab.20.0838.

Liu, Y., R. Jha, and H. H. Stein; North Central Coordinating Committee on Swine Nutrition (NCCC-42). 2018. Nutritional composition, gross energy concentration, and in vitro digestibility of dry matter in 46 sources of bakery meals. *J. Anim. Sci*. 96:4685–4692. doi:10.1093/jas/sky310.

Luiciano, A., C. D. Espinosa, L. Pinotti, and H. H. Stein. 2022. Standardized total tract digestibility of phosphorus in bakery meal fed to pigs and effects of bakery meal on growth performance of weanling pigs. *Anim. Feed Sci. Technol*. 284:115148. doi: 10.1016/j.anifeedsci.2021.115148.

Maison, T., and H. H. Stein. 2014. Digestibility by growing pigs of amino acids in canola meal from North America and 00-rapeseed meal and 00-rapeseed expellers from Europe. *J. Anim. Sci*. 92:3502–3514. doi:10.2527/jas.2014-7748.

Mathai, J. K., J. K. Htoo, J. Thomson, K. J. Touchette, and H. H. Stein. 2016. Effects of dietary fiber on the ideal standardized ileal digestible threonine:lysine ratio for 25 to 50 kg growing gilts. *J. Anim. Sci*. 94:4217–4230. doi: 10.2527/jas.2016-0680.

Myers, W. D., P. A. Ludden, V. Nayigihugu, and B. W. Hess. 2004. Technical note: a procedure for the preparation and quantitative analysis of samples for titanium dioxide. *J. Anim. Sci*. 82:179–183. doi:10.2527/2004.821179x.

NRC. 2012. *Nutrient requirements of swine*. 11th rev. ed. Natl. Acad. Press, Washington, DC. doi:10.17226/13298

Rutherfurd, S. M., A. C. Fanning, B. J. Miller, and P. J. Moughan. 2015. Protein digestibility-corrected amino acid scores and digestible indispensable amino acid scores differentially describe protein quality in growing male rats. *J. Nutr*. 145:372–379. doi:10.3945/jn.114.195438.

Sandström, V., A. Chrysafi, M. Lamminen, M. Troell, M. Jalava, J. Piipponen, S. Siebert, O. van Hal, V. Virkki, and M. Kummu. 2022. Food system by-products upcycled in livestock and aquaculture feeds can increase global food supply. *Nat. Food*. 3:729–740. doi:10.1038/s43016-022-00589-6.

Shurson, G. C. 2020. What a waste - Can we improve sustainability of food animal production systems by recycling food waste streams into animal feed in an era of health, climate and economic crises? *Sustainability*. 12:7071. doi:10.3390/su12177071.

Slominski, B. A., D. Boros, L. D. Campbell, W. Guenter, and O. Jones. 2004. Wheat by-products in poultry nutrition. Part I. Chemical and nutritive composition of wheat screenings, bakery by-products and wheat mill run. *Can. J. Anim. Sci*. 84:421–428. doi:10.4141/a03-112.

Sotak-Peper, K. M., J. C. Gonzalez-Vega, and H. H. Stein. 2017. Amino acid digestibility in soybean meal sourced from different regions of the United States and fed to pigs. *J. Anim. Sci*. 95:771–778. doi:10.2527/jas.2016.0443.

Stein, H. H., C. Pedersen, M. L. Gibson, and M. G. Boersma. 2006. Amino acid and energy digestibility in ten samples of distillers dried grain with solubles by growing pigs. *J. Anim. Sci*. 84:853–860. doi:10.2527/2006.844853x.

Stein, H. H., B. Sève, M. F. Fuller, P. J. Moughan, and C. F. M. de Lange; Committee on Terminology to Report AA Bioavailability and Digestibility. 2007. Invited review: amino acid bioavailability and digestibility in pig feed ingredients: terminology and application. *J. Anim. Sci*. 85:172–180. doi:10.2527/jas.2005-742.

Tretola, M., M. Ottoboni, A. R. Di Rosa, C. Giromini, E. Fusi, R. Rebucci, F. Leone, V. Dell'Orto, V. Chiofalo, and L. Pinotti. 2017. Review article. Former food products safety evaluation: computer vision as an innovative approach for the packaging remnants detection. *J. Food Qual*. 1064580:1–6. doi:10.1155/2017/1064580.

Tretola, M., A. Luciano, M. Ottoboni, A. Baldi, and L. Pinotti. 2019a. Influence of traditional vs alternative dietary carbohydrates sources on the large intestinal microbiota in post-weaning piglets. *Animals*. 9:516. doi:10.3390/ani9080516.

Tretola, M., M. Ottoboni, A. Luciano, L. Rossi, A. Baldi, and L. Pinotti. 2019b. Former food products have no detrimental effects on diet digestibility, growth performance and selected plasma variables in post-weaning piglets. *Ital. J. Anim. Sci*. 18:987–996. doi:10.1080/1828051x.2019.1607784.

Wellington, M. O., J. K. Htoo, A. G. van Kessel, and D. A. Columbus. 2018. Impact of dietary fiber and immune system stimulation on threonine requirement for protein deposition in growing pigs. *J. Anim. Sci*. 96:5222–5232. doi:10.1093/jas/sky381.

Wellington, M. O., A. K. Agyekum, K. Hamonic, J. K. Htoo, A. G. van Kessel, and D. A. Columbus. 2019. Effect of supplemental threonine above requirement on growth performance of *Salmonella typhimurium* challenged pigs fed high-fiber diets. *J. Anim. Sci*. 97:3636–3647. doi:10.1093/jas/skz225.