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Amino acid and phosphorus digestibility and concentration of digestible and metabolizable energy in hydrolyzed feather meal fed to growing pigs[1]

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ABSTRACT: Two experiments were conducted to determine the standardized ileal digestibility (SID) of AA (Exp. 1), the standardized total tract digestibility (STTD) of P, and the concentration of DE and ME (Exp. 2) in hydrolyzed feather meal (FM) fed to growing pigs. Eight samples of FM were obtained from 4 different processing plants (FM1, FM2, FM3, and FM4). Each plant provided samples of FM without and with added blood. In Exp. 1, 10 barrows (initial BW: 24.0 ± 0.8 kg) were prepared with a T-cannula in the distal ileum and allotted to a 10 × 10 Latin square design with 10 diets and ten 7-d periods. A N-free diet, a diet based on soybean meal (SBM), and 8 diets based on a combination of SBM and each of the 8 sources of FM were formulated. Values for the SID of CP and AA in each source of FM were calculated using the difference procedure. The SID of CP and all AA was different ($P < 0.001$) among sources of FM. Among the indispensable AA, the overall effect of addition of blood was statistically significant ($P < 0.05$) for the SID of Ile, Leu, Lys, Phe, and Val, but for some sources, the SID of these AA was increased by addition of blood, whereas for other sources, the SID was reduced or not changed (interaction, $P < 0.05$). As an example, the SID of Lys in FM3 and FM4 with added blood were greater ($P < 0.05$) than in FM3 and FM4 without blood, but no difference in the SID of Lys was observed for FM1 and FM2 without and with blood (interaction, $P < 0.01$). In Exp. 2, 72 growing barrows (initial BW: 13.3 ± 1.5 kg) were used with 9 diets and 8 replicate pigs per diet. A corn-diet consisting of 98.4% corn was formulated and 8 additional diets were formulated by mixing corn with 25% FM. The STTD of P and the DE and ME of each source of FM were calculated using the difference procedure. The STTD of P tended ($P = 0.09$) to be different among FM sources and the STTD of P in FM with added blood was less than in FM without blood. On a DM basis, DE and ME values were affected ($P < 0.05$) by both source of FM and addition of blood. However, an interaction ($P < 0.05$) between source of FM and addition of blood for ME was observed because addition of blood to FM3 and FM4 reduced ($P < 0.05$) the ME, whereas addition of blood to FM1 and FM2 had no impact on ME. In summary, the SID of AA, STTD of P, and the energy concentration vary among sources of FM and the effects of adding blood to FM is not consistent among sources.

Key words: amino acids, digestibility, energy, feather meal, phosphorus, pigs

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INTRODUCTION

Hydrolyzed feather meal (**FM**) is produced by steam-hydrolyzing fresh poultry feathers, which is a co-product of the poultry processing industry (van Heugten and van Kempen, 2002). This process breaks keratins, which are coiled polypeptide chains, to produce a more digestible, high-protein product and also reduces microbial contamination (Apple et al., 2003). There are, however, limited data on AA digestibility of FM fed to pigs (Chiba, 2001), and to our knowledge, the apparent ileal digestibility (**AID**) data published by Knabe et al. (1989) are the only data available. However, values for AID may vary because of variations in the composition of FM among processing plants and within a processing plant (Cotanch et al., 2007). It is,

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therefore, also expected that the standardized ileal digestibility (**SID**) of AA in FM vary among processing plants, but this hypothesis has not been verified.

The nutritional value of FM is also dependent on the energy concentration and P digestibility. There is very limited data on the energy value of different FM sources fed to pigs; however, results of studies with poultry indicated that the energy concentration in FM depends on the concentration of fat (Dale, 1992; Ahmadi et al., 2008) and the degree of processing (Rizwan et al., 2000). There are also no data for the standardized total tract digestibility (**STTD**) of P in FM, but increasing levels of FM in corn–soybean meal diets fed to growing pigs resulted in a linear improvement in the apparent total tract digestibility (**ATTD**) of P (van Heugten and van Kempen, 2002). Feather meal may also contain coagulated poultry blood added either before or after hydrolysis (Goedeken et al., 1990), but there are no data on the influence of added blood on the nutritional value of FM. Therefore, the objectives of the present experiments were to determine the SID of CP and AA, the STTD of P, and the concentration of DE and ME in different sources of FM without and with added blood.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocols for the experiments. A total of 8 FM samples were obtained from the 4 members of the Poultry Protein and Fat Council (U.S. Poultry and Egg Association, Tucker, GA), and each processing plant provided FM samples (FM1, FM2, FM3, and FM4**)** without and with added blood (Table 1). Pigs with similar genetic makeup (G-Performer boars × Fertilium 25 females; Genetiporc, Alexandria, MN) were used in both experiments.

Table 1. Analyzed chemical composition of different sources of hydrolyzed feather meal (FM) without or with added blood (as-fed basis)[1,2,3]

	Source of feather meal												
	FM1		FM2		FM3		FM4		Average				
Item	No blood	With blood	No blood	With blood	No blood	With blood	No blood	With blood	No blood	With blood	Overall	SD	CV, %
DM, %	95.48	93.59	91.37	98.63	90.91	90.55	90.21	91.26	91.99	93.51	92.75	2.96	3.2
CP, %	76.87	80.64	82.41	81.32	80.79	82.23	84.80	84.75	81.22	82.24	81.73	2.54	3.1
GE, kcal/kg	5,560	5,248	5,801	5,662	5,445	5,379	5,309	5,398	5,529	5,422	5,475	187	3.4
AEE,[4] %	11.83	6.17	10.65	8.69	9.16	6.47	5.78	6.65	9.36	7.00	8.18	2.26	27.6
Ash, %	2.85	3.02	1.79	2.24	1.23	1.11	1.29	1.41	1.79	1.95	1.87	0.75	40.3
Ca, %	0.81	0.40	0.43	0.56	0.45	0.37	0.37	0.38	0.52	0.43	0.47	0.15	31.9
P, %	0.45	0.38	0.27	0.37	0.25	0.24	0.22	0.27	0.30	0.32	0.31	0.08	27.0
Indispensable AA, %													
Arg	5.45	5.27	5.15	5.37	6.16	5.68	5.75	5.79	5.63	5.53	5.58	0.33	5.9
His	0.67	1.29	0.59	1.00	0.77	1.44	0.78	1.33	0.70	1.27	0.98	0.33	33.6
Ile	3.66	3.61	3.46	3.78	4.22	3.96	3.81	4.06	3.79	3.85	3.82	0.25	6.5
Leu	6.26	6.72	6.19	6.78	7.28	7.35	6.79	7.41	6.63	7.07	6.85	0.47	6.9
Lys	1.91	2.83	1.60	2.28	1.93	2.90	1.89	2.69	1.83	2.68	2.25	0.50	22.0
Met	0.57	0.71	0.49	0.59	0.58	0.69	0.55	0.63	0.55	0.66	0.60	0.07	12.1
Phe	3.68	3.93	3.75	3.99	4.31	4.28	4.08	4.37	3.96	4.14	4.05	0.26	6.4
Thr	3.43	3.60	3.40	3.60	4.01	3.90	3.93	3.94	3.69	3.76	3.73	0.25	6.6
Trp	0.46	0.63	0.35	0.38	0.51	0.69	0.46	0.54	0.45	0.56	0.50	0.12	23.2
Val	5.91	5.74	5.90	6.34	6.97	6.40	5.75	6.53	6.13	6.25	6.19	0.44	7.1
Dispensable AA, %													
Ala	3.67	3.99	3.56	3.82	3.96	4.27	3.79	4.20	3.75	4.07	3.91	0.25	6.3
Asp	5.04	5.50	4.82	5.30	5.62	5.78	5.36	5.86	5.21	5.61	5.41	0.36	6.6
Cys	3.54	3.26	4.05	4.12	4.53	3.60	4.23	3.96	4.09	3.74	3.91	0.42	10.6
Glu	8.44	8.67	7.69	8.01	8.94	8.94	8.85	8.43	8.48	8.51	8.50	0.45	5.3
Gly	6.38	5.93	5.70	5.67	6.82	6.02	6.46	5.89	6.34	5.88	6.11	0.41	6.6
Pro	7.45	6.59	7.60	7.22	8.47	7.20	7.95	7.62	7.87	7.16	7.51	0.56	7.4
Ser	7.87	7.41	7.44	7.24	8.94	8.07	9.67	7.38	8.48	7.53	8.00	0.87	10.9
Tyr	2.24	2.57	1.81	2.25	2.55	2.49	2.30	2.56	2.23	2.47	2.35	0.26	11.0

[1]Samples of FM were obtained from the 4 member companies of the Poultry Protein and Fat Council (U.S. Poultry and Egg Association, Tucker, GA).

[2]Feather meal samples were hydrolyzed at 127 to 150°C with 345 to 586 kPa.

[3]Blood was added after hydrolyzation (approximately 9, 2, 10, and 3% for FM1, FM2, FM3, and FM4, respectively).

[4]Acid-hydrolyzed ether extract.

Amino Acid Digestibility: Experiment 1

Ten growing barrows (initial BW: 24.0 ± 0.8 kg) were equipped with a T-cannula in the distal ileum and allotted to a 10 × 10 Latin square design with 10 diets and ten 7-d periods. Pigs were housed in individual pens (1.2 × 1.5 m) in an environmentally controlled room. Pens had smooth, plastic-coated sides and fully-slatted tribar metal floors; a feeder and a nipple drinker were installed in each pen. Ten diets were prepared (Tables 2 and 3). One diet contained soybean meal (**SBM**) as the sole source of CP and AA, and 8 diets were formulated based on a combination of SBM and 1 of 8 different FM sources. The last diet was a N-free diet that was used to measure basal endogenous ileal losses of CP and AA. Cornstarch, sugar, and soybean oil were included in all diets, and vitamins and minerals were provided to meet or exceed current requirement estimates for growing pigs (NRC, 1998). All diets also contained 0.4% chromic oxide as an indigestible marker. All pigs were fed at a daily level of 3 times the maintenance energy requirement of the pigs (i.e., 106 kcal ME per $kg^{0.75}$; NRC, 1998), and feed was provided daily at 0800 and 1700 h. Animals had free access to water throughout the experiment.

Pig weights were recorded at the beginning of each period and the amount of feed supplied each day was recorded. The initial 5 d of each period were considered an adaptation period to the diet. Ileal digesta were collected for 8 h on d 6 and 7 by attaching a plastic bag to the cannula barrel, which allowed for collection of digesta flowing into the bag. Bags were removed whenever they were filled with digesta, or at least once every 30 min, and digesta were immediately frozen at –20°C to prevent bacterial degradation of AA in the digesta. On the completion of each experimental period, animals were deprived of feed overnight, and a new experimental diet was offered the following morning.

At the conclusion of the experiment, ileal samples were thawed, mixed within animal and diet, and a subsample was collected for chemical analysis. A sample of each FM source and SBM of each diet was also collected. Digesta samples were lyophilized and finely ground through a 1-mm screen in a Wiley mill (Model 4; Thomas Scientific, Swedesboro, NJ) before chemical analysis. All ingredient samples were analyzed for GE using bomb calorimetry (Model 6300, Parr Instruments, Moline, IL), DM (Method 930.15; AOAC International, 2007), CP (N × 6.25; Method 990.03; AOAC International, 2007), AA [Method 982.30 E (a, b, c); AOAC International, 2007], acid-hydrolyzed ether extract (**AEE**; Method 2003.06; AOAC International, 2007), and ash (Method 975.03, AOAC International, 2007). Calcium and P in these samples were analyzed by the inductively coupled plasma spectroscopy method (Method 985.01 A, B, and C; AOAC International, 2007) after wet ash sample preparation [Method 975.03 B(b); AOAC International, 2007]. Diets and ileal digesta samples were also analyzed for DM, CP, and AA, and Cr was analyzed in these samples using an inductive coupled plasma atomic emission spectrometric procedure (Method 990.08, AOAC International, 2007) after nitric acid-perchloric acid wet ash sample preparation (Method 968.088D; AOAC International, 2007).

Values for AID, ileal endogenous losses, and SID of CP and AA in each diet were calculated as previously explained (Stein et al., 2007). The AID and SID for CP and AA in the SBM diet also represent the AID and SID of CP and AA in SBM because SBM was the sole AA contributing ingredient in this diet. However, for the other diets, AID and SID values represented the combination of AA from SBM and FM, and the AID and SID of AA in each source of FM were, therefore, calculated using the difference procedure (Fan and Sauer, 1995).

Homogeneity of variances was confirmed and outliers were tested using the UNIVARIATE procedure (SAS Inst. Inc., Cary, NC), but no outliers were detected. Data were analyzed using the MIXED procedure. The model included source, blood, and source × blood interaction as the fixed effects and pig and period as the random effects. Least square means were calculated for each independent vari-

Table 2. Composition of experimental diets (as-fed basis), Exp. 1

	Diet		
Item	Soybean meal	Feather meal[1]	N-free
Ingredient		%	
Soybean meal	36.00	12.00	–
Feather meal	–	25.00	–
Soybean oil	3.00	3.00	4.00
Solka floc[2]	–	–	4.00
Dicalcium phosphate	1.00	1.00	1.60
Ground limestone	0.60	0.60	0.60
Sucrose	20.00	20.00	20.00
Chromic oxide	0.40	0.40	0.40
Cornstarch	38.30	37.30	68.20
Magnesium oxide	–	–	0.10
Potassium carbonate	–	–	0.40
Salt	0.40	0.40	0.40
Vitamin-trace mineral premix[3]	0.40	0.30	0.30
Total	100.00	100.00	100.00

[1]Eight diets containing 8 sources of hydrolyzed feather meal without or with added blood obtained from the 4 members of the Poultry Protein and Fat Council (U.S. Poultry and Egg Association, Tucker, GA) were formulated.

[2]Fiber Sales and Development Corp., Urbana, OH.

[3]Provided the following quantities of vitamins and minerals per kilogram of complete diet: Vitamin A as retinyl acetate, 11,128 IU; vitamin D_3 as cholecalciferol, 2204 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.58 mg; pyridoxine as pyridoxine hydrocloride, 0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin as nicotinamide and nicotinic acid, 44 mg; folic acid, 1.58 mg; biotin, 0.44 mg; Cu, 10 mg as copper sulfate; Fe, 125 mg as iron sulfate; I, 1.26 mg as potassium iodate; Mn, 60 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; and Zn, 100 mg as zinc oxide.

able. When a fixed effect was a significant source of variation, means were separated using the PDIFF option of SAS. The pig was the experimental unit for all calculations, and the α level used to determine significance among means was 0.05 and tendencies were declared at $P < 0.10$.

Energy Measurements and Phosphorous Digestibility: Experiment 2

A total of 72 growing barrows (initial BW: 13.3 ± 1.5 kg) were used with 9 diets and 8 replicate pigs per diet. Pigs were placed in metabolism cages that were equipped with a feeder and a nipple drinker, fully slatted floors, a screen floor, and urine trays, which allowed for the total, but separate, collection of urine and fecal materials from each pig. A corn-diet consisting of 98.40% corn and vitamins and minerals was formulated (Tables 4 and 5). Eight additional diets were formulated by mixing corn with 25% FM. The quantity of feed provided per pig daily was calculated as 3 times the estimated requirement for maintenance energy for the smallest pig in each replicate and divided into 2 equal meals. Water was available at all times. The experiment lasted 14 d. The initial 7 d were considered an adaptation period to the diet, while urine and fecal materials were collected during the following 5 d according to standard procedures using the marker to marker approach (Adeola, 2001). Urine was collected in urine buckets over a preservative of 50 mL of 6 *N* HCl. Fecal samples and 20% of the collected urine were stored at –20°C immediately after collection.

At the conclusion of the experiment, urine samples were thawed and mixed within animal and diet, and a subsample was lyophilized and analyzed for GE (Kim et al., 2009). Fecal samples were dried in a forced air oven and finely ground through a 1-mm screen in a Wiley mill (Model 4; Thomas Scientific, Swedesboro, NJ) before analysis. Fecal and diet samples were analyzed in duplicate for DM, GE, and P. Following analysis, values for ATTD and DE and ME were calculated for energy in each diet using the direct procedure and in each ingredient using the difference procedure as previously explained (Widmer et al., 2007). The ATTD of P in each ingredient was also calculated using the difference procedure, and the STTD of P was calculated for each ingredient (Widmer et al., 2007) by correcting the ATTD of P by the values for the basal endogenous losses of P (Almeida and Stein, 2010). A basal endogenous loss of 200 mg P per kg DMI was assumed (Stein, 2011). Data were analyzed as outlined for Exp. 1.

RESULTS AND DISCUSSION

Composition of Feather Meal

The GE and AEE in the different FM sources ranged from 5,248 to 5,801 kcal/kg and 5.78 to 11.83% (as-fed basis), respectively (Table 1), which is within the range

Table 3. Analyzed chemical composition of experimental diets (as-fed basis), Exp. 1[1]

	Diet									
	FM1		FM2		FM3		FM4		Soybean	
Item	No blood	With blood	No blood	With blood	No blood	With blood	No blood	With blood	meal	N-free
CP (N × 6.25), %	25.9	25.6	27.6	26.5	26.5	26.5	27.0	25.7	17.2	0.36
Indispensable AA										
Arg	1.73	1.68	1.76	1.59	1.84	1.65	1.77	1.74	1.26	–
His	0.29	0.43	0.28	0.34	0.31	0.43	0.29	0.44	0.44	–
Ile	1.22	1.18	1.22	1.10	1.29	1.18	1.24	1.27	0.80	0.01
Leu	2.03	2.11	2.12	1.97	2.16	2.12	2.11	2.23	1.36	0.02
Lys	0.82	1.05	0.79	0.87	0.84	0.99	0.77	0.99	1.10	0.02
Met	0.21	0.24	0.20	0.20	0.21	0.21	0.19	0.21	0.22	–
Phe	1.20	1.25	1.26	1.18	1.29	1.25	1.25	1.31	0.90	–
Thr	1.04	1.10	1.17	1.08	1.17	1.12	1.16	1.13	0.68	0.01
Trp	0.20	0.21	0.15	0.18	0.20	0.19	0.20	0.18	0.25	–
Val	1.85	1.74	1.79	1.60	1.92	1.74	1.84	1.94	0.84	0.01
Dispensable AA										
Ala	1.17	1.23	1.18	1.13	1.19	1.22	1.16	1.28	0.76	0.01
Asp	1.95	2.05	1.98	1.88	2.05	1.98	1.95	2.06	1.99	0.02
Cys	1.07	0.95	1.26	1.06	1.23	0.95	1.17	1.04	0.28	–
Glu	3.05	3.09	3.04	2.82	3.18	2.93	3.04	3.03	3.11	0.01
Gly	1.82	1.68	1.75	1.52	1.82	1.59	1.80	1.70	0.74	0.01
Pro	2.19	1.88	2.19	1.93	2.37	1.92	2.29	2.09	0.89	0.04
Ser	1.89	1.85	2.30	2.00	2.29	1.95	2.32	1.93	0.80	0.01
Tyr	0.63	0.73	0.63	0.60	0.67	0.61	0.63	0.63	0.58	0.01

[1]Hydrolyzed feather meal samples (FM1, FM2, FM3, and FM4) were obtained from the 4 members of the Poultry Protein and Fat Council (U.S. Poultry and Egg Association, Tucker, GA).

of previously reported values (Dale, 1992; Sauvant et al., 2004; Cotanch et al., 2006). Ash concentration was 1.11 to 3.02%, whereas Ca and P ranged from 0.49 to 0.62% and 0.23 to 0.29% (as-fed basis), respectively. These values are also in agreement with published values (Dale, 1992; Cotanch et al., 2006). The concentration of CP and indispensable AA in the FM sources used in this experiment were also within the range of values reported in FM obtained from 18 different poultry processing plants (Cotanch et al., 2006).

Previous reference data (NRC, 1998; Sauvant et al., 2004) do not indicate if the values for FM contain added blood. The average CP, GE, and AEE concentration of FM without blood were 81.22%, 5,529 kcal/kg, and 9.36% (as-fed basis), respectively, whereas FM with added blood had 82.24% CP, 5,422 kcal GE/kg, and 7.0% AEE. The ash, Ca, and P of FM without and with added blood was 1.79, 0.53, and 0.25%, and 1.95, 0.52, and 0.26%, respectively, which agree with previous values (Cotanch et al., 2006).

The difference procedure was used to determine the digestibility of AA and P and energy concentration in FM, and SBM and corn were used as the ingredients in the basal diet for the AA and P and energy experiments, respectively. As a consequence, accurate results for FM will be calculated only if the results for SBM and corn are accurate. The values obtained for the SID of AA in SBM are in good agreement with values reported from previous experiments (NRC, 1998; Cervantes-Pahm and Stein, 2010). Likewise, values for the STTD of P and DE and ME obtained for corn in the present experiment are in close agreement with previous data (NRC, 1998; Sauvant et al., 2004; Kim et al., 2009; Almeida and Stein, 2012). These observations indicate that the values for the SID of AA, the STTD of P, and the DE and ME that were calculated for FM in the present experiments are also accurate.

Amino Acid Digestibility

The SID of Lys in FM3 and FM4 with added blood were greater ($P < 0.05$) than in FM3 and FM4 without blood, but this difference was not observed when blood was added to FM1 and FM2 (interaction, $P < 0.01$; Table 6). The SID of CP, Ile, Leu, and Val was less (interaction, $P < 0.05$) in FM1 and FM2 with added blood compared with FM1 and FM2 without blood, and the SID of Met in FM1 was also reduced (interaction, $P < 0.05$) in FM1 with added blood compared with FM1 without blood. There were no differences in the SID of Arg, His, Thr, and Trp in FM without and with added blood. The SID of Arg, His, and Trp in FM2 were less ($P < 0.05$) than in the other FM sources. The SID of Arg and Thr in FM1 and the SID of Thr in FM2 were also less ($P < 0.05$) than in FM3 and FM4.

These results indicate that AA digestibility in FM varies among sources, and this may be due to differences in processing. Processing conditions such as steam pressure and time of hydrolysis affect the quality and digestibility of FM (Moritz and Latshaw, 2001). The reason for the different responses to adding blood to FM may also be a result of differences in the timing of blood addition be-

Table 4. Composition of experimental diets (as-fed basis), Exp. 2

	Diet	
Ingredient, %	Corn	Feather meal[1]
Corn	98.40	73.40
Feather meal	–	25.00
Limestone	0.90	0.90
Salt	0.40	0.40
Vitamin-trace mineral premix[2]	0.30	0.30
Total	100.00	100.00

[1]Eight diets containing 8 different sources of hydrolyzed feather meal without or with added blood obtained from the 4 members of the Poultry Protein and Fat Council (U.S. Poultry and Egg Association, Tucker, GA) were formulated.

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

Table 5. Analyzed chemical composition of experimental diets (as-fed basis), Exp. 2[1]

		Diet							
		FM1		FM2		FM3		FM4	
Item	Corn	No blood	With blood	No blood	With blood	No blood	With blood	No blood	With blood
DM, %	88.2	89.7	89.2	91.2	90.3	89.6	89.7	90.6	92.1
GE, kcal/kg	3,768	4,229	4,178	4,201	4,259	4,296	4,249	4,247	4,248
Ash, %	2.53	3.16	3.10	2.99	2.76	2.75	2.71	2.62	2.84
Ca, %	0.40	0.62	0.53	0.51	0.55	0.50	0.51	0.49	0.49
P, %	0.25	0.30	0.27	0.23	0.29	0.24	0.24	0.23	0.25

[1]Hydrolyzed feather meal samples (FM1, FM2, FM3, and FM4) were obtained from the 4 members of the Poultry Protein and Fat Council (U.S. Poultry and Egg Association, Tucker, GA).

cause blood may be added to the feathers either before or after steam hydrolysis of the feathers. Adding blood to feathers before hydrolysis reduces performance of ruminant animals compared with adding blood after hydrolysis because of reduced ruminal protein escape and reduced ATTD of protein (Goedeken et al., 1990). To our knowledge, there are no data on the effects of the time of blood addition on the digestibility of protein and AA in feather meal fed to pigs, but it is possible that the time of addition of blood to the feathers may help explain the differences in CP and AA digestibility among sources.

Hydrolyzed feather meal is relatively low in Lys and some other AA and feather meal, therefore, must be incorporated into diets based on the AA concentration. This method, however, can increase the dietary CP concentration, which may lead to contamination of water and odorous emissions (Chiba, 2000). Therefore, supplementation of diets containing FM with crystalline AA and balancing diets based on AA digestibility is the most effective way to utilize FM in pig diets in an environmentally-friendly manner (Divakala et al., 2009). The current data will enable such an approach to be used in diet formulation.

Phosphorus Digestibility

All pigs readily consumed their respective diets, but P intake was greater ($P < 0.01$) for pigs fed FM with added blood compared with pigs fed FM without blood (Table 7). This was due to the greater ADFI ($P = 0.04$) in pigs fed FM with added blood. Pigs fed diets containing FM1 and FM2 also had greater ($P < 0.04$) P intake than pigs fed diets containing FM3. Pigs fed diets containing FM with added blood also had greater ($P < 0.01$) fecal P output than pigs fed FM without blood. This was due to the greater ($P < 0.001$) fecal output in pigs fed FM with added blood. Addition of blood to FM2 increased ($P < 0.01$) the amount of P absorbed whereas no differences were observed when blood was added to the other FM sources (interaction, $P < 0.01$).

Table 6. Standardized ileal digestibility (%) of CP and AA by growing pigs in hydrolyzed feather meal (FM) without or with added blood (Exp. 1)[1,2,3]

	Source of feather meal											
	FM1		FM2		FM3		FM4			*P*-value		
Item	No blood	With blood	No blood	With blood	No blood	With blood	No blood	With blood	SEM	Source	Blood	Source × blood
CP	69.5^{ab}	60.9^{d}	67.0^{bc}	57.4^{cd}	70.9^{ab}	76.3^{a}	71.0^{ab}	70.5^{ab}	2.7	<0.001	0.08	0.02
Indispensable AA												
Arg	81.3	78.3	77.8	69.2	85.7	86.0	83.6	84.9	2.1	<0.001	0.11	0.11
His	67.2	56.6	56.9	34.4	69.1	64.8	66.4	77.1	6.4	<0.001	0.16	0.10
Ile	79.8^{bc}	71.5^{de}	76.0^{cd}	65.6^{e}	86.2^{a}	96.3^{a}	81.7^{abc}	83.1^{ab}	2.3	<0.001	0.01	0.02
Leu	75.4^{ab}	67.2^{c}	70.8^{bc}	58.7^{d}	80.5^{a}	81.2^{a}	76.5^{ab}	77.3^{ab}	2.5	<0.001	<0.01	0.02
Lys	59.0^{b}	55.0^{bc}	48.1^{c}	55.5^{bc}	59.0^{b}	79.4^{a}	59.4^{b}	71.2^{a}	3.6	<0.001	<0.001	<0.01
Met	70.2^{bc}	62.6^{de}	64.7^{cde}	58.2^{e}	71.9^{ab}	77.3^{a}	68.4^{bcd}	71.7^{ab}	2.6	<0.001	0.41	0.01
Phe	77.3^{abc}	70.1^{c}	73.7^{bc}	61.7^{d}	83.3^{a}	83.5^{a}	79.6^{ab}	80.0^{ab}	2.4	<0.001	<0.01	0.03
Thr	66.4	59.8	65.2	56.3	72.4	76.1	69.7	70.3	2.8	<0.001	0.16	0.10
Trp	83.8	79.8	67.4	73.7	84.6	85.2	85.9	81.8	3.4	<0.001	0.91	0.39
Val	77.6^{ab}	69.0^{c}	72.4^{bc}	60.2^{d}	82.9^{a}	83.0^{a}	77.4^{ab}	79.9^{a}	2.3	<0.001	<0.01	<0.01
Mean	75.5^{ab}	68.0^{c}	71.0^{bc}	60.8^{d}	80.4^{a}	81.8^{a}	76.9^{ab}	78.6^{a}	2.4	<0.001	0.03	0.03
Dispensable AA												
Ala	71.0^{bcd}	64.0^{d}	66.9^{cd}	53.7^{e}	76.1^{ab}	80.0^{a}	73.2^{abc}	75.4^{ab}	2.8	<0.001	0.08	<0.01
Asp	47.4^{abc}	33.9^{d}	44.3^{bc}	38.9^{cd}	49.7^{ab}	57.1^{a}	49.1^{abc}	54.7^{a}	3.8	<0.001	0.56	0.02
Cys	62.3	53.8	53.2	45.3	60.5	61.0	58.4	57.5	3.4	<0.001	0.09	0.42
Glu	65.2	56.9	61.0	52.7	68.4	73.0	67.4	67.9	3.1	<0.001	0.19	0.09
Gly	71.0	67.0	66.8	55.9	73.3	78.9	74.8	75.4	3.4	<0.001	0.39	0.12
Pro	66.7	65.8	60.6	36.7	62.4	67.7	69.8	72.4	7.8	<0.001	0.46	0.26
Ser	73.1	68.5	74.6	66.9	79.7	81.0	78.4	75.2	2.2	<0.001	0.03	0.26
Tyr	72.4	69.1	65.9	57.9	76.2	78.9	72.7	73.9	2.7	<0.001	0.32	0.16
Mean	66.5	60.0	62.5	50.8	68.4	72.6	69.0	69.5	3.4	<0.001	0.18	0.12
Total AA	68.8	62.0	64.6	54.0	71.9	75.4	70.8	72.2	2.9	<0.001	0.15	0.07

[a–e]Values within a row lacking a common superscript letter are different ($P < 0.05$).

[1]Data are least squares means of 10 observations for each treatment.

[2]Feather meal samples (FM1, FM2, FM3, and FM4) were obtained from the 4 members of the Poultry Protein and Fat Council (U.S. Poultry and Egg Association, Tucker, GA).

[3]Standardized ileal digestibility values were calculated by correcting values for apparent ileal digestibility for the basal ileal endogenous losses. Basal ileal endogenous losses were determined as (g/kg of DMI): CP, 25.35; Arg, 0.89; His, 0.38; Ile, 0.54; Leu, 0.94; Lys, 0.51; Met, 0.13; Phe, 0.56; Thr, 0.90; Trp, 0.12; Val, 0.82; Ala, 0.93; Asp, 1.36; Cys, 0.56; Glu, 1.60; Gly, 2.13; Pro, 7.33; Ser, 0.89; and Tyr, 0.47.

There was a tendency for an interaction ($P = 0.06$) between blood addition and source of FM because the ATTD of P was reduced in FM3 when blood was added but that was not the case for the other sources of FM. The diet containing FM3 also had less ($P = 0.03$) STTD of P compared with diets containing FM1 and FM4, with FM2 being intermediate. There was also a tendency ($P = 0.09$) for less STTD of P in diets containing FM with added blood compared with those without blood.

Relative bioavailability of P in FM was reported to be 31% (NRC, 1998), whereas the ATTD of P was 20% (Sauvant et al., 2004). Both of these values are much lower than the ATTD of P determined in the present study (62.4 to 92.0%). However, adding increasing levels of FM (0 to 10%) to corn-SBM diets fed to growing pigs linearly improved P digestibility from about 32 to 42% (van Heugten and van Kempen, 2002), which indicates that the digestibility of P in FM is greater than the values reported by NRC (1998) and Sauvant et al. (2004). The reason the values for ATTD of P obtained in this experiment are greater than the values determined by van Heughten and van Kempen (2002) is most likely that our values are only for the FM, whereas the values determined by van Heughten and van Kempen (2002) are for the diets including corn, SBM, and FM. Because values for the ATTD of P in corn and SBM are much less than in FM (NRC, 2012), it is expected that the ATTD of P in a mixed diet containing corn, SBM, and FM is less than in FM alone. Thus, the values obtained in this experiment support the data by van Heughten and van Kempen (2002) and are also in relatively good agreement with other published values (Jongbloed and Kemme, 1990; Bünzen et al., 2009; NRC, 2012).

To our knowledge, the STTD of P in FM fed to pigs has never been reported. The STTD of P tended ($P = 0.09$) to be different between FM sources, with FM3 having less ($P < 0.05$) STTD of P than FM4, whereas FM1 and FM2 were intermediate. Although we did not observe an interaction between addition of blood and source of FM for the STTD of P, it appears that the reason for a reduced STTD of P in FM3 may be a result of the low STTD of P in FM3 with added blood. Adding blood to FM tended to reduce ATTD ($P = 0.07$) and reduced STTD of P ($P = 0.05$) compared with FM without blood. These results indicate that most of the P in FM may be utilized by the pig and that the digestibility of P is greater than previously reported. The reason for the apparent negative effect of blood on P digestibility of FM is not known. However, the concentration of P in avian blood is only 0.30% (Almeida and Stein, 2011) so it is doubtful that the relatively small amounts of blood that were included in the FM used in this experiment had any direct influence on the ATTD and STTD of P. It is more likely that the addition of blood may have changed the time needed to dry the product or the temperature used in drying, which may be the reason for the observed effects of blood on the ATTD and STTD of P.

Energy Measurements

There were no differences in GE intake among pigs fed the different FM sources; however, GE intake of pigs fed FM with added blood was greater ($P = 0.04$) than for pigs fed FM without blood due to greater ADFI (Table 8). Likewise, source of FM did not affect fecal and urinary energy losses, but the inclusion of blood in FM increased ($P < 0.001$) fecal energy loss and tended

Table 7. Daily P balance, apparent total tract digestibility (ATTD, %), and standardized total tract digestibility (STTD, %) of P in pigs fed different sources of hydrolyzed feather meal (FM) without or with added blood (Exp. 2)[1]

	Source of feather meal											
	FM1		FM2		FM3		FM4			*P*-value		
Item	No blood	With blood	No blood	With blood	No blood	With blood	No blood	With blood	SEM	Source	Blood	Source × blood
ADFI, g	381	454	428	456	405	417	422	473	26	0.45	0.04	0.68
Fecal output, g/d	36.2	48.5	42.6	53.1	35.4	50.9	36.1	46.3	4.4	0.49	<0.001	0.93
P in feces, %	1.19	1.20	1.16	1.14	1.37	1.19	1.24	1.18	0.09	0.47	0.30	0.71
P intake, g/d	1.26	1.35	1.10	1.44	1.09	1.12	1.08	1.31	0.07	0.05	<0.01	0.17
P output, g/d	0.43	0.58	0.49	0.57	0.48	0.60	0.45	0.54	0.06	0.81	<0.01	0.95
P absorbed, g/d	0.83^{a}	0.77^{ab}	0.61^{cd}	0.87^{a}	0.61^{bcd}	0.51^{d}	0.63^{bcd}	0.76^{abc}	0.06	<0.01	0.15	<0.01
ATTD in diet, %	66.7	57.2	55.8	60.1	56.2	45.5	58.1	58.6	3.7	0.05	0.41	0.06
STTD in diet,[2] %	72.8	64.0	63.6	66.4	63.6	52.9	66.0	65.9	3.7	0.03	0.09	0.15
ATTD in ingredient,[3] %	98.2	76.6	79.8	85.3	83	41.8	69.2	89.6	14.8	0.08	0.07	0.23
STTD in ingredient,[3] %	102.6	82.6	89.3	90.1	91.1	50.2	104.5	97.1	11.9	0.09	0.05	0.33

[a-d]Values within a row lacking a common superscript letter are different ($P < 0.05$).

[1]Data are least squares means of 8 observations for all treatments. FM samples (FM1, FM2, FM3, and FM4) were obtained from the 4 members of the Poultry Protein and Fat Council (U.S. Poultry and Egg Association, Tucker, GA).

[2]Values for STTD were calculated by correcting values of ATTD for endogenous P loss, which was assumed to be 200 mg/kg DMI (Stein, 2011).

[3]Calculated using the difference procedure. The ATTD and STTD of P in corn was 46.7 and 53.8%, respectively.

Table 8. Daily energy balance (as-fed basis) for pigs fed diets containing different sources of hydrolyzed feather meal (FM) without or with added blood (Exp. 2)[1,2]

	Source of feather meal											
	FM1		FM2		FM3		FM4			*P*-value		
Item	No blood	With blood	No blood	With blood	No blood	With blood	No blood	With blood	SEM	Source	Blood	Source × blood
GE intake, kcal	1,797	2,126	1,972	2,142	1,941	1,973	1,987	2,183	124	0.65	0.04	0.70
Fecal GE loss, kcal	198	260	232	289	184	279	197	253	25	0.48	< 0.001	0.85
Urinary GE loss, kcal	118	136	118	108	82	123	86	162	22	0.71	0.06	0.27
ATTD, % of GE	89.3	87.8	88.3	86.4	90.4	85.8	90.0	88.4	0.9	0.28	< 0.001	0.29
DE of diet, kcal/kg	3,775	3,667	3,707	3,681	3,885	3,644	3,821	3,756	40	0.10	< 0.001	0.06
ME of diet, kcal/kg	3,444[b]	3,403[b]	3,460[b]	3,470[b]	3,679[a]	3,385[b]	3,633[a]	3,457[b]	55	0.16	< 0.01	0.05

[a,b]Values within a row lacking a common superscript letter are different ($P < 0.05$).

[1]Data are least squares means of 8 observations for all treatments.

[2]Feather meal samples (FM1, FM2, FM3, and FM4) were obtained from the 4 members of the Poultry Protein and Fat Council (U.S. Poultry and Egg Association, Tucker, GA).

to increase ($P = 0.06$) urinary energy loss. The greater fecal energy losses in pigs fed FM with added blood resulted in reduced ($P < 0.001$) ATTD of GE. There was a tendency ($P = 0.06$) for an interaction between source of FM and blood addition for DE of the diet due to the reduced DE in FM3 with added blood compared with the DE in FM3 without blood. The addition of blood to FM3 and FM4 also reduced ($P < 0.05$) ME of the diet, but this was not the case for FM1 and FM2 (interaction, $P = 0.05$; Table 9).

The DE and ME of the different FM sources determined in the present experiment ranged from 4,581 to 5,545 kcal/kg and 4,271 to 54,45 kcal/kg (as-fed basis), respectively. When expressed on an as-fed and DM basis, there was a tendency ($P = 0.06$) for an interaction between source of FM and addition of blood on DE due to a reduction in DE of FM3 when blood was added, whereas there was no effect of adding blood on the DE of the other FM sources. There was also an interaction ($P = 0.05$) for ME due to less ($P < 0.05$) ME in FM3 and FM4 with added blood compared with FM3 and FM 4 without blood, whereas this effect was not observed for FM1 and FM2. Among the FM sources without blood, FM3 and FM4 had greater ($P < 0.05$) ME than FM1 and FM2. No differences were observed in the ME of the different FM sources with added blood. The DE and ME obtained in the present experiment were greater than previous values (NRC, 1998; 2012). It is not clear why this effect was obtained, but the ATTD of GE that was observed in the present experiment (89%) is greater than the value of 62% that can be calculated from NRC (2012). Variability in fat concentration among sources of FM contributes to differences in energy values (Dale, 1992), and the average concentration of fat for the FM used in this experiment is greater than the value (5.97%) published by NRC (2012), which may have contributed to the greater ATTD of GE that we observed. The effect of blood addition on the energy value of FM was inconsistent, and depends on the source of FM and may also depend on the time of blood addition. It is not clear, however, if the energy values reported by NRC (2012) were derived from FM sources without or with blood addition, and the timing of blood addition is also unknown. Nevertheless, these results indicate that values for DE and ME of FM published by NRC (2012) may underestimate the DE and ME of FM and therefore also result in an underestimation of the DE and ME of diets containing FM.

Table 9. Concentration of DE and ME in different sources of hydrolyzed feather meal (FM) without or with added blood (Exp. 2)[1,2]

	Source of feather meal											
	FM1		FM2		FM3		FM4			*P*-value		
Item	No blood	With blood	No blood	With blood	No blood	With blood	No blood	With blood	SEM	Source	Blood	Source × blood
As-fed basis												
DE, kcal/kg	5,104	4,672	4,835	4,728	5,545	4,581	5,290	5,028	162	0.10	<0.001	0.06
ME, kcal/kg	4,508[b]	4,344[b]	4,572[b]	4,612[b]	5,445[a]	4,271[b]	5,264[a]	4,557[b]	220	0.16	<0.01	0.05
DM basis												
DE, kcal/kg	5,462	5,089	4,974	4,901	6,004	4,970	5,772	5,423	177	<0.001	<0.001	0.06
ME, kcal/kg	4,398[b]	4,302[b]	4,300[b]	4,361[b]	5,474[a]	4,206[b]	5,320[a]	4,488[b]	240	0.04	<0.001	0.04

[a,b]Values within a row lacking a common superscript letter are different ($P < 0.05$).

[1]Data are least squares means of 8 observations for all treatments.

[2]Feather meal samples (FM1, FM2, FM3, and FM4) were obtained from the 4 members of the Poultry Protein and Fat Council (U.S. Poultry and Egg Association, Tucker, GA).

Conclusions

The SID of AA, STTD of P, and the energy concentration in FM vary among sources of FM, probably because of differences in processing. The effect of adding blood to FM also varies among sources. Therefore, it is important to consider the source and product type (without or with added blood) to obtain a more accurate assessment of the nutritional value of FM to effectively use this ingredient in practical swine diets. However, regardless of blood addition, results of the present work indicate that the FM contains more DE and ME than reported previously.

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