Published online June 8, 2017

Amino acid digestibility by weanling pigs of processed ingredients originating from soybeans, 00-rapeseeds, or a fermented mixture of plant ingredients[1]

D. M. D. L. Navarro,* Y. Liu,*[2] T. S. Bruun,† and H. H. Stein*‡[3]

*Department of Animal Sciences, University of Illinois, Urbana 61801;
†Danish Pig Research Centre, Danish Agriculture & Food Council, Axeltorv 3, DK-1609
Copenhagen, Denmark; and ‡Division of Nutritional Sciences, University of Illinois, Urbana 61801

ABSTRACT: An experiment was conducted to determine the apparent ileal digestibility (AID) and the standardized ileal digestibility (SID) of CP and AA in 4 sources of processed soybean products, in conventional dehulled soybean meal (SBM-CV), in conventional 00-rapeseed expellers (RSE), and in a fermented coproduct mixture (FCM) that contained rapeseed meal, wheat, soy molasses, and potato peel fed to weanling pigs. The 4 processed soybean products included 2 sources of enzyme-treated soybean meal (ESBM-1 and ESBM-2), extruded soybean meal, and soy protein concentrate (SPC). Twenty-seven weanling barrows (9.29 ± 0.58 kg initial BW) were surgically equipped with a T-cannula in the distal ileum. Pigs were randomly allotted to three 9 × 5 Youden squares with 9 pigs and five 7-d periods in each square. Seven cornstarch-based diets were prepared using each of the protein sources as the sole source of CP and AA. A N-free diet was prepared to calculate basal endogenous losses of CP and AA, and this diet was fed to 2 groups of pigs, which resulted in a total of 9 dietary treatments. Results indicate that the SID of CP was greater ($P < 0.05$) in ESBM-1 than in SPC, RSE, or FCM. The SID of Arg, His, Ile, Leu, Met, and Phe were greater ($P < 0.05$) in ESBM-1 than in SPC, and the SID of Lys was greater ($P < 0.05$) in SBM-CV than in ESBM-2. The SID of Thr, Trp, Val, and total indispensable AA were not different among the soybean products, but the SID of total dispensable AA in ESBM-1 was greater ($P < 0.05$) than in SPC. Therefore, the SID of total AA was greater ($P < 0.05$) in ESBM-1 than in SPC, but no other differences were observed among soybean meal (SBM) products. The SID of most AA in RSE and the SID of all AA in FCM were less ($P < 0.05$) than in all the SBM products, but the SID of all AA in RSE were greater ($P < 0.05$) than in FCM. Results of this research indicate that although processing of SBM results in increased concentration of CP, processing may also reduce the digestibility of AA, which is likely due to heat damage during processing. There are, however, differences among processed soy products, with some products having greater SID of AA than others. Results also indicate that fermentation of a mixture of rapeseed meal, wheat, and relatively low quality coproducts does not result in SID values that are similar to those of unfermented 00-rapeseed expellers or soybean products.

Key words: amino acid digestibility, enzyme-treated soybean meal, extruded soybean meal, pigs, rapeseed expellers, soy protein concentrate

J. Anim. Sci. 2017.95:2658–2669
doi:10.2527/jas2016.1356

INTRODUCTION

Soybean meal (**SBM**) is the most commonly used plant protein source in swine diets (Stein et al., 2008; Goerke et al., 2012). However, SBM may contain antinutritional factors including antigens, trypsin inhibitors, α-galactosides, and lectins, which are unfavorable to younger pigs (Friesen et al., 1993; Mawson et al., 1994; Zhang et al., 2001; Choct et al., 2010). To avoid providing these antinutritional factors, diets for weanling pigs often contain animal protein sources, which

[1]Financial support for this research from the Danish Pig Research Centre, Copenhagen, Denmark, is appreciated.

[2]Present address: Department of Animal Science, University of California, Davis 95616.

[3]Corresponding author: hstein@illinois.edu

Received December 29, 2016.
Accepted April 14, 2017.

are more expensive than SBM. However, SBM can be processed to soy protein concentrate (**SPC**), fermented SBM, or enzyme-treated SBM, which all have reduced concentrations of antinutritional factors compared with SBM, and processed soybean products are, therefore, more tolerable to young pigs than conventional SBM (Lenehan et al., 2007; Jones et al., 2010; Kim et al., 2010).

Rapeseeds that are low in erucic acid and glucosinolates are referred to as 00-rapeseeds, and 00-rapeseed meal and 00-rapeseed expellers are the coproducts produced from 00-rapeseeds (Maison and Stein, 2014). Because of a relatively high concentration of fiber and residual glucosinolates, these ingredients are usually included in diets for weanling pigs at relatively low concentrations, but it is possible that fermentation of rapeseed products together with other coproducts may improve the nutritional value. If that is the case, it is possible that a fermented coproduct may be used as a source of AA in diets for weanling pigs, but research to demonstrate this effect is lacking. Therefore, the objective of this experiment was to determine the apparent ileal digestibility (**AID**) and the standardized ileal digestibility (**SID**) of CP and AA by weanling pigs in 4 sources of processed soybean products, in conventional dehulled SBM (**SBM-CV**), in conventional 00-rapeseed expellers (**RSE**), and in a fermented coproduct mixture (**FCM**) that contained rapeseed meal, wheat, soy molasses, and potato peel.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocol for this experiment. The pigs used in the experiment were the offspring of G-Performer boars mated to Fertilis 25 females (Genetiporc USA LLC, Alexandria, MN). Ingredients used in the experiment (Table 1) included 2 sources of enzyme-treated SBM (**ESBM-1**; Hamlet Protein Inc., Horsens, Denmark) and (**ESBM-2**; Dansk Vilomix Inc., Mørke, Denmark), extruded SBM (**SBM-EX**) that was subsequently treated with an enzyme preparation (Agro Korn Inc., Videbæk, Denmark), SPC (IMCOPA, Paraná, Brazil), SBM-CV that was sourced from Brazil, RSE (The Protein and Oilfabric Scanola Inc., Aarhus, Denmark), and FCM (European Protein Inc., Bække, Denmark).

Collection of Ingredients

Four samples of each ingredient were collected by the Danish Pig Research Centre at local swine production units or at feed mills in Denmark. Samples were collected from October 2012 to February 2013 to ensure that the ingredients used in the experiment represented different production batches. The 4 samples of each ingredient were thoroughly mixed and then divided using a riffle type divider (Rationel Kornservice Inc., Esbjerg, Denmark), and a representative subsample was collected and used in the experiment. Therefore, all ingredients were from commercial sources but were not collected directly from the manufacturer.

Diets, Animals, Housing, and Experimental Design

Eight diets were prepared (Tables 2 and 3). Seven diets contained 1 of the 7 AA containing ingredients (i.e., ESBM-1, ESBM-2, SBM-EX, SPC, SBM-CV, RSE, or FCM) as the sole source of AA. A N-free diet was also prepared and used to calculate basal endogenous losses of CP and AA. Vitamins and minerals were included in all diets to meet or exceed requirement estimates (NRC, 2012). Each diet also contained 0.4% chromic oxide as an indigestible marker. No antibiotic growth promoters were used in the diets.

Twenty-seven barrows were weaned at approximately 21 d of age and fed a starter diet containing 20% SBM-CV for 2 wk after weaning. Pigs were then surgically equipped with a T-cannula in the distal ileum using procedures adapted from Stein et al. (1998) when they had an average BW of 9.29 ± 0.58 kg. Following the surgery, pigs were allowed 5 d for recovery and then randomly allotted to three 9 × 5 Youden squares with 9 pigs and 5 periods in each square. Within each square, 2 pigs were assigned to the N-free diet and 1 pig was assigned to each of the remaining diets. As a consequence, there were a total of 15 replications for all the AA-containing diets and 30 replications for the N-free diet. Pigs were housed in individual pens (1.2 by 1.5 m) that had smooth side panels and fully slatted tri-bar stainless steel floors in an environmentally controlled room, and each pen was equipped with a feeder and a nipple drinker.

All pigs were fed at a daily level of 3 times the estimated maintenance energy requirement (i.e., 197 kcal ME/kg$^{0.60}$; NRC, 2012) throughout the experiment. Daily allotments of feed were divided into 2 equal meals that were provided at 0700 and 1600 h. Pigs had free access to water throughout the experiment.

Data Recording and Sample Collection

Pig weights were recorded at the beginning of each period and at the conclusion of the experiment. The amount of feed supplied each day was also recorded. The initial 5 d of each period was considered an adaptation period to the diet. Ileal digesta were collected for 8 h on d 6 and 7 as explained by Stein et al. (1999). In short, a plastic bag was attached to the cannula barrel and digesta flowing into the bag was collected. Bags were removed whenever they were filled with digesta,

Table 1. Analyzed nutrient composition of 2 sources of enzyme-treated soybean meal, extruded soybean meal, soy protein concentrate, conventional dehulled soybean meal, conventional 00-rapeseed expellers, and a fermented coproduct mixture containing fermented 00-rapeseed meal, wheat, soy molasses, and potato peel, as-fed basis

	Ingredient[1]						
Item	ESBM-1	ESBM-2	SBM-EX	SPC	SBM-CV	RSE	FCM
GE, kcal/kg	4,555	4,380	4,454	4,499	4,140	4,533	4,154
DM, %	91.98	91.17	92.85	91.71	88.67	88.58	87.09
CP, %	56.82	52.07	53.28	62.05	47.81	30.13	32.00
Ca, %	0.31	0.33	0.29	0.32	0.30	0.78	0.66
P, %	0.70	0.73	0.64	0.63	0.60	0.96	0.91
Ash, %	6.47	6.85	6.36	5.97	6.09	6.52	6.85
OM, %	85.51	84.32	86.49	85.74	82.58	82.06	80.24
AEE,[2] %	1.81	0.70	1.82	1.01	1.23	10.22	4.31
NDF, %	9.16	9.48	12.73	19.69	7.76	24.54	22.88
ADF, %	4.85	4.99	5.09	10.26	5.13	18.93	14.81
Trypsin inhibitor activity, TIU[3]/mg	2.00	1.60	2.50	1.60	2.70	1.40	<1.00
Glucosinolates, µmol/g	–	–	–	–	–	16.11	2.77
Carbohydrates, %							
Sucrose	0.06	1.90	5.18	0.98	6.29	6.04	1.46
Stachyose	0.18	1.72	4.77	1.92	4.88	1.65	1.15
Raffinose	0.04	0.37	1.13	0.33	0.93	0.34	0.28
Indispensable AA, %							
Arg	4.00	3.64	3.75	4.54	3.44	1.73	1.80
His	1.43	1.31	1.30	1.57	1.22	0.79	0.75
Ile	2.63	2.38	2.40	2.93	2.18	1.21	1.11
Leu	4.31	3.89	4.02	4.85	3.60	1.96	2.12
Lys	3.64	3.14	3.17	3.90	3.02	1.78	1.65
Met	0.74	0.70	0.67	0.82	0.65	0.59	0.59
Phe	2.86	2.57	2.71	3.22	2.37	1.16	1.27
Thr	2.10	1.92	1.95	2.35	1.79	1.28	1.31
Trp	0.74	0.65	0.70	0.77	0.66	0.39	0.37
Val	2.82	2.57	2.49	3.08	2.35	1.47	1.58
Total	25.27	22.77	23.16	28.03	21.28	12.36	12.55
Dispensable AA, %							
Ala	2.43	2.22	2.20	2.66	2.03	1.26	1.43
Asp	6.28	5.72	5.94	7.08	5.35	2.10	2.27
Cys	0.74	0.70	0.65	0.77	0.62	0.65	0.68
Glu	9.54	8.65	8.96	10.69	8.17	4.47	4.93
Gly	2.33	2.13	2.12	2.54	1.96	1.43	1.52
Pro	2.92	2.63	2.63	3.13	2.33	1.74	1.98
Ser	2.45	2.22	2.40	2.81	2.10	1.17	1.19
Tyr	1.99	1.81	1.88	2.19	1.68	0.85	0.93
Total	28.68	26.08	26.78	31.87	24.24	13.67	14.93
Total AA, %	53.95	48.85	49.94	59.90	45.52	26.03	27.48
Calculated values							
Lys:CP ratio,[4] %	6.41	6.03	5.95	6.29	6.32	5.91	5.16

[1]ESBM-1 = enzyme-treated soybean meal 1; ESBM-2 = enzyme-treated soybean meal 2; SBM-EX = extruded soybean meal; SPC = soy protein concentrate; SBM-CV = conventional dehulled soybean meal; RSE = conventional 00-rapeseed expellers; FCM = fermented coproduct mixture.

[2]AEE = acid hydrolyzed ether extract.

[3]TIU = trypsin inhibitor units.

[4]The Lys:CP ratio was expressed as the concentration of Lys as a percentage of the concentration of CP in each sample (González-Vega et al., 2011).

or at least once every 30 min, and stored at −20°C to prevent bacterial degradation of the AA in the digesta. On the completion of one experimental period, animals were deprived of feed overnight, and the following morning, a new experimental diet was offered.

Chemical Analysis

At the conclusion of the experiment, ileal samples were thawed and mixed within animal and diet, and a subsample was collected for chemical analysis. Samples

Table 2. Ingredient composition of experimental diets containing enzyme-treated soybean meal, extruded soybean meal, soy protein concentrate, conventional dehulled soybean meal, conventional 00-rapeseed expellers, and a fermented coproduct mixture containing fermented 00-rapeseed meal, wheat, soy molasses, and potato peel, as-fed basis

	Diet[1]							
Ingredient, %	ESBM-1	ESBM-2	SBM-EX	SPC	SBM-CV	RSE	FCM	N free
ESBM-1	35.00	–	–	–	–	–	–	–
ESBM-2	–	35.00	–	–	–	–	–	–
SBM-EX	–	–	35.00	–	–	–	–	–
SPC	–	–	–	30.00	–	–	–	–
SBM-CV	–	–	–	–	40.00	–	–	–
RSE	–	–	–	–	–	40.00	–	–
FCM	–	–	–	–	–	–	40.00	–
Soybean oil	3.00	3.00	3.00	3.00	3.00	3.00	3.00	4.00
Solka floc[2]	–	–	–	–	–	–	–	4.00
Monocalcium phosphate	0.85	0.85	0.85	0.85	0.85	0.50	0.50	2.40
Limestone	1.45	1.45	1.45	1.45	1.45	1.50	1.50	0.50
Sucrose	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
Chromic oxide	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Cornstarch	38.60	38.60	38.60	43.60	33.60	33.90	33.90	67.50
Magnesium oxide	–	–	–	–	–	–	–	0.10
Potassium carbonate	–	–	–	–	–	–	–	0.40
Sodium chloride	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin–mineral premix[3]	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

[1]ESBM-1 = enzyme-treated soybean meal 1; ESBM-2 = enzyme-treated soybean meal 2; SBM-EX = extruded soybean meal; SPC = soy protein concentrate; SBM-CV = conventional dehulled soybean meal; RSE = conventional 00-rapeseed expellers; FCM = fermented coproduct mixture.

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

[3]The vitamin–micromineral premix provided the following quantities of vitamins and microminerals per kilogram of complete diet: 11,136 IU vitamin A as retinyl acetate, 2,208 IU vitamin D_3 as cholecalciferol, 66 IU vitamin E as DL-alpha tocopheryl acetate, 1.42 mg vitamin K as menadione dimethylprimidinol bisulfite, 0.24 mg thiamin as thiamine mononitrate, 6.59 mg riboflavin, 0.24 mg pyridoxine as pyridoxine hydrochloride, 0.03 mg vitamin B_{12}, 23.5 mg d-pantothenic acid as d-calcium pantothenate, 44.1 mg niacin, 1.59 mg folic acid, 0.44 mg biotin, 20 mg Cu as copper sulfate and copper chloride, 126 mg Fe as ferrous sulfate, 1.26 mg I as ethylenediamine dihydriodide, 60.2 mg Mn as manganese sulfate 0.3 mg Se as sodium selenite and selenium yeast, and 125.1 mg Zn as zinc sulfate.

of each diet and of each AA-containing ingredient were collected as well. Digesta samples were lyophilized and ground through a 1-mm screen in a Wiley mill (model 4; Thomas Scientific, Swedesboro, NJ) prior to chemical analysis. All samples of ingredients and ileal digesta were analyzed in duplicate, with the exception that ileal digesta from N-free fed pigs were analyzed in duplicate in 2 separate samples. All diet samples were analyzed in duplicate in 4 separate samples. All samples were analyzed for DM by oven drying samples at 135°C for 2 h (method 930.15; AOAC, 2007) and also for ash (method 942.05; AOAC, 2007). The concentration of N in all samples was determined using the combustion procedure (method 990.03; AOAC, 2007) on an Elementar Rapid N-cube protein/nitrogen apparatus (Elementar Americas Inc., Mt. Laurel, NJ). Aspartic acid was used as a calibration standard, and CP was calculated as N × 6.25. Amino acids were analyzed in all samples on an Amino Acid Analyzer (model L8800; Hitachi High Technologies America Inc., Pleasanton, CA) using ninhydrin for postcolumn derivatization and norleucine as the internal standard. Before analysis, samples were hydrolyzed with 6 *N* HCl for 24 h at 110°C (method 982.30 E(a); AOAC, 2007). Methionine and Cys were analyzed as methionine sulfone and cysteic acid after cold performic acid oxidation overnight before hydrolysis (method 982.30 E(b); AOAC, 2007). Tryptophan was determined after NaOH hydrolysis for 22 h at 110°C (method 982.30 E(c); AOAC, 2007). The Cr concentration in diets and ileal digesta samples was determined using an inductive coupled plasma atomic emission spectrometric method (method 990.08; AOAC, 2007) after nitric acid–perchloric acid wet ash sample preparation (method 968.088D; AOAC, 2007). Diet and ingredient samples were also analyzed for ADF (method 973.18; AOAC, 2007) and NDF (Holst, 1973). Ingredients were also analyzed for Ca and P (method 975.03; AOAC, 2007), and concentration of acid hydrolyzed ether extract (**AEE**) was measured in all ingredients by acid hydrolysis using 3 *N* HCl (Sanderson, 1986) followed by crude fat extraction using petroleum ether (method 2003.06; AOAC, 2007) on an automated analyzer (Soxtec 2050; FOSS North America, Eden Prairie, MN). All ingredient samples were analyzed for trypsin inhibitor activity (method Ba

Table 3. Analyzed nutrient composition of experimental diets containing enzyme-treated soybean meal, extruded soybean meal, soy protein concentrate, conventional dehulled soybean meal, conventional 00-rapeseed expellers, and a fermented coproduct mixture containing fermented 00-rapeseed meal, wheat, soy molasses, and potato peel, as-fed basis

	Diet[1]							
Item	ESBM-1	ESBM-2	SBM-EX	SPC	SBM-CV	RSE	FCM	N free
GE, kcal/kg	4,083	4,032	4,031	3,978	3,921	4,125	3,957	3,716
DM, %	92.93	94.59	92.82	92.49	90.56	91.84	90.91	91.51
CP, %	19.98	18.10	18.76	18.81	19.21	12.19	12.47	0.25
Ash, %	5.02	5.43	4.84	4.56	5.67	5.48	5.45	3.64
OM, %	87.91	89.16	87.98	87.92	84.88	86.37	85.46	87.87
NDF, %	3.80	3.38	4.49	6.08	4.07	11.59	10.13	4.82
ADF, %	1.96	1.86	1.98	2.46	2.48	8.54	6.22	3.24
Cr, %	0.21	0.22	0.22	0.22	0.21	0.21	0.22	0.19
Indispensable AA, %								
Arg	1.40	1.25	1.33	1.46	1.36	0.78	0.67	0.01
His	0.51	0.45	0.46	0.51	0.49	0.35	0.29	0.00
Ile	0.93	0.80	0.83	0.93	0.87	0.51	0.44	0.01
Leu	1.55	1.38	1.43	1.61	1.48	0.93	0.81	0.03
Lys	1.27	1.08	1.13	1.27	1.20	0.81	0.62	0.00
Met	0.26	0.25	0.24	0.26	0.26	0.26	0.22	0.00
Phe	1.01	0.90	0.98	1.06	0.97	0.53	0.47	0.02
Thr	0.74	0.69	0.72	0.78	0.73	0.59	0.51	0.01
Trp	0.28	0.26	0.27	0.26	0.28	0.19	0.17	<0.04
Val	1.00	0.86	0.86	0.97	0.92	0.67	0.58	0.00
Total	8.95	7.92	8.25	9.11	8.56	5.62	4.78	0.12
Dispensable AA, %								
Ala	0.88	0.78	0.81	0.88	0.82	0.59	0.55	0.02
Asp	2.23	2.00	2.14	2.33	2.15	0.97	0.86	0.02
Cys	0.26	0.24	0.23	0.25	0.25	0.30	0.25	0.01
Glu	3.43	3.07	3.28	3.54	3.30	2.05	1.89	0.03
Gly	0.83	0.74	0.77	0.83	0.79	0.67	0.58	0.01
Pro	1.02	0.91	0.95	1.03	0.99	0.81	0.72	0.09
Ser	0.86	0.82	0.90	0.97	0.87	0.54	0.47	0.01
Tyr	0.65	0.58	0.62	0.66	0.63	0.37	0.32	0.01
Total	10.16	9.14	9.70	10.49	9.80	6.30	5.64	0.20

[1]ESBM-1 = enzyme-treated soybean meal 1; ESBM-2 = enzyme-treated soybean meal 2; SBM-EX = extruded soybean meal; SPC = soy protein concentrate; SBM-CV = conventional dehulled soybean meal; RSE = conventional 00-rapeseed expellers; FCM = fermented coproduct mixture.

12-75; AOCS, 2006) and for sucrose, stachyose, and raffinose (Janauer and Englmaier, 1978), and RSE and FCM were also analyzed for glucosinolates (method Ak 1-92; AOCS, 1998). Diets and ingredients were analyzed for GE using a bomb calorimeter (model 6300; Parr Instrument Co., Moline, IL) with benzoic acid being the internal standard.

Calculations and Statistical Analysis

Apparent ileal digestibility values for ash and OM in all diets and of CP and AA in the 7 CP-containing diets were calculated. Values for the AID of ash and OM represent the AID for the diet, but because the soybean products, RSE, or FCM contributed all CP and AA to the diets, the AID of CP and AA for the diets also represent the AID of CP and AA for each ingredient. Equation [1] (Stein et al., 2007) was used to calculate the AID:

$$\mathrm{AID} = 1 - [(\mathrm{AA_d}/\mathrm{AA_f}) \times (\mathrm{Cr_f}/\mathrm{Cr_d})] \times 100, \quad [1]$$

in which AID is the apparent ileal digestibility value of an AA (%), $\mathbf{AA_d}$ is the concentration of that AA in the ileal digesta DM, $\mathbf{AA_f}$ is the AA concentration of that AA in the feed DM, $\mathbf{Cr_f}$ is the chromium concentration in the feed DM, and $\mathbf{Cr_d}$ is the chromium concentration in the ileal digesta DM. The AID of ash, CP, and OM was also calculated using this equation.

The basal endogenous flow to the distal ileum of each AA was determined based on the flow obtained after feeding the N-free diet using Eq. [2] (Stein et al., 2007):

$$\mathrm{IAA_{end}} = [\mathrm{AA_d} \times (\mathrm{Cr_f}/\mathrm{Cr_d})], \quad [2]$$

in which $\mathbf{IAA_{end}}$ is the basal endogenous loss of an AA (mg/kg DMI). The basal endogenous loss of CP was determined using the same equation.

Table 4. Apparent ileal digestibility (AID) of ash and OM in diets containing enzyme-treated soybean meal, extruded soybean meal, soy protein concentrate, conventional dehulled soybean meal, conventional 00-rapeseed expellers, a fermented coproduct mixture containing fermented 00-rapeseed meal, wheat, soy molasses, and potato peel, and a N-free diet fed to pigs[1]

	Diet[2]								Pooled	
Item, %	ESBM-1	ESBM-2	SBM-EX	SPC	SBM-CV	RSE	FCM	N-free	SEM	*P*-value
Ash	37.86[bcd]	37.15[bcd]	31.70[cde]	40.55[abc]	52.87[a]	22.54[e]	26.10[de]	48.32[ab]	3.65	<0.01
OM	84.41[bc]	82.52[c]	83.31[bc]	85.36[b]	84.21[bc]	76.89[d]	75.71[d]	91.39[a]	0.70	<0.01

[a–e]Means within a row with different superscripts differ ($P < 0.05$).

[1]Data are least squares means of 15 observations for all treatments except that data are least squares means of 30 observations for the N-free diet; AID = 1 − (ash or OM in digesta/ash or OM in feed) × (Cr in feed/Cr in digesta) × 100%.

[2]ESBM-1 = enzyme-treated soybean meal 1; ESBM-2 = enzyme-treated soybean meal 2; SBM-EX = extruded soybean meal; SPC = soy protein concentrate; SBM-CV = conventional dehulled soybean meal; RSE = conventional 00-rapeseed expellers; FCM = fermented coproduct mixture.

By correcting the AID for the IAA_{end} of each AA, standardized ileal AA digestibility values were calculated using Eq. [3] (Stein et al., 2007):

$$SID = [(AID + IAA_{end})/AA_f], \quad [3]$$

in which SID is the standardized ileal digestibility value (%). The SID of CP was also calculated using this equation.

Normality of data was verified and outliers were identified using the UNIVARIATE procedure (SAS Inst. Inc., Cary, NC). An observation was considered an outlier if the value was more than 3 SD away from the grand mean. Data were analyzed by ANOVA using the PROC MIXED of SAS in a randomized complete block design with the pig as the experimental unit. The statistical model included diet as the fixed effect and pig and period as random effects. When diet was a significant source of variation, treatment means were separated and compared using the LSMEANS statement and Bonferroni correction in PROC MIXED. Statistical significance and tendency were considered at $P < 0.05$ and $0.05 \le P < 0.10$, respectively.

RESULTS

The final BW of pigs was 19.53 ± 2.74 kg. The analyzed concentration of CP in the SBM products ranged from 47.81 to 62.05%, and RSE and FCM contained 30.13 and 32.00% CP, respectively. The SBM products contained 4,140 to 4,555 kcal/kg GE, 0.29 to 0.33% Ca, 0.60 to 0.73% P, 0.70 to 1.81% AEE, 7.76 to 19.69% NDF, and 4.85 to 10.26% ADF. However, RSE and FCM contained 4,533 and 4,154 kcal/kg GE, 0.78 and 0.66% Ca, 0.96 and 0.91% P, 10.22 and 4.31% AEE, 24.54 and 22.88% NDF, and 19.93 and 14.81% ADF, respectively. The trypsin inhibitor activity in the SBM products ranged from 1.60 to 2.70 trypsin inhibitor units (**TIU**)/mg, and there was 1.40 TIU/mg in RSE but less than 1.00 TIU/mg in FCM. The concentrations of glucosinolates were 16.11 μmol/g in RSE and 2.77 μmol/g in FCM. The SBM products contained 0.06 to 6.29% sucrose, 0.18 to 4.88% stachyose, and 0.04 to 0.93% raffinose, whereas RSE and FCM contained 6.04 and 1.46% sucrose, 1.65 and 1.15% stachyose, and 0.34 and 0.28% raffinose, respectively. The SBM products contained 21.28 to 28.03% indispensable AA and 24.24 to 31.87% dispensable AA, whereas RSE and FCM contained 12.36 and 12.55% indispensable AA, respectively, and 13.67 and 14.93% dispensable AA, respectively.

Among the diets containing SBM products, the AID of ash in the SBM-CV diet was greater ($P < 0.05$) than in the ESBM-1 diet, the ESBM-2 diet, and the SBM-EX diet but not different from the SPC diet (Table 4). No difference was observed in the AID of OM among diets containing SBM products, except that the SPC diet had greater ($P < 0.05$) AID of OM than the ESBM-2 diet. No differences were observed in the AID of ash and OM between the RSE diet and the FCM diet. The N-free diet had greater ($P < 0.05$) AID of ash than the SBM-EX diet, the RSE diet, and the FCM diet and had greater ($P < 0.05$) AID of OM than all other diets.

Among the SBM products, the AID and SID of CP in ESBM-1 was greater ($P < 0.05$) than in SPC, but not different from ESBM-2, SBM-EX, and SBM-CV (Tables 5 and 6). No differences were observed in AID or SID of CP among ESBM-2, SBM-EX, SPC, and SBM-CV. The AID and SID of CP in the 2 rapeseed products was less ($P < 0.05$) than in all SBM products, except that no difference was observed in the SID of CP among ESBM-2, SPC, and RSE. However, the AID and SID of CP were greater ($P < 0.05$) in RSE than in FCM.

Among the SBM products, ESBM-1 had greater ($P < 0.05$) AID of Arg, His, Ile, Leu, Met, Phe, and Trp than SPC, greater ($P < 0.05$) AID of Arg, Thr, and Val than ESBM-2, and greater ($P < 0.05$) AID of Val than SBM-EX. The AID of Lys was greater ($P < 0.05$) in SBM-CV than in ESBM-2 but not different from the other SBM products. Therefore, the AID of total indispensable AA was greater ($P < 0.05$) in ESBM-1 than

Table 5. Apparent ileal digestibility of CP and AA in enzyme-treated soybean meal, extruded soybean meal, soy protein concentrate, conventional dehulled soybean meal, conventional 00-rapeseed expellers, and a fermented coproduct mixture containing fermented 00-rapeseed meal, wheat, soy molasses, and potato peel fed to pigs[1]

	Ingredient[2]							Pooled	
Item, %	ESBM-1	ESBM-2	SBM-EX	SPC	SBM-CV	RSE	FCM	SEM	P-value
CP	81.9^{a}	75.1^{ab}	76.6^{ab}	72.7^{b}	78.9^{ab}	65.0^{c}	56.5^{d}	2.27	<0.01
Indispensable AA									
Arg	91.6^{a}	87.4^{b}	89.4^{ab}	87.2^{b}	90.1^{ab}	80.7^{c}	70.1^{d}	1.23	<0.01
His	89.4^{a}	86.1^{abc}	85.9^{abc}	85.0^{bc}	87.5^{ab}	82.1^{c}	72.7^{d}	1.47	<0.01
Ile	88.7^{a}	85.3^{ab}	86.5^{ab}	84.3^{b}	86.5^{ab}	75.8^{c}	68.0^{d}	1.31	<0.01
Leu	88.5^{a}	85.7^{ab}	86.4^{ab}	84.5^{b}	86.5^{ab}	79.8^{c}	72.6^{d}	1.33	<0.01
Lys	84.5^{ab}	79.1^{bc}	83.2^{ab}	83.7^{ab}	86.2^{a}	75.7^{c}	58.4^{d}	1.69	<0.01
Met	90.3^{a}	87.6^{abc}	87.7^{abc}	86.1^{bc}	89.4^{ab}	85.1^{c}	80.6^{d}	1.08	<0.01
Phe	89.6^{a}	86.6^{ab}	87.7^{ab}	85.9^{b}	86.9^{ab}	79.7^{c}	73.7^{d}	1.30	<0.01
Thr	80.7^{a}	76.5^{b}	78.3^{ab}	79.6^{ab}	80.5^{ab}	69.7^{c}	60.8^{d}	1.46	<0.01
Trp	89.5^{a}	85.8^{bc}	87.2^{ab}	85.9^{bc}	88.6^{ab}	83.3^{c}	79.2^{d}	1.29	<0.01
Val	85.3^{a}	80.7^{b}	81.0^{b}	81.6^{ab}	83.3^{ab}	72.0^{c}	63.4^{d}	1.46	<0.01
Mean	87.5^{a}	83.7^{b}	85.7^{ab}	84.4^{ab}	86.3^{ab}	77.6^{c}	68.0^{d}	1.19	<0.01
Dispensable AA									
Ala	81.1^{a}	75.8^{abc}	77.6^{ab}	74.2^{bc}	79.5^{ab}	70.9^{c}	62.1^{d}	2.10	<0.01
Asp	85.3^{a}	82.6^{a}	81.9^{a}	82.7^{a}	84.5^{a}	73.7^{b}	61.5^{c}	1.38	<0.01
Cys	74.8^{ab}	69.2^{bc}	71.0^{ab}	71.5^{ab}	77.1^{a}	74.2^{ab}	62.5^{c}	2.86	<0.01
Glu	87.6^{a}	84.3^{ab}	85.3^{ab}	85.6^{ab}	87.6^{a}	83.3^{b}	77.3^{c}	1.64	<0.01
Gly	64.6^{a}	52.5^{a}	57.4^{a}	52.4^{a}	63.5^{a}	53.2^{a}	31.0^{b}	4.19	<0.01
Pro	31.0^{a}	−0.2^{abc}	16.1^{abc}	−13.8^{c}	26.4^{ab}	−5.1^{bc}	−74.7^{d}	14.67	<0.01
Ser	86.7^{a}	83.6^{a}	86.3^{a}	86.3^{a}	86.9^{a}	73.2^{b}	65.6^{c}	1.12	<0.01
Tyr	89.2^{a}	85.7^{a}	87.3^{a}	86.2^{a}	87.2^{a}	75.4^{b}	70.1^{c}	1.24	<0.01
Mean	78.1^{a}	70.4^{bc}	73.2^{ab}	69.8^{bc}	76.9^{ab}	64.7^{c}	46.5^{d}	2.78	<0.01

[a–d]Means within a row with different superscripts differ ($P < 0.05$).

[1]Data are least squares means of 15 observations for all treatments.

[2]ESBM-1 = enzyme-treated soybean meal 1; ESBM-2 = enzyme-treated soybean meal 2; SBM-EX = extruded soybean meal; SPC = soy protein concentrate; SBM-CV = conventional dehulled soybean meal; RSE = conventional 00-rapeseed expellers; FCM = fermented coproduct mixture.

in ESBM-2, but no differences were observed among the other SBM products. The AID of all indispensable AA was less ($P < 0.05$) in FCM than in all SBM products, and the AID of all AA in RSE was also less ($P < 0.05$) than in ESBM-1 and SBM-CV, and the AID of most AA in RSE was less ($P < 0.05$) than in ESBM-2, SBM-EX, and SPC. The AID of all indispensable AA was greater ($P < 0.05$) in RSE than in FCM.

Among the SBM products, the AID of Ala was greater ($P < 0.05$) in ESBM-1 than in SPC, the AID of Cys was greater ($P < 0.05$) in SBM-CV than in ESBM-2, the AID of Pro was greater ($P < 0.05$) in ESBM-1 and SBM-CV than in SPC, and the AID of total dispensable AA was greater ($P < 0.05$) in ESBM-1 than in ESBM-2 and SPC. The AID of Ala, Glu, and total dispensable AA was less ($P < 0.05$) in RSE than in ESBM-2 and SPC, and the AID of Asp, Ser, and Tyr was less ($P < 0.05$) in RSE than in all SBM products. The AID of all dispensable AA was also less ($P < 0.05$) in FCM than in RSE and in all SBM products. The AID of total AA was greater ($P < 0.05$) in ESBM-1 than in SPC, but no difference was observed in the AID of total AA among the other SBM products. The AID of total AA was less ($P < 0.05$) in the 2 rapeseed products than in all SBM products, except that the AID of total AA was not different between RSE and SPC. However, the AID of total AA was greater ($P < 0.05$) in RSE than in FCM.

Among the SBM products, ESBM-1 had greater ($P < 0.05$) SID of Arg, His, Ile, Leu, Met, and Phe than SPC and the SID of Lys was greater ($P < 0.05$) in SBM-CV than in ESBM-2, but no other differences were observed among the SBM products. Therefore, no differences were observed in the SID of total indispensable AA among the SBM products. The SID of most indispensable AA was less ($P < 0.05$) in RSE than in the SBM products, with the exception that the SID of Arg, His, Lys, Met, and Trp in ESBM-2, the SID of His, Met, and Trp in SBM-EX, the SID of Arg, His, Leu, Met, and Trp in SPC, and the SID of His and Trp in SBM-CV were not different from the SID of these AA in RSE. However, the SID of total indispensable AA was less ($P < 0.05$) in RSE than in all SBM products. The SID of all indispensable AA was also less ($P < 0.05$) in FCM than in RSE and all SBM products.

Table 6. Standardized ileal digestibility of CP and AA in enzyme-treated soybean meal, extruded soybean meal, soy protein concentrate, conventional dehulled soybean meal, conventional 00-rapeseed expellers, and a fermented coproduct mixture containing fermented 00-rapeseed meal, wheat, soy molasses, and potato peel fed to pigs[1,2]

	Ingredient[3]							Pooled	
Item, %	ESBM-1	ESBM-2	SBM-EX	SPC	SBM-CV	RSE	FCM	SEM	*P*-value
CP	89.9[a]	85.2[abc]	86.2[ab]	82.2[bc]	88.0[ab]	79.5[c]	70.6[d]	2.27	<0.01
Indispensable AA									
Arg	96.9[a]	93.5[abc]	95.0[ab]	92.3[bc]	95.4[ab]	90.1[c]	81.1[d]	1.23	<0.01
His	93.4[a]	90.6[ab]	90.3[ab]	88.9[b]	91.5[ab]	87.9[b]	79.6[c]	1.47	<0.01
Ile	91.7[a]	88.9[ab]	89.9[ab]	87.3[b]	89.7[ab]	81.3[c]	74.4[d]	1.31	<0.01
Leu	91.7[a]	89.2[ab]	89.6[ab]	87.5[bc]	89.7[ab]	84.9[c]	78.4[d]	1.32	<0.01
Lys	87.3[ab]	82.5[bc]	86.4[ab]	86.5[ab]	89.2[a]	80.2[c]	64.2[d]	1.69	<0.01
Met	92.9[a]	90.5[abc]	90.6[abc]	88.8[bc]	92.1[ab]	87.8[c]	83.7[d]	1.10	<0.01
Phe	92.6[a]	90.1[ab]	90.8[ab]	88.8[b]	89.9[ab]	85.3[c]	79.9[d]	1.30	<0.01
Thr	87.5[a]	83.9[a]	85.3[a]	86.0[a]	87.3[a]	78.1[b]	70.6[c]	1.47	<0.01
Trp	93.3[a]	90.0[ab]	91.1[ab]	90.00[ab]	92.3[ab]	89.0[b]	85.3[c]	1.29	<0.01
Val	90.0[a]	86.2[a]	86.4[a]	86.4[a]	88.2[a]	78.9[b]	71.4[c]	1.46	<0.01
Mean	91.4[a]	88.3[a]	89.9[a]	88.3[a]	90.3[a]	83.8[b]	75.2[c]	1.19	<0.01
Dispensable AA									
Ala	88.3[a]	83.9[ab]	85.4[ab]	81.3[b]	87.0[ab]	81.5[b]	73.2[c]	2.10	<0.01
Asp	88.5[a]	86.3[a]	85.3[a]	85.8[a]	87.8[a]	81.1[b]	69.7[c]	1.38	<0.01
Cys	82.3[ab]	77.3[b]	79.3[ab]	79.0[ab]	84.6[a]	80.5[ab]	70.2[c]	2.88	<0.01
Glu	90.1[a]	87.1[a]	87.9[a]	88.1[a]	90.2[a]	87.5[a]	81.8[b]	1.64	<0.01
Gly	86.6[a]	77.7[a]	81.1[a]	74.5[ab]	86.2[a]	80.2[a]	61.9[b]	4.19	<0.01
Pro	101.2[a]	80.3[ab]	91.6[a]	55.4[b]	97.2[a]	83.1[ab]	22.5[c]	14.67	<0.01
Ser	92.0[a]	89.2[a]	91.3[a]	90.4[a]	91.8[a]	81.4[b]	74.8[c]	1.14	<0.01
Tyr	92.4[a]	89.5[a]	90.9[a]	90.4[a]	90.6[a]	81.2[b]	76.7[c]	1.15	<0.01
Mean	90.0[a]	83.8[ab]	85.6[ab]	81.3[b]	88.9[ab]	83.7[ab]	67.4[c]	2.78	<0.01

[a–d]Means within a row with different superscripts differ ($P < 0.05$).

[1]Data are least squares means of 15 observations for all treatments.

[2]Standardized ileal digestibility values were calculated by correcting the values for apparent ileal digestibility for the basal ileal endogenous losses. Endogenous losses (g/kg of DMI) of CP and AA were as follows: CP, 18.92; Arg, 0.82; His, 0.22; Ile, 0.31; Leu, 0.52; Lys, 0.39; Met, 0.08; Phe, 0.32; Thr, 0.54; Trp, 0.12; Val, 0.50; Ala, 0.66; Asp, 0.78; Cys, 0.21; Glu, 0.92; Gly, 1.99; Pro, 7.33; Ser, 0.48; and Tyr, 0.24.

[3]ESBM-1 = enzyme-treated soybean meal 1; ESBM-2 = enzyme-treated soybean meal 2; SBM-EX = extruded soybean meal; SPC = soy protein concentrate; SBM-CV = conventional dehulled soybean meal; RSE = conventional 00-rapeseed expellers; FCM = fermented coproduct mixture.

Among the SBM products, the SID of Ala was greater ($P < 0.05$) in ESBM-1 than in SPC, the SID of Cys was greater ($P < 0.05$) in SBM-CV than in ESBM-2, and the SID of Pro was greater ($P < 0.05$) in ESBM-1, SBM-EX, and SBM-CV than in SPC, but no other differences were observed among the SBM products. However, the SID of total dispensable AA was greater ($P < 0.05$) in ESBM-1 than in SPC but not different from other SBM products. Compared with the SBM products, RSE had less ($P < 0.05$) SID of Ala than ESBM-1, less ($P < 0.05$) SID of Cys than SBM-CV, and less ($P < 0.05$) SID of Asp, Ser, and Tyr than all SBM products, but the SID of total dispensable AA in RSE was not different from the SBM products. However, the SID of all dispensable AA in FCM was less ($P < 0.05$) than in RSE and all the SBM products. The SID of total AA was greater ($P < 0.05$) in ESBM-1 than in SPC and RSE, and FCM had the least ($P < 0.05$) SID of total AA among all ingredients.

DISCUSSION

Nutritional Characteristics of Ingredients

The chemical composition of SBM-CV was close to expected values (Goebel and Stein, 2011; NRC, 2012; Rojas and Stein, 2013), except for concentrations of sucrose, stachyose, and raffinose, which were less than previously reported. In contrast, concentrations of ADF and NDF were slightly greater than values reported by the NRC (2012) but in good agreement with those reported by Rojas and Stein (2013) and less than values reported by Goebel and Stein (2011).

The chemical composition of ESBM-1 was similar to what was reported by Goebel and Stein (2011), except for concentrations of sucrose, stachyose, and raffinose, which were less than previously observed. However, the concentrations of CP and indispensable AA in ESBM-1 were less than the concentrations reported by Yang et al. (2007).

Concentrations of CP and AA in ESBM-2 were in agreement with values for fermented soybean meal that were reported by Cervantes-Pahm and Stein (2010) and Rojas and Stein (2013), but concentrations of sucrose, stachyose, and raffinose in ESBM-2 were greater than the values reported by Rojas and Stein (2013). This indicates that the process used to produce ESBM-2 was not completely efficient in removing the α-galactosides from the product, which may be a result of different fermentation and incubation conditions. This observation implies that there are differences among different types of enzyme-treated soybean meal (**ESBM**) and that some sources are better suited to be used in diets for young pigs than others.

Concentrations of CP and AA in SBM-EX were close to those determined in ESBM-2, but unlike ESBM-2, SBM-EX is produced by extrusion of dehulled soybean meal with a subsequent enzyme treatment. Concentrations of sucrose, stachyose, and raffinose in SBM-EX were greater than the values reported by Rojas and Stein (2013) for fermented soybean meal, which is likely because SBM-EX was not fermented.

Concentrations of CP and most indispensable AA in SPC were similar to the values for SPC reported by Yang et al. (2007) and Casas et al. (2017) but less than the values reported by Lenehan et al. (2007) and the NRC (2012). This may have been a result of different sources of SBM used during the production of the products. However, the very high concentrations of ADF and NDF in SPC indicate that soy hulls may have been added to this ingredient, which resulted in a reduction in the concentration of CP. It therefore appears that the SPC used in this experiment was somewhat different from traditional sources of SPC. However, working with a different source of SPC from Brazil, much greater concentrations of ADF and NDF compared with those published by the NRC (2012) were recently reported (Casas et al., 2017), indicating that the high concentration of ADF and NDF and the lower concentration of CP may be a characteristic of Brazilian SPC. If indeed that is the case, this implies that SPC from Brazil has a different nutritional value than SPC produced in the United States.

The composition of the RSE was in agreement with expected values, and to our knowledge, no values for the composition of the FCM product in this experiment used have been published. It was, however, surprising that there was sucrose in the FCM product, because sucrose is easily fermented and the fact that sucrose was analyzed in this ingredient may indicate that the fermentation process was not complete.

Ileal Digestibility of Ash and OM

The greater AID of OM in the N-free diet than in any of the other diets was expected because of the low concentration of fiber in the N-free diet. The lack of a difference in the digestibility of OM among the diets containing ESBM-1, ESBM-2, and SBM-EX also was expected because the inclusion rate of soybean products was similar in these diets and results, therefore, indicate that the AID of the digestible nutrients in these 3 ingredients is not different. The observation that the AID of OM in the SPC diet was greater than in the ESBM-2 diet is likely a consequence of the increased concentration of cornstarch in the diet containing SPC compared with the diet containing ESBM-2. However, the AID of OM in the diet containing SBM-CV was expected to be less than in the diets containing the other soybean products because of the reduced inclusion of cornstarch in this diet, but the observation that this was not the case indicates that the AID of nutrients in SBM-CV *per se* may be greater than in the other soybean products. However, the design of the experiment did not allow us to determine the actual AID of OM in the ingredients.

The reduced AID of OM in the diets containing RSE and FCM compared with all other diets mainly reflects the increased fiber concentration in these diets. The inclusion of cornstarch, sucrose, and soybean oil was similar to the inclusion in the diet containing SBM-CV, so the reduced AID of OM in the diets containing RSE or FCM indicate that the AID of OM in RSE and FCM is less than in SBM-CV.

The majority of the ash in all diets was from the minerals that were added to the diets, but between 30 and 45% of the ash in the diets originated from the ash in the protein-containing ingredients. The AID of ash that were calculated for the diets containing ESBM-1, ESBM-2, SBM-EX, or SPC is close to values reported for a corn–soybean meal diet fed to growing–finishing pigs (Urriola and Stein, 2012). However, the observation that the AID of ash in diets containing ESBM-1, ESBM-2, or SBM-EX was less than in the diet containing SBM-CV indicates that the ash fraction in these ingredients may have become less digestible due to the processing. It is also possible that the secretion of minerals into the intestinal tract was greater when diets containing some ingredients vs. other ingredients were provided, because the type of fiber in an ingredient influences the endogenous secretions of minerals into the digestive tract (Urriola and Stein, 2012). In this experiment, however, it was not possible to distinguish between minerals in the ileal digesta of endogenous origin and of dietary origin.

Ileal Digestibility of Amino Acids

Values for AID and SID of CP and AA for SBM-CV concur with previous estimates (Smiricky et al., 2002; Baker et al., 2010; NRC, 2012) but were slightly greater than the values reported by Urbaityte et al. (2009) and

Cervantes-Pahm and Stein (2010). Therefore, the present values are within the range of previously reported values and the source of SBM-CV used in this experiment can be considered a normal source of dehulled SBM.

Values for the AID and SID of AA in ESBM-1 that were obtained in this experiment are very close to or slightly greater than previous values reported for this ingredient (Cervantes-Pahm and Stein, 2010; NRC, 2012). The fact that the SID of most AA in ESBM-1 was not different from values observed in SBM-CV is also in agreement with previous observations.

To our knowledge, no values for AID and SID of CP and AA in ESBM-2 have previously been reported. The observation that the SID of some AA is less in ESBM-2 than in ESBM-1 indicates that the enzyme treatment or the process used to produce ESBM-2 is less efficient in maintaining high AA digestibility compared with the process used to produce ESBM-1. Specifically, the low SID of Lys in ESBM-2 indicates that the heating applied during drying of this product is more severe compared with that used to dry ESBM-1. The fact that the Lys:CP ratio was less for ESBM-2 than for the other soy proteins except for SBM-EX further indicates that this product may have been subjected to stronger heating, because the Lys:CP ratio is an indication of heat damage in soy proteins (González-Vega et al., 2011). In most feed ingredients, the SID of Thr is the least among the indispensable AA because of relatively high concentrations of Thr in the endogenous protein that is lost at the end of the distal ileum. However, for ESBM-2, the SID of Lys was the least among the indispensable AA, which further indicates that this ingredient may have been overheated. Therefore, when purchasing ESBM, it is important to make sure that a product that has been sufficiently incubated with enzymes to hydrolyze the α-galactosides is secured and that the product has not been overheated during drying. This is important because it has been clearly demonstrated that α-galactosides in soy products have a negative impact on growth performance and intestinal health of weanling pigs (Zhang et al., 2001). For manufacturers of ESBM, it is important that quality controls to determine concentrations of residual α-galactosides are in place to avoid selling products that have been insufficiently processed and, therefore, will have a negative impact on pig growth performance. In addition, procedures to monitor heating during drying are needed to ensure that overheating, which reduces SID of AA is avoided.

We are not aware of previous data for the SID of AA in SBM-EX, but the current data indicate that the extrusion process used to produce SBM-EX does not change the SID of AA compared with SBM-CV. The exception to this is that the SID for Lys is less in SBM-EX than in SBM-CV, which is likely a result of overheating this product during the extrusion process, because the Lys:CP ratio for SBM-EX was the least among all soy proteins. The implication of this observation is similar to that described for ESBM in that the quality of SBM-EX can be evaluated based on the Lys:CP ratio to make sure overheating has not caused reduced SID of AA.

There are also no values for AID and SID of CP and AA reported for the specific SPC that was used in this experiment. However, values observed in this experiment for SPC are less than the values reported by Smiricky et al. (2002) and by Cervantes-Pahm and Stein (2008), but the latter 2 experiments were conducted with growing pigs rather than weanling pigs. However, Urbaityte et al. (2009) and Casas et al. (2017) determined SID of AA in different sources of SPC using weanling pigs and reported values that were slightly greater than the values observed in this experiment. It is generally assumed that SID values for AA in SPC are greater than in SBM-CV because many of the carbohydrates and fibers have been removed during production of SPC. In previous experiments in which SID values for AA have been compared between SPC and SBM-CV, values for SPC were greater than for SBM-CV (Cervantes-Pahm and Stein, 2008; Urbaityte et al., 2009; Casas et al., 2017). However, in the present experiment, SID values for SPC were not greater than those in SBM-CV, which indicates that the production processes used to produce the SPC used in this experiment are less efficient in improving AA digestibility compared with what has been observed in previous research. It is also surprising that concentrations of ADF and NDF in SPC are twice as high as in SBM-CV and some of the other soy proteins used in this experiment. Usually, concentrations of ADF and NDF or crude fiber are comparable to or less than in SBM-CV (Cervantes-Pahm and Stein, 2008; Urbaityte et al., 2009; NRC, 2012). It is, therefore, likely that soy hulls or another source of fiber was added during the production process of SPC, which make this ingredient different from traditional SPC, and this may also have contributed to the reduced SID of AA in the SPC used in this experiment. As a consequence, and as discussed above, it appears that SPC produced in Brazil may have a different nutritional value than SPC from the United States. It will, therefore, be important for buyers of SPC to know the origin and the nutritional quality of the product they are purchasing.

The values for AID and SID of CP and AA in RSE are greater than values reported in previous experiments (Woyengo et al., 2010; NRC, 2012), which indicates that the RSE used in this experiment was of high quality although the concentration of CP was less than previously observed (NRC, 2012; Maison and Stein, 2014). Therefore, the present results indicate that weanling pigs have a relatively good digestibility of AA in RSE.

The AID and SID of CP and AA in FCM were less than in all other ingredients, but based on currently available information, it is not possible to determine the reason for these low values. It is likely that because wheat, soy molasses, and potato peel are used in the production of FCM, the increased concentration of fiber has reduced the digestibility of AA. In addition, the extremely low digestibility of Lys in FCM indicates that this product may have been overheated during processing or that Lys possibly was fermented during the fermentation process. The observation that the SID of Lys was less than the SID of Thr is a further indication that the FCM product used in this experiment was overheated. The low AID for OM also indicates that some of the ingredients used in the production of FCM may have had low digestibility. Based on the data obtained in this experiment, it is concluded that because of the low AID and SID of CP and AA in FCM, use of FCM in diets fed to weanling pigs will result in more nitrogen being excreted from the pigs than if the other ingredients tested in this experiment are used.

Conclusions

Results of this research indicate that although processing of soybeans may improve the nutritional value, this is not always the case, and processing may sometimes result in reduced AA digestibility due to overheating. It is also evident that differences among different brands of the same products such as ESBM or SPC may exist, and specifically, there appears to be differences in concentrations of α-galactosides and ADF and NDF, which directly impacts the nutritional value of these ingredients. In addition, for all processed feed ingredients, there is a risk of overheating during drying, which will result in a reduced concentration of Lys and reduced Lys digestibility. As a consequence, producers of all processed feed ingredients should have quality procedures in place that ensure overheating is avoided, and purchasers of processed feed ingredients need to have tools available that allow them to determine if the product they are purchasing has been overheated. Results also indicate that fermentation of a mixture of rapeseed meal, wheat, and relatively low quality coproducts does not result in AID and SID values that are similar to those of unfermented 00-rapeseed expellers or soybean products, and based on the results of this experiment, usage of this ingredient in diets for weanling pigs cannot be recommended.

LITERATURE CITED

American Oil Chemists' Society (AOCS). 1998. Official methods and recommended practices. 3rd ed. AOAC, Urbana, IL.

American Oil Chemists' Society (AOCS). 2006. Official methods and recommended practices. 5th ed. AOCS, Urbana, IL.

AOAC. 2007. Official methods of analysis. 18th ed. AOAC Int., Gaithersburg, MD.

Baker, K. M., B. G. Kim, and H. H. Stein. 2010. Amino acid digestibility in conventional, high-protein, or low-oligosaccharide varieties of full-fat soybeans and in soybean meal by weanling pigs. Anim. Feed Sci. Technol. 162:66–73. doi:10.1016/j.anifeedsci.2010.08.012

Casas, G. A., C. Huang, and H. H. Stein. 2017. Effect of particle size of soy protein concentrate on amino acid digestibility and concentration of metabolizable energy and effects of soy protein concentrate on growth performance and blood characteristics of weanling pigs. J. Anim. Sci. 95:827–836. doi:10.2527/jas.2016.1083

Cervantes-Pahm, S. K., and H. H. Stein. 2008. Effect of dietary soybean oil and soybean protein concentrate on the concentration of digestible amino acids in soybean products fed to growing pigs. J. Anim. Sci. 86:1841–1849. doi:10.2527/jas.2007-0721

Cervantes-Pahm, S. K., and H. H. Stein. 2010. Ileal digestibility of amino acids in conventional, fermented, and enzyme-treated soybean meal and in soy protein isolate, fishmeal, and casein fed to weanling pigs. J. Anim. Sci. 88:2674–2683. doi:10.2527/jas.2009-2677

Choct, M., Y. Dersjant-Li, J. McLeish, and M. Peisker. 2010. Soy oligosaccharides and soluble non-starch polysaccharides: A review of digestion, nutritive and anti-nutritive effects on pigs and poultry. Asian-Australas. J. Anim. Sci. 23:1386–1398. doi:10.5713/ajas.2010.90222

Friesen, K. G., R. D. Goodband, J. L. Nelssen, F. Blecha, D. N. Reddy, P. G. Reddy, and L. J. Kats. 1993. The effects of pre- and post-weaning exposure to soybean meal on growth performance and on the immune response in the early-weaned pig. J. Anim. Sci. 71:2089–2098.

Goebel, K. P., and H. H. Stein. 2011. Phosphorus digestibility and energy concentration of enzyme-treated and conventional soybean meal fed to weanling pigs. J. Anim. Sci. 89:764–772. doi:10.2527/jas.2010-3253

Goerke, M., M. Eklund, N. Sauer, M. Rademacher, H.-P. Piepho, and R. Mosenthin. 2012. Standardized ileal digestibilities of crude protein, amino acids, and contents of antinutritional factors, mycotoxins, and isoflavones of European soybean meal imports fed to piglets. J. Anim. Sci. 90:4883–4895. doi:10.2527/jas.2011-5026

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

Holst, D. O. 1973. Holst filtration apparatus for Van Soest detergent fiber analysis. J. Assoc. Off. Anal. Chem. 56:1352–1356.

Janauer, G. A., and P. Englmaier. 1978. Multi-step time program for the rapid gas-liquid chromatography of carbohydrates. J. Chromatogr. A 153:539–542. doi:10.1016/S0021-9673(00)95518-3

Jones, C. K., J. M. DeRouchey, J. L. Nelssen, M. D. Tokach, S. S. Dritz, and R. D. Goodband. 2010. Effects of fermented soybean meal and specialty animal protein sources on nursery pig performance. J. Anim. Sci. 88:1725–1732. doi:10.2527/jas.2009-2110

Kim, S. W., E. van Heugten, F. Ji, C. H. Lee, and R. D. Mateo. 2010. Fermented soybean meal as a vegetable protein source for nursery pigs: I. Effects on growth performance of nursery pigs. J. Anim. Sci. 88:214–224. doi:10.2527/jas.2009-1993

Lenehan, N. A., J. M. DeRouchy, R. D. Goodband, M. D. Tokach, S. S. Dritz, J. L. Nelssen, C. N. Groesbeck, and K. R. Lawrence. 2007. Evaluation of soy protein concentrates in nursery pig diets. J. Anim. Sci. 85:3013–3021. doi:10.2527/jas.2007-0071

Maison, T., and H. H. Stein. 2014. Amino acid digestibility in canola meal, 00-rapeseed meal, and 00-rapeseed expellers fed to growing pigs. J. Anim. Sci. 92:3502–3514. doi:10.2527/jas.2014-7748

Mawson, R., R. K. Heaney, Z. Zdunczyk, and H. Kozlowska. 1994. Rapeseed meal-glucosinolates and their antinutritional effects. Part 3. Animal growth and performance. Nahrung 38:167–177. doi:10.1002/food.19940380209

NRC. 2012. Nutrient requirements of swine. 11th rev. ed. Natl. Acad. Press, Washington, DC.

Rojas, O. J., and H. H. Stein. 2013. Concentration of digestible, metabolizable, and net energy and digestibility of energy and nutrients in fermented soybean meal, conventional soybean meal, and fish meal fed to weanling pigs. J. Anim. Sci. 91:4397–4405. doi:10.2527/jas.2013-6409

Sanderson, P. 1986. A new method of analysis of feeding stuffs for the determination of crude oils and fats. In: W. Haresign and D. J. A. Cole, editors, Recent advances in animal nutrition. Butterworths, London, UK. p. 77–81. doi:10.1016/B978-0-407-01162-5.50009-5

Smiricky, M. R., C. M. Grieshop, D. M. Albin, J. E. Wubben, V. M. Gabert, and G. C. Fahey Jr. 2002. The influence of soy oligosaccharides on apparent and true ileal amino acid digestibilities and fecal consistency in growing pigs. J. Anim. Sci. 80:2433–2441. doi:10.2527/2002.8092433x

Stein, H. H., S. Aref, and R. A. Easter. 1999. Comparative protein and amino acid digestibilities in growing pigs and sows. J. Anim. Sci. 77:1169–1179. doi:10.2527/1999.7751169x

Stein, H. H., L. L. Berger, J. K. Drackley, G. F. Fahey Jr., D. C. Hernot, and C. M. Parsons. 2008. Nutritional properties and feeding values of soybeans and their coproducts. In: L. A. Johnson, P. J. White, and R. Galloway, editors, Soybeans: Chemistry, production, processing and utilization. AOCS Press, Urbana, IL. p. 613–660. doi:10.1016/B978-1-893997-64-6.50021-4

Stein, H. H., B. Seve, M. F. Fuller, P. J. Moughan, and C. F. M. de Lange. 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

Stein, H. H., C. F. Shipley, and R. A. Easter. 1998. Technical note: A technique for inserting a T-cannula into the distal ileum of pregnant sows. J. Anim. Sci. 76:1433–1436. doi:10.2527/1998.7651433x

Urbaityte, R., R. Mosenthin, M. Eklund, H.-P. Piepho, N. Sauer, and M. Rademacker. 2009. Standardized ileal crude protein and amino acid digestibilities in protein supplements for piglets. Arch. Anim. Nutr. 63:356–378. doi:10.1080/17450390903052631

Urriola, P. E., and H. H. Stein. 2012. Comparative digestibility of energy and nutrients in fibrous feed ingredients fed to Meishan and Yorkshire pigs. J. Anim. Sci. 90:802–812. doi:10.2527/jas.2010-3254

Woyengo, T. A., E. Kiarie, and C. M. Nyachoti. 2010. Energy and amino acid utilization in expeller-extracted canola meal fed to growing pigs. J. Anim. Sci. 88:1433–1441. doi:10.2527/jas.2009-2223

Yang, Y. X., Y. G. Kim, J. D. Lohakare, J. H. Yun, J. K. Lee, M. S. Kwon, J. I. Park, J. Y. Choi, and B. J. Chae. 2007. Comparative efficacy of different soy protein sources on growth performance, nutrient digestibility and intestinal morphology in weaned pigs. Asian-Australas. J. Anim. Sci. 20:775–783. doi:10.5713/ajas.2007.775

Zhang, L., D. Li, S. Qiao, J. Wang, L. Bai, Z. Wang, and I. K. Han. 2001. The effect of soybean galactooligosaccharides on nutrient and energy digestibility and digesta transit time in weanling piglets. Asian-Australas. J. Anim. Sci. 14:1598–1604. doi:10.5713/ajas.2001.1598