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Amino acid composition and digestible amino acid content in animal protein by-product meals fed to growing pigs[1]

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Abstract

An industry survey and animal experiment were conducted to evaluate the amino acid (AA) compositional variability and standardized ileal digestibility (SID) of AA in animal protein by-products fed to growing pigs. Animal protein by-product meals (212) were categorized into 8 groupings (blood meal, chicken by-product meal, chicken meal, feather meal, meat and bone meal, meat meal, poultry by-product meal, and poultry meal) and analyzed for total AA. Amino acid analysis among (e.g., Lys in blood meal averaged 9.20% compared with 2.31% for feather meal, DM basis) and within (e.g., Lys range of 1.54% in blood meal and 1.44% in feather meal, DM basis) the by-product classifications varied as expected, but on average the total AA values were similar to that reported in the literature. For the determination of the SID of AA, 15 barrows (average initial and final BW of 31.6 and 78.7 kg, respectively) were fitted with a T-cannula in the distal ileum and allotted to 15 diets over nine 7-d periods, resulting in 9 replications per diet. Pigs were fed a basal diet based on soybean meal and dehulled-degermed corn, 13 diets containing 17.5% animal protein by-product meal to partially replace a portion of the soybean meal and dehulled-degermed corn in the basal diet, or a N-free diet. Pigs were re-allotted to diets based on minimizing the number to times that the N-free diet would precede or follow feeding either of the blood or feather meal diets because of concern with inadequate diet consumption, as well as to prevent diets from being re-fed to the same pig during the next or subsequent periods. Values for the apparent ileal AA digestibility of each diet were determined, adjusted to SID based upon the endogenous AA losses determined by feeding the N-free diet, and the SID of AA in each animal protein by-product meal calculated using the difference procedure. The SID of AA varied among (e.g., SID of Lys averaged 91% in chicken meal but 47% in feather meal) and within (e.g., SID of Lys in three meat and bone meals was 80%, 71%, and 54%) the animal protein by-product meals, as would be expected and are consistent with variation reported in the literature. Overall, the data provide total AA composition for 212 samples and SID of AA for 13 samples of animal protein by-product meals, including data on their variability, which is critical for their use in feed formulation programs.

Key words: amino acids, animal protein by-products, growing pigs, standardized ileal amino acid digestibility

Introduction

Rendered animal by-products contain a variety of inedible carcass tissues including blood, feathers, muscle, bones, fat, and offal, with over 20 million tonnes of these raw animal components being processed into various protein, fat, and mineral by-products annually (Garcia et al., 2006; NRA, 2006). Ultimately, about 4 million tonnes of animal-derived protein by-products are produced annually, with about 85% utilized as animal feed ingredients (ERS, 2011) to enhance the environmental and economical sustainability of food production (Informa, 2011; Gooding, 2012). Animal protein by-products are concentrated sources of energy, amino acids (AA), and minerals (NRC, 2012), and can provide substantial amounts of energy and nutrients to pigs and reduce diet cost depending upon their price relative to competing ingredients. Although determining the AA digestibility of animal protein by-product meals is not a new concept (Jorgensen et al., 1984; Moughan and Smith, 1985; Batterham et al., 1986a, 1986b), the rendering process continues to evolve (NRA, 2006) and the nutrient profile among sources of each type of by-product can be highly variable. This suggests that additional information on AA composition and ileal AA digestibility is necessary when developing precision nutrition feeding programs for swine. In a literature review, the Committee on the Nutrient Requirement of Swine (NRC, 2012) shows that data on the AA composition of meat and bone meal are most prevalent, with limited published data available for other animal protein by-product meals. Therefore, the objectives of this study were to determine the total concentrations of AA among sources and types of animal protein by-products, and to determine the apparent ileal digestibility (**AID**) and subsequent standardized ileal digestibility (**SID**) of selected sources of animal protein by-product meals in growing pigs.

Materials and Methods

The Institutional Animal Care and Use Committee at Iowa State University (Ames, IA) approved the animal experimental protocol.

Sample Collection

Samples of a variety of animal protein by-products representing different geographical locations and animal rendering facilities were collected and previously analyzed for GE, proximate, and biogenic amines (Kerr et al., 2017). These samples were further analyzed for 11 AA using near infrared spectroscopy (Evonik Industries AG, Hanau, Germany). Prior to analysis, samples were organized into 8 by-product categories (Table 1) which included blood meal (n = 26), chicken by-product meal (n = 19), chicken meal (n = 9), feather meal (n = 23), meat and bone meal (n = 97), meat meal (n = 16), poultry by-product meal (n = 16), and poultry meal (n = 6). Dry matter content of each sample was determined as previously described by Kerr et al. (2017).

Apparent Ileal Digestible AA Determination

Source selection and experimental diets

Thirteen sources of animal protein by-product meals were selected based on an expected wide range in AA composition and were the same sources evaluated in a previous energy digestibility experiment (Kerr et al., 2017). For the determination of ileal AA digestibility, 15 separately mixed diets were formulated including a basal diet based on soybean meal and dehulled-degermed corn, 13 diets containing 17.5% animal protein by-product meal to partially replace a portion of the soybean meal and dehulled-degermed corn in the basal diet, and a N-free diet to measure endogenous losses of CP and AA (Table 2). All diets contained titanium dioxide (0.5%) as an indigestible marker, with vitamins and minerals included in all diets to meet requirements (NRC, 2012). A sample from each animal protein by-product meal and diet was collected at the time of diet mixing for subsequent laboratory analysis. The chemical composition of each animal protein by-product meal, the basal diet, and the N-free diet is shown in Table 3.

Animals, housing, experimental design, and diets

To determine apparent ileal AA digestibility, a total of 19 growing barrows (Genetiporc F25 females × B6.0 sires, Hendersonville, TN) with an initial body weight (BW) of 31.6 ± 2.7 kg were used and a cannula was surgically installed at the distal ileum to allow for collection of ileal digesta (Stein et al., 1998). Following surgery, each pig was individually housed in a temperature-controlled room in a pen (1.2 × 1.5 m) with slatted concrete sides and a partially slatted floor and was equipped with a feeder and nipple drinker. After an 8- to 10-d recovery period, 15 barrows were selected and randomly allotted to each of the 15 experimental diets, which were offered in in meal form in an amount equivalent to 3 times the maintenance energy requirement (i.e., 106 kcal ME/kgBW$^{0.75}$; using an average group body weight and an assumed diet ME of 3,400 kcal/kg), and this daily amount of feed was divided into 2 equal meals. The amount of feed provided was recorded daily, and pig weights were recorded at the beginning and end of each of the nine 7-d feeding and collection periods. The initial 5 d of each period was used as a diet adaptation period, and ileal digesta were collected on days 6 and 7 for 8 h following the morning feedings. Ileal digesta was collected into a 225-mL plastic bag which was attached to the cannula barrel using a cable tie, with the bag removed whenever they were filled with digesta or at least every 30 min. Immediately after collection, all samples were stored at −20 °C to avoid bacterial degradation of AA. At the conclusion of the experiment, samples were thawed and mixed within animal, diet, and period, and a subsample was obtained for subsequent analysis. Between each of the 9 feeding periods, pigs were re-allotted to diets based on minimizing the number to times that the N-free diet would precede or follow feeding either of the blood or feather meal diets because of concern with inadequate diet consumption, as well as prevent diets from being re-fed to the same pig during the next or subsequent periods.

Chemical analysis of samples

Ileal digesta samples were oven-dried at 75 °C in a forced air oven for 24 h and ground through a 1-mm screen prior to chemical analysis. Samples of the diets and digesta were analyzed at a commercial laboratory (University of Missouri Agricultural Experimental Station Chemistry Laboratory, Columbia, MO) for DM (Method 934.01; AOAC, 2006), CP (Method 990.03; AOAC, 2006), and AA (Method 982.30 E (a, b, c); AOAC, 2006). Titanium dioxide was analyzed based on the method of Leone (1973), where samples are ashed in an oven and then digested with sulfuric acid and hydrogen peroxide, followed by measuring absorbance using an ultraviolet spectrophotometer against a standard curve.

Calculations and statistical analysis

Values for AID AA, ileal endogenous AA losses, and SID AA were determined for each diet as described elsewhere (Stein et al., 2007; Adeola et al., 2016). Because diets containing the animal protein by-product meals represented the combination of AA

Table 1. Crude protein and amino acid analysis of animal protein by-products, DM basis[1]

	DM	CP	Arg	Cys	His	Ile	Leu	Lys	Met	Phe	Thr	Trp	Val
Blood meal													
Average (n = 26)	90.91	100.72	4.29	0.96	6.70	1.28	12.77	9.20	1.05	6.88	4.05	1.71	8.54
SD	0.98	4.12	0.13	0.21	1.10	0.75	1.29	0.44	0.27	0.41	0.78	0.04	0.96
Lowest	88.52	94.38	3.99	0.59	5.34	0.55	10.99	8.40	0.73	6.21	3.07	1.63	7.16
Highest	92.33	105.89	4.51	1.25	7.99	2.48	14.21	9.94	1.46	7.58	5.15	1.81	9.55
Chicken by-product meal													
Average (*n* = 19)	95.76	67.32	4.33	0.71	1.38	2.51	4.51	3.87	1.28	2.52	2.53	0.66	3.09
SD	0.61	6.17	0.47	0.08	0.17	0.31	0.52	0.60	0.19	0.25	0.29	0.09	0.33
Lowest	94.36	51.16	3.18	0.52	1.05	1.75	3.25	2.60	0.88	1.89	1.80	0.47	2.22
Highest	96.82	72.53	4.74	0.81	1.64	2.78	4.97	4.58	1.48	2.75	2.80	0.75	3.39
Chicken meal													
Average (*n* = 9)	95.48	67.92	4.47	0.51	1.45	2.47	4.38	4.21	1.38	2.44	2.45	0.60	2.88
SD	0.96	2.14	0.15	0.08	0.11	0.17	0.29	0.30	0.09	0.14	0.15	0.06	0.18
Lowest	93.82	65.75	4.31	0.41	1.33	2.26	4.07	3.86	1.28	2.30	2.27	0.53	2.67
Highest	96.64	70.93	4.69	0.64	1.62	2.75	4.89	4.66	1.50	2.68	2.68	0.71	3.19
Feather meal													
Average (*n* = 23)	92.13	92.07	6.26	4.36	1.00	4.36	7.63	2.31	0.65	4.51	4.30	0.66	6.76
SD	1.00	3.20	0.33	0.30	0.32	0.21	0.28	0.43	0.04	0.16	0.14	0.08	0.29
Lowest	90.45	87.98	5.83	3.77	0.70	4.06	7.04	1.90	0.58	4.16	4.05	0.58	6.33
Highest	94.22	97.61	6.81	4.83	1.75	4.74	8.06	3.34	0.74	4.75	4.55	0.87	7.29
Meat and bone meal													
Average (*n* = 97)	94.93	56.93	3.82	0.67	1.14	1.75	3.51	2.98	0.82	2.03	1.93	0.38	2.48
SD	1.02	3.39	0.25	0.05	0.13	0.16	0.25	0.26	0.10	0.14	0.14	0.05	0.16
Lowest	91.90	48.03	3.36	0.53	0.80	1.26	2.77	2.29	0.59	1.61	1.50	0.25	2.02
Highest	97.11	64.77	4.33	0.84	1.44	2.12	4.17	3.60	1.06	2.38	2.30	0.50	2.93
Meat meal													
Average (*n* = 16)	95.85	58.56	3.89	0.69	1.28	1.92	3.76	3.22	0.92	2.15	2.07	0.44	2.63
SD	0.76	3.32	0.26	0.06	0.15	0.15	0.30	0.21	0.08	0.15	0.15	0.04	0.17
Lowest	94.02	52.48	3.39	0.59	1.06	1.58	3.31	2.88	0.75	1.90	1.77	0.37	2.37
Highest	96.83	63.44	4.29	0.80	1.63	2.20	4.39	3.67	1.01	2.46	2.32	0.52	2.98
Poultry by-product meal													
Average (*n* = 16)	95.71	63.52	4.28	0.72	1.11	2.04	3.80	3.26	1.04	2.21	2.15	0.45	2.65
SD	0.45	5.12	0.27	0.13	0.18	0.38	0.61	0.50	0.18	0.31	0.34	0.13	0.41
Lowest	94.44	54.99	3.84	0.49	0.85	1.56	3.14	2.70	0.73	1.86	1.79	0.30	2.25
Highest	96.24	71.45	4.74	0.91	1.35	2.56	4.64	3.97	1.28	2.63	2.63	0.63	3.25
Poultry meal													
Average (*n* = 6)	95.84	67.10	4.48	0.74	1.23	2.27	4.20	3.65	1.18	2.42	2.38	0.52	2.90
SD	0.49	1.67	0.09	0.07	0.10	0.14	0.28	0.23	0.08	0.14	0.13	0.05	0.17
Lowest	94.99	63.78	4.33	0.67	1.07	2.05	3.73	3.31	1.05	2.16	2.14	0.45	2.57
Highest	96.42	68.38	4.60	0.87	1.34	2.42	4.46	3.87	1.26	2.54	2.50	0.59	3.05

[1]Analyzed using near-infrared spectroscopy by Evonik Nutrition & Care GmbH, 63457, Hanau, Germany.

from the basal diet and an animal protein by-product meal, the AID of AA in each source of animal protein by-product meal were calculated using the difference procedure (Fan and Sauer, 1995). Determination of SID AA was accomplished by correcting AID AA digestibility for ileal endogenous AA losses, which was determined from pigs consuming the N-free diet. For the sample survey portion of this study, no data were considered as outliers and the descriptive statistics (i.e., number of observations, mean, SD, maximum and minimum values) are shown in Table 1. For the ileal AA digestibility experiment, the entire data for some animals (i.e., BW, feed intake, and AA digestibility) were removed from the data set if they did not completely consume their daily feed allowance up to the time of collection or on the collection days, exhibited signs of digestive upset (e.g., emesis), or lacked ileal flow. In addition, data were evaluated using Proc UNIVARIATE (SAS Institute, Cary, NC) to determine whether there were outliers, and data point was considered an outlier if the value was more than 2 standard deviations from the mean within a specific AA and animal protein by-product meal.

Results and Discussion

The objectives of this study were to evaluate the total AA composition and SID of AA in a variety of animal protein by-product meals, which can be used to update nutrient profiles of these ingredients for precision swine diet formulation. Although others have reported that AID or SID AA values differ across different soybean by-products (Cervantes-Pahm and Stein, 2010; Lagos and Stein, 2017), corn co-products (Curry et al., 2014; Adeola and Ragland, 2016), or animal protein by-products (Almeida et al., 2013; Rojas and Stein, 2013; Sulabo et al., 2013), as well as being highly variable within each of these different by-products, it should be common knowledge that differences both between and within ingredients exist and, therefore, detailed comparison of the current data with those from previous studies not very instructive. Instead, the data presented herein are intended for updating existing AA composition and SID of AA databases such as NRC (2012) and the National Animal Nutrition Program database (https://animalnutrition.org/). Although it has been debated whether ileal digesta samples should be oven-dried or freeze-dried prior to determining ileal AA concentrations (Wallis and Balnave, 1983; Dale et al., 1985; Olojede et al., 2018; Lagos and Stein, 2019), samples in the current experiment were oven-dried. This was based on 1—no difference in SID of CP due to drying method and no indication of an interaction between drying method and SID of specific AA as reported by Lagos and Stein (2019), which would have suggested differential losses or damage to specific AA depending upon their chemical makeup (e.g., formation of Amadori products), and 2—no difference between oven drying and freeze-drying on apparent ileal AA digestibility as reported by Olojede et al. (2018).

The summary of the total AA composition of the animal protein by-product meals determined from multiple samples in the present survey is shown in Table 1, with a full listing of these data available at the University of Minnesota Conservancy program (http://hdl.handle.net/11299/184114; accessed 19 February 2019). The AA composition of the selected subset of samples evaluated for AA digestibility is shown in Table 3. These values are comparable to compositional values summarized in other publications (Yin et al., 1993; Hendriks et al., 2002; NRC, 2012) as well as recent publications evaluating blood products (Almeida et al., 2013), feather meal (Sulabo et al., 2013), and poultry by-products (Rojas and Stein, 2013). Furthermore, the variation (i.e., standard deviation, low and high values) in AA composition of the animal protein by-product meals used in the present study (Table 1) is comparable to those reported elsewhere (Knabe, 1995; Hendriks et al., 2002; NRC, 2012). The reported variation in AA content in animal protein by-product feed ingredients used in animal feeds is generally no different from other by-products used in swine feed formulation (NRC, 2012). Because of the considerable variation in AA composition among and within animal protein by-products, it is important to report estimates of variation for calculating confidence intervals for these ingredients in databases used in feed formulation software. These estimates are especially useful in feed formulation software programs that allow for input of variability of analysis in feed ingredients into their programming features (i.e., stochastic feed formulation).

Table 2. Composition of experimental diets, as-fed basis

Ingredient, %	Basal	Animal protein by-product meal[1]	N-free
Animal protein by-product meal	0.00	17.50	0.00
Soybean meal	23.57	16.07	0.00
Dehulled-degermed corn	31.43	21.43	0.00
Corn starch	20.00	20.00	67.35
Sucrose	20.00	20.00	20.00
Soybean oil	2.00	2.00	4.00
Cellulose	1.75	1.75	4.00
Monocalcium phosphate	0.00	0.00	2.40
Limestone	0.00	0.00	0.50
Titanium dioxide	0.50	0.50	0.50
Magnesium oxide	0.00	0.00	0.10
Potassium carbonate	0.00	0.00	0.40
Vitamin premix[2]	0.20	0.20	0.20
Trace mineral mix[3]	0.20	0.20	0.20
Sodium chloride	0.35	0.35	0.35
Total	100.00	100.00	100.00

[1]Animal protein by-products included: spray-dried blood meal, chicken by-product meal, chicken meal, feather meal, meat and bone meal, meat meal, poultry by-product meal, and poultry meal.
[2]Provided the following per kilogram of diet: 6,125 IU vitamin A, 700 IU vitamin D_3, 50 IU vitamin E, 30 mg vitamin K, 0.05 mg vitamin B_{12}, 11 mg riboflavin, 56 mg niacin, and 27 mg pantothenic acid.
[3]Provided the following per kilogram of diet: 22 mg Cu (as $CuSO_4$), 220 mg Fe (as $FeSO_4$), 0.4 mg I (as $Ca(IO_3)_2$), 52 mg Mn (as $MnSO_4$), 220 mg Zn (as $ZnSO_4$), and 0.4 mg Se (Na_2SeO_3).

Although it has previously been reported that palatability of some animal protein by-product meals may cause reductions in feed intake (Wahlstsrom and Libal, 1977; Hansen et al., 1993; Kerr et al., 2004a, 2004b), it has been reported that the inclusion of these same feedstuffs at 20% of the diet did not affect feed intake (Kerr et al., 2017). In addition, others (Adedokun and Adeola, 2005, Olukosi and Adeola, 2009; Almeida et al., 2013; Rojas and Stein, 2013; Sulabo et al., 2013; Castilho et al., 2015) have fed similar dietary levels of these animal protein by-product meals and did not observe any reductions in feed intake. Nevertheless, there were a few instances in the current study where pigs adapted slowly to the diets or would appear to consume feed so rapidly that emesis occurred, but this situation was not attributed to a particular diet or specific animal protein by-product classification. In the current study, the end-of-collection BW and average daily feed intake (ADFI) for pig-groups 1 through 9 were 39.2 and 1.39, 42.7 and 1.44, 46.3 and 1.58, 53.1 and 1.67, 55.5 and 1.79, 62.3 and 1.89, 67.1 and 2.04, 71.6 and 2.17, and 78.7 and 2.28 kg, respectively. Although feed consumption of some of the experimental diets was a potential concern, the overall end-of-collection BW (57.3 kg) and ADFI (1.804 kg) were unaffected by diet ($P > 0.10$).

Based on feeding a N-free diet, basal endogenous AA losses were determined to be CP, 17.32; Ala, 0.51; Arg, 0.38; Asp, 0.65; Cys, 0.14; Gly, 1.37; His, 0.09; Ile, 0.26; Leu, 0.39; Lys, 0.19; Met, 0.06; Phe, 0.24; Ser, 0.37; Thr, 0.46; Trp, 0.07; Tyr, 0.17; Val, 0.40, g/kg DM intake. The basal endogenous AA losses determined in the present study were lower than the average of 33 studies reviewed by Adeola et al. (2016), but estimates of endogenous AA can be variable due to differences in experimental conditions used in individual studies, such as pig genotype, intestinal health of the pig, methods of digesta sampling, and analytical procedures (Boisen and Moughan, 1996; Jansman et al., 2002). Because the endogenous AA values were within the range of published values, it appears that the experimental conditions, sample collection, and analytical methods, and subsequent calculation of SID of AA using estimates basal endogenous AA losses used in the current experiment were acceptable.

In commercial feed formulation, AA digestibility values expressed on a SID basis are preferred over an AID basis because the effects of basal endogenous losses are eliminated, and SID values are believed to be additive in mixed diets (Stein et al., 2007; NRC, 2012). As a result, AID values were not reported for the diets or animal protein by-product meals to avoid confusion of the AA digestibility measure that should be used in feed formulation. Lysine, Ile, and Trp are very relevant when formulating diets for swine that include animal protein by-product meals, therefore, only the SID AA coefficients for these AA were compared with the literature. Because the NRC (2012) most likely summarized AA digestibility data up to the year 2010, the current data were compared with this publication along with recent publications evaluating SID of AA for animal protein by-products (Almeida et al., 2013; Rojas and Stein, 2013; Sulabo et al., 2013).

Blood Meal

In the current study, estimates of SID of Lys, Ile, and Trp in blood meal averaged 82%, 69%, and 91% (Table 4), respectively, when compared with 93%, 73%, and 91%, respectively, for blood meal listed the NRC (2012), and 100%, 110%, and 99%, respectively,

Table 3. Crude protein (CP) and amino acid composition (%) of animal protein by-product meals, the basal diet, and the N-free diet fed to growing pigs, DM basis[1]

Item	BM-1	BM-2	CBM	CM	FM-1	FM-2	MB-1	MB-2	MB-3	MM-1	MM-2	PBM	PM	Basal	N-Free
DM	90.25	93.01	98.41	96.24	90.43	94.35	98.48	95.70	97.56	97.92	97.97	98.03	98.48	95.42	95.99
CP	98.33	95.35	69.20	69.52	91.36	86.35	54.04	54.54	59.83	60.29	55.65	58.04	49.26	12.60	0.22
Ala	7.88	6.98	4.36	4.48	4.64	4.15	3.93	3.93	4.07	4.01	3.48	4.07	3.37	0.69	0.01
Arg	4.06	4.54	4.48	4.72	6.06	5.81	3.44	3.53	3.96	3.99	3.80	3.87	3.07	0.91	0.01
Asp	9.98	8.87	5.49	5.70	6.48	5.88	3.99	3.92	4.31	4.45	4.54	3.99	3.26	1.47	0.03
Cys	1.13	1.31	0.76	0.64	5.04	4.29	0.45	0.44	0.62	0.61	0.57	0.47	0.50	0.22	0.00
Glu	8.78	8.73	8.59	9.13	9.51	8.64	6.39	6.41	6.96	7.28	7.52	6.49	5.30	2.60	0.03
Gly	4.01	3.70	5.95	6.14	6.27	5.99	6.36	6.80	6.99	6.74	4.52	7.71	6.04	0.58	0.01
His	5.94	5.30	1.40	1.74	1.45	1.23	1.12	1.00	1.15	1.22	1.40	0.87	0.75	0.36	0.00
Ile	0.92	2.70	2.82	2.85	4.32	4.18	1.76	1.65	1.80	1.92	2.20	1.79	1.39	0.66	0.01
Leu	12.39	10.50	4.76	4.72	7.79	7.24	3.33	3.21	3.57	3.71	3.87	3.02	2.66	1.23	0.02
Lys	9.24	8.18	4.33	4.82	3.01	2.65	3.33	2.87	3.21	3.32	3.33	2.96	2.59	0.81	0.02
Met	1.39	1.26	1.38	1.52	0.77	0.68	0.86	0.74	0.86	0.90	0.97	0.95	0.65	0.19	0.01
Phe	7.25	6.01	2.67	2.59	4.56	4.37	1.89	1.83	2.00	2.03	2.18	1.83	1.51	0.73	0.01
Pro	3.67	3.49	3.67	3.84	7.40	7.31	3.72	3.88	4.15	4.07	3.04	4.28	3.50	0.84	0.03
Ser	4.48	3.86	2.32	2.22	7.69	7.50	1.74	1.76	2.11	2.05	1.84	1.76	1.61	0.63	0.01
Thr	4.83	4.47	2.59	2.62	4.21	3.93	1.77	1.73	1.94	1.95	2.01	1.73	1.43	0.54	0.01
Trp	1.71	1.64	0.71	0.74	0.54	0.64	0.44	0.40	0.45	0.47	0.49	0.38	0.36	0.18	0.00
Tyr	3.09	3.11	2.34	1.60	2.69	2.64	1.39	1.32	1.57	1.61	1.88	1.33	1.16	0.43	0.01
Val	8.95	7.31	3.45	3.20	7.18	6.75	2.47	2.30	2.57	2.65	2.72	2.12	1.99	0.70	0.00

[1]Analyzed at the University of Missouri Agricultural Experiment Station Chemical Laboratories, Columbia, MO. Abbreviations: BM, spray-dried blood meal; CBM, chicken by-product meal; CM, chicken meal; FM, feather meal; MB, meat and bone meal; MM, meat meal; PBM, poultry by-product meal; PM, poultry meal.

for spray-dried animal blood reported by Almeida et al. (2013). In contrast, the current values were similar for SID of Lys but greater for SID of Ile and Trp (79%, 49%, and 77%, respectively) for porcine blood meal reported by Almeida et al. (2013).

Chicken and Poultry Meals

According to AAFCO (2015), the main differences between chicken or poultry "meals" and "by-product meals" are that "meals" are mainly comprised of skin and flesh, with or without bones, whereas feet, legs, beaks, and intestinal contents may be included in "by-product" meals. In the current study, poultry-based by-products were classified into four separate by-product types based on the description provided by the sources of each ingredient. Although it may initially appear that these poultry by-product meals are similar and it would be more convenient and simpler to determine averages of AA composition for chicken meal, poultry meal, chicken by-product meal, and poultry by-product meal, the "chicken" by-products evaluated in the current experiment contained greater CP and less ash content than the "poultry" by-products as reported by Kerr et al. (2017). Thus, the AA composition data of each type of these by-products were reported rather than combining them to determine an overall average. This approach is supported by the differences in SID of AA among these types of by-products, especially between chicken and poultry meal (Table 4).

The NRC (2012) does not provide SID of AA for chicken meal or chicken by-product meal. Therefore, the only values available to compare with were values reported by Rojas and Stein (2013). In the current study, chicken meal had a greater SID of Lys, Ile, and Trp of 91%, 90%, and 88%, respectively, compared with 61%, 66%, and 70%, respectively, reported by Rojas and Stein (2013). Similar as for chicken meal or chicken by-product meal, the NRC (2012) provided no SID of AA for poultry meal for comparison to the current data. However, for poultry by-product meal, the SID of Lys, Ile, and Trp were 78%, 77%, and 81%, respectively, in the current study, which were lower than the values of 85%, 81%, and 78%, respectively, reported in the NRC (2012), but greater than the SID of Lys, Ile, and Trp of 69%, 68%, and 73%, respectively, reported by Rojas and Stein (2013).

Feather Meal

The SID of Lys (47% and 62%), Ile (47% and 78%), and Trp (61% and 79%) of the two feather meal sources evaluated in the current study differed widely, even though they were relatively similar in total Lys, Ile, and Trp content (Table 4), and in CP and ash content (91.4% and 86.4%, respectively; 2.4% and 1.8%, respectively), but were substantially different in crude fat content (5.4% vs. 11.0%, respectively; Kerr et al., 2017). The range in SID for AA in the feather meal sources observed in the current study was similar to the range in SID for AA reported by Sulabo et al. (2013). Because of the high variability in SID of AA observed in the current study as well as that reported by Sulabo et al. (2013), it was elected not to average these values for comparative purposes. The values for feather meal reported in NRC (2012) for SID of Lys, Ile, and Trp as 56%, 76%, and 63%, respectively.

Meat Meal and Meat and Bone Meal

The SID of AA were evaluated in 2 meat meal sources. For the first meat meal source, the SID of Lys, Ile, and Trp (71%, 76%, and 82%, respectively, Table 4) were relatively similar to the values (78%, 78%, and 76%, respectively) published in NRC (2012). In contrast, the second meat meal source had lower values of SID of Lys, Ile, and Trp of 53%, 56%, and 76%, respectively, compared

Table 4. Standardized ileal digestibility (%) of amino acids in animal protein by-product meals fed to growing pigs[1]

Item[2]	BM-1 (9)	BM-2 (8)	CBM (9)	CM (8)	FM-1 (7)	FM-2 (7)	MB-1 (8)	MB-2 (8)	MB-3 (8)	MM-1 (8)	MM-2 (9)	PBM (8)	PM (9)
Ala	74.6	73.0	65.1	88.5	26.5	56.3	77.5	50.8	69.5	73.7	47.3	76.9	65.6
(SD)	(11.1)	(7.3)	(9.5)	(4.4)	(9.8)	(11.0)	(5.7)	(9.0)	(9.2)	(4.8)	(14.3)	(10.1)	(12.6)
Arg	76.1	81.1	76.9	94.0	47.6	70.4	86.0	66.2	76.6	81.8	65.7	88.1	77.6
SD	(10.3)	(3.8)	(5.6)	(3.3)	(9.0)	(6.8)	(1.4)	(7.9)	(4.4)	(5.5)	(12.0)	(3.1)	(10.9)
Asp	77.6	79.5	55.0	76.3	30.3	42.2	74.5	38.1	57.3	59.4	39.7	65.0	62.2
SD	(9.0)	(4.4)	(8.5)	(8.1)	(6.6)	(10.8)	(2.0)	(9.9)	(7.9)	(5.3)	(13.2)	(11.1)	(13.0)
Cys	81.1	69.5	55.1	91.4	19.5	24.0	74.9	56.3	55.6	68.6	42.6	74.0	54.0
SD	(8.4)	(5.6)	(12.1)	(3.0)	(8.1)	(10.3)	(4.2)	(15.0)	(7.4)	(8.7)	(12.9)	(13.2)	(14.5)
Gly	56.7	62.2	63.1	81.0	30.3	57.7	60.3	41.9	62.3	61.5	48.8	72.3	64.5
SD	(24.8)	(19.1)	(5.6)	(11.8)	(15.4)	(17.8)	(19.6)	(6.3)	(9.9)	(10.6)	(18.4)	(10.0)	(22.0)
His	85.0	81.1	78.5	94.5	43.5	64.8	91.0	75.2	85.4	87.5	63.9	88.8	89.0
SD	(7.3)	(4.7)	(8.2)	(3.7)	(5.8)	(7.0)	(4.0)	(11.4)	(7.5)	(7.3)	(9.5)	(16.4)	(8.4)
Ile	72.0	65.9	66.7	90.3	47.4	77.6	80.1	58.9	72.7	76.2	55.5	77.0	66.8
SD	(10.0)	(4.3)	(7.7)	(3.5)	(5.4)	(4.1)	(4.0)	(7.3)	(4.0)	(4.7)	(8.3)	(5.9)	(7.1)
Leu	71.8	71.6	70.0	90.9	38.1	69.7	82.2	62.9	74.5	79.2	58.9	78.3	72.2
SD	(5.8)	(7.1)	(7.4)	(2.6)	(7.1)	(4.7)	(3.4)	(8.1)	(3.6)	(4.4)	(8.0)	(8.5)	(8.2)
Lys	79.2	84.0	71.4	90.9	47.2	62.0	79.7	54.0	71.0	71.1	52.8	77.9	74.7
SD	(7.9)	(5.6)	(8.8)	(3.1)	(3.2)	(8.3)	(3.5)	(9.4)	(6.5)	(5.3)	(11.2)	(10.6)	(10.4)
Met	82.0	90.8	75.2	95.2	51.8	66.5	85.5	61.3	77.8	82.0	57.5	82.4	79.1
SD	(6.9)	(4.7)	(4.5)	(2.3)	(5.3)	(7.4)	(4.8)	(9.5)	(4.7)	(4.4)	(8.5)	(6.0)	(8.4)
Phe	77.8	75.9	72.2	90.7	48.3	75.0	82.9	67.6	79.2	82.5	62.0	80.6	76.2
SD	(6.1)	(5.3)	(7.5)	(2.6)	(6.4)	(3.8)	(4.6)	(7.4)	(4.4)	(4.3)	(9.5)	(7.6)	(7.5)
Ser	79.9	85.0	66.9	86.7	42.2	65.2	73.9	57.2	65.7	74.2	54.9	76.4	68.7
SD	(7.3)	(2.3)	(7.1)	(7.2)	(5.9)	(7.3)	(8.3)	(7.6)	(4.7)	(5.5)	(12.0)	(9.5)	(9.3)
Thr	81.1	83.7	69.7	92.1	39.1	60.2	82.1	58.5	73.4	80.1	51.5	82.5	45.5
SD	(9.1)	(4.2)	(9.7)	(5.4)	(6.0)	(9.3)	(6.1)	(11.0)	(6.2)	(4.6)	(12.8)	(11.3)	(13.3)
Trp	87.3	94.0	80.8	87.9	61.2	79.3	81.5	59.9	80.9	82.2	75.8	80.7	57.1
SD	(7.3)	(3.3)	(7.8)	(4.6)	(5.6)	(4.2)	(4.1)	(7.3)	(3.5)	(5.5)	(9.4)	(8.9)	(12.0)
Tyr	84.6	87.5	72.3	95.0	58.0	74.2	83.7	64.2	77.6	82.1	61.9	79.2	63.8
SD	(7.7)	(4.1)	(8.6)	(3.3)	(5.5)	(6.2)	(3.3)	(7.6)	(4.6)	(3.7)	(10.8)	(6.2)	(10.1)
Val	73.7	71.1	64.8	87.9	35.0	67.6	77.5	53.4	69.9	74.8	48.3	72.5	50.5
SD	(10.6)	(5.2)	(8.1)	(5.7)	(8.0)	(8.6)	(6.0)	(10.6)	(5.3)	(4.7)	(10.9)	(11.2)	(12.0)

[1]Pig body weight and feed intake averaged 57.3 kg and 1.804 kg/d, respectively. BM = spray-dried blood meal; CBM = chicken by-product meal; CM = chicken meal; FM = feather meal; MB = meat and bone meal; MM = meat meal; PBM = poultry by-product meal; PM = poultry meal. Number in parentheses represents the number of observations per animal protein by-product meal.

[2]Coefficients of standardized ileal digestibility were calculated by correcting the coefficient of apparent ileal digestibility AA values of the complete diet for basal endogenous AA as determined by feeding a N-free diet (g/kg DMI): CP, 17.32; Ala, 0.51; Arg, 0.38; Asp, 0.65; Cys, 0.14; Gly, 1.37; His, 0.09; Ile, 0.26; Leu, 0.39; Lys, 0.19; Met, 0.06; Phe, 0.24; Ser, 0.37; Thr, 0.46; Trp, 0.07; Tyr, 0.17; Val, 0.40.

with the first meat meal source or the NRC (2012; Table 4). In the current study, the meat and bone meals had an average SID of Lys, Ile, and Trp of the 2 sources evaluated was 68%, 71%, and 74%, respectively, and are comparable to the 73%, 73%, and 62%, respectively, reported by NRC (2012). There was, however, a substantial range in these values as shown in Table 4.

In summary, animal protein by-product meals provide an excellent source of energy, AA, and minerals, and can be nutritionally and economically important feedstuffs for use in swine feed formulations. However, perhaps the greatest challenge in capturing the greatest nutritional and economic value of animal protein by-products is managing the variation in AA content and digestibility among sources of each type of by-product. The present study, along with data reported in previous publications (e.g., NRC, 2012), indicates that there are a substantial range in nutrient concentrations, DE and ME, and SID AA coefficients among types and sources of animal protein by-products. Additional research is needed to explore practical methods for improving AA digestibility of these animal protein by-products to enhance the nutritional efficiency of pork production. The use of meta-analysis approaches to develop SID AA prediction equations, similar to those developed for oilseed meals (Messad et al., 2016) and distillers dried grains with solubles (Zeng et al., 2017), would be useful for managing variability in AA digestibility among sources of each animal protein by-product in precision swine feed formulation.

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