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Nutritional value of soy protein concentrate ground to different particle sizes and fed to pigs[1]

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ABSTRACT: Two experiments were conducted to determine the standardized ileal digestibility (SID) of CP and AA and concentrations of DE and ME in soy protein concentrate (SPC) ground to 3 particle sizes and in soybean meal and fish meal when fed to weanling pigs. An additional experiment was conducted to determine effects on growth performance and blood characteristics of including SPC in diets fed to weanling pigs. In Exp. 1, a N-free diet and diets containing soybean meal, fish meal, or SPC ground to a mean particle size of 70, 180, or 700 μm as the only source of AA were fed to 6 barrows (initial BW: 12.90 ± 1.51 kg) that had a T-cannula installed in the distal ileum. In Exp. 2, 36 barrows (13.70 ± 1.86 kg BW) were allotted to a randomized complete block design with 6 diets and 6 replicate pigs per diet. A corn-based diet and diets containing corn and soybean meal, fish meal, or SPC ground to the 3 particle sizes were used. In Exp. 3, 160 pigs (initial BW: 7.06 ± 1.07 kg) were allotted to 4 dietary treatments with 8 pens per treatment and 5 pigs per pen. Pigs were fed one of 4 diets during phase 1 (d 0 to 14 postweaning), and a common diet in phase 2 (d 14 to 28 postweaning). The 4 diets used in phase 1 included a control diet containing fish meal and spray-dried plasma protein, and diets in which fish meal, spray-dried plasma protein, or both fish meal and spray-dried plasma protein were replaced by SPC ground to 180 μm. Results of Exp. 1 indicated that the SID of His, Lys, and Thr tended ($P < 0.10$) to be greater in SPC ground to 180 μm than in soybean meal, and the SID of Arg, Ile, Phe, and Trp was greater ($P < 0.05$) in SPC ground to 70 or 180 μm than in soybean meal. There were no differences in the DE and ME (DM-basis) among corn, soybean meal, fish meal, and SPC ground to 70, 180, or 700 μm. Results of Exp. 3 indicated that growth performance of pigs fed the 4 experimental diets in phase 1 was not different in phase 1, phase 2, or in the entire experiment. In conclusion, grinding SPC to approximately 180 μm maximizes SID of indispensable AA without impacting ME and diets based on soybean meal and SPC as the main protein sources may be fed to pigs during the initial 2 wk postweaning without affecting growth performance.

Key words: amino acid digestibility, energy digestibility, particle size, pigs, soy protein concentrate

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INTRODUCTION

Weanling pigs require high-quality proteins to overcome the stress associated with weaning and the transition to less digestible diets (Pluske et al., 1997). Plant proteins are less expensive than animal proteins, but may contain antinutritional factors that may have negative effects on gut health and growth performance after weaning (Jones et al., 2010). Inclusion of

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soybean meal in diets for weanling pigs is usually limited because of the negative effects of antinutritional factors, such as oligosaccharides, glycinin, β-conglycinin, and trypsin inhibitors on pig growth performance (Lenehan et al., 2007; Zhang et al., 2013). However, processing of soybean meal may result in a reduction in concentrations of antinutritional factors, and therefore in increased tolerance by weanling pigs. Soy protein concentrate (**SPC**) is produced by removing the soluble carbohydrates and some of the nonprotein constituents from defatted soy flakes (Campbell et al., 1985), which reduces the concentration of properties of conventional soybean meal that are not tolerated by weanling pigs.

It has been demonstrated that a reduction in particle size of soybean meal to 185μm increases the digestibility of most indispensable AA (Fastinger and Mahan, 2003). Likewise, improved values of DE and ME have been reported for soybean meal and corn if the particle size is reduced (Fastinger and Mahan, 2003; Rojas and Stein, 2015). Therefore, the first objective was to determine the apparent ileal digestibility (**AID**) and the standardized ileal digestibility (**SID**) of CP and AA and the apparent total digestibility (**ATTD**) of energy and concentrations of DE and ME in SPC ground to 3 different particle sizes (70, 180, or 700 μm) and to compare these values to the AID and SID of CP and AA and DE and ME in soybean meal and fish meal when fed to weanling pigs. The second objective was to determine effects on growth performance and blood characteristics of including SPC in diets fed to weanling pigs.

MATERIALS AND METHODS

The protocols for these experiments were reviewed and approved by the Institutional Animal Care and Use Committee at the University of Illinois, Urbana. Pigs used in the experiments were the offspring of Line 359 boars mated to C-46 sows (Pig Improvement Company, Hendersonville, TN). The SPC and the soybean meal used in these experiments was sourced from Selecta (Goiânia/GO–Brazil), and the fish meal (Select Menhaden) was sourced from Omega Protein (Houston, TX). The 3 sources of SPC were obtained from one batch of soybean meal and ground to average particle sizes of 70, 180, and 700 μm, respectively, and designated as SPC-70, SPC-180, and SPC-700. The soybeans used to produce the SPC were grown in the Mato Grosso region in Brazil and beans were dehulled and defatted using standard procedures for production of de-hulled soybean meal. The SPC was then produced from the soybean meal using an alcohol extraction procedure , which removes most of the low-molecular weight carbohydrates from the soybean meal. The resulting SPC was then desolventized to remove residual ethanol from the product. The SPC-700 product was produced without further processing, but the SPC-70 and SPC-180 products were produced by micronizing the SPC at low temperature and using screens with 70 and 180 microns openings, espectively. The corn was obtained from the University of Illinois Feed Mill (Champaign, IL). The same batches of SPC, soybean meal, and fish meal were used in the 3 experiments (Table 1).

Experiment 1: Amino Acid Digestibility

Experiment 1 was designed to determine the AID and SID of CP and AA in soybean meal, fish meal, and SPC-70, SPC-180, and SPC-700. Each source of protein was included in 1 diet as the only AA containing ingredient. A nitrogen-free diet that was used to measure basal endogenous losses of AA and CP was also formulated. Therefore, 6 diets were prepared (Table 2). Vitamins and minerals were included in all diets to meet or exceed current requirement estimates (NRC, 2012). All diets also contained 0.4% chromic oxide as an indigestible marker and all diets were provided as meal.

Six barrows (initial BW: 12.90 ± 1.51 kg) were equipped with a T-cannula in the distal ileum (Stein et al., 1998) and allotted to a 6 × 6 Latin square design with 6 diets and six 7-d periods in each square. No pig received the same diet more than once during the experiment and there were 6 replicate pigs per treatment. Pigs were housed in individual pens (1.2 × 1.5 m) in an environmentally controlled room. Pens had smooth sides and fully slatted tribar floors. A feeder and a nipple drinker were installed in each pen and pigs had free access to feed and water throughout the experiment.

Pig weights were recorded at the beginning of each period and at the conclusion of the experiment. The initial 5 d of each period were considered an adaptation period to the diet. Ileal digesta were collected for 8 h (from 0700 to 1500 h) on d 6 and 7 by attaching a plastic bag to the cannula barrel and digesta flowing into the bag were collected. Bags were removed whenever they were filled with digesta, or at least once every 30 min, and immediately stored at –20°C to prevent bacterial degradation of 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. At the conclusion of the experiment, ileal samples were thawed, mixed within animal and diet, and a subsample was collected for chemical analysis. Digesta samples were lyophilized and finely ground prior to chemical analysis.

Experiment 2: Energy Measurements

Experiment 2 was conducted to determine the ATTD of GE and the DE and ME in corn, soybean

Table 1. Analyzed composition (as-fed basis) of corn, soybean meal, soy protein concentrate ground to a mean particle size of 70, 180, or 700 μm (SPC-70, SPC-180, and SPC-700, respectively), and fish meal

	Ingredient					
Item	Corn	Soybean meal	SPC-70	SPC-180	SPC-700	Fish meal
DM, %	85.38	89.99	95.81	94.92	94.13	90.99
Ash, %	1.05	7.07	6.88	6.94	6.86	18.71
CP, %	7.22	51.42	62.94	63.79	62.46	64.16
GE, kcal/kg	3934	4322	4564	4529	4507	4287
AEE,[1]%	3.59	0.75	0.71	0.70	0.96	8.66
ADF, %	1.86	5.11	5.01	8.83	8.91	–
NDF, %	7.48	8.65	14.85	14.11	10.96	–
TDF[2], %	8.70	17.50	22.60	22.10	23.50	–
IDF[2], %	8.10	16.20	19.70	20.10	20.40	–
SDF[2],%	0.60	1.30	2.90	2.10	2.90	–
Trypsin inhibitors, TIU[3]/mg	–	4.86	2.46	2.74	1.82	–
Ca, %	0.08	0.28	0.34	0.40	0.36	5.04
P, %	0.22	0.65	0.74	0.75	0.72	3.05
Carbohydrates, %						
Fructose	–	< 0.2	< 0.2	< 0.2	< 0.2	–
Glucose	–	< 0.2	< 0.2	< 0.2	< 0.2	–
Sucrose	–	6.39	1.21	0.85	1.24	–
Maltose	–	< 0.2	< 0.2	< 0.2	< 0.2	–
Lactose	–	< 0.2	< 0.2	< 0.2	< 0.2	–
Stachyose	–	5.28	2.45	2.45	2.25	–
Raffinose	–	1.54	0.45	0.42	0.43	–
Mean particle size, μm	808	1048	122	209	745	594
SD, $\log_{10}$, particle size	0.43	0.27	0.14	0.34	0.41	0.15
Amino acids,%						
Indispensable AA						
Arg	0.31	3.75	4.60	4.65	4.48	3.67
His	0.22	1.32	1.63	1.65	1.61	1.24
Ile	0.25	2.49	3.07	3.16	3.04	2.51
Leu	0.85	3.99	4.97	5.10	4.92	4.28
Lys	0.26	3.23	3.94	4.03	3.89	4.53
Met	0.13	0.69	0.84	0.85	0.84	1.63
Phe	0.35	2.71	3.33	3.41	3.30	2.37
Thr	0.25	1.97	2.44	2.49	2.41	2.44
Trp	0.05	0.69	0.86	0.88	0.83	0.62
Val	0.33	2.57	3.17	3.22	3.12	3.01
Total	3.00	23.41	28.85	29.44	28.44	26.30
Dispensable AA						
Ala	0.51	2.27	2.71	2.74	2.67	3.86
Asp	0.46	5.78	7.10	7.28	7.02	5.36
Cys	0.15	0.67	0.80	0.82	0.78	0.44
Glu	1.30	9.20	11.12	11.50	10.94	7.91
Gly	0.27	2.18	2.59	2.62	2.57	4.58
Pro	0.59	2.57	3.17	3.21	3.13	2.94
Ser	0.32	2.29	2.89	3.14	2.80	2.25
Tyr	0.17	2.04	2.49	2.51	2.38	2.01
Total	3.77	27.00	32.87	33.82	32.29	29.35
Calculated value						
Lys:CP, %	3.60	6.28	6.26	6.32	6.23	7.06

[1]AEE = acid hydrolyzed ether extract.

[2]TDF = total dietary fiber; SDF = soluble dietary fiber; IDF = insoluble dietary fiber.

[3]TIU = trypsin inhibitor units.

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

	Diet[1]					
Item	Soybean meal	SPC-70	SPC-180	SPC-700	Fish meal	N-free
Ingredient, %						
Soybean meal	46.00	–	–	–	–	–
SPC-70	–	35.00	–	–	–	–
SPC-180	–	–	35.00	–	–	–
SPC-700	–	–	–	35.00	–	–
Fish meal	–	–	–	–	30.00	–
Soybean oil	3.00	3.00	3.00	3.00	1.00	4.00
Ground limestone	0.75	0.75	0.75	0.75	–	0.45
Dicalcium phosphate	1.10	1.25	1.25	1.25	–	2.15
Lactose	20.00	20.00	20.00	20.00	20.00	20.00
Cornstarch	28.05	38.90	38.90	38.90	47.90	67.80
Solka floc[2]	–	–	–	–	–	4.00
Magnesium oxide	–	–	–	–	–	0.10
Potassium carbonate	–	–	–	–	–	0.40
Sodium chloride	0.40	0.40	0.40	0.40	0.40	0.40
Chromic oxide	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
Analyzed composition,%						
DM	90.96	92.97	92.59	92.62	90.60	91.06
CP	23.60	22.53	22.76	23.74	19.14	0.83
Indispensable AA						
Arg	1.69	1.56	1.57	1.60	1.07	0.01
His	0.61	0.57	0.57	0.59	0.41	0.00
Ile	1.17	1.07	1.11	1.13	0.80	0.02
Leu	1.85	1.74	1.79	1.81	1.34	0.03
Lys	1.49	1.39	1.41	1.43	1.47	0.05
Met	0.31	0.29	0.29	0.29	0.52	0.00
Phe	1.24	1.15	1.18	1.22	0.72	0.01
Thr	0.85	0.82	0.83	0.85	0.73	0.01
Trp	0.29	0.30	0.30	0.24	0.16	0.01
Val	1.23	1.13	1.15	1.18	0.91	0.02
Dispensable AA						
Ala	1.05	0.97	0.98	1.00	1.15	0.02
Asp	2.66	2.46	2.53	2.55	1.65	0.03
Cys	0.30	0.28	0.28	0.28	0.14	0.03
Glu	4.27	3.97	4.06	4.12	2.47	0.07
Gly	1.02	0.94	0.95	0.97	1.32	0.01
Pro	1.21	1.13	1.14	1.19	0.91	0.07
Ser	0.91	0.93	0.95	0.94	0.61	0.01
Tyr	0.74	0.69	0.69	0.70	0.48	0.01

[1]SPC-70, SPC-180, and SPC-700 indicates soy protein concentrate ground to 70, 180, or 700 μm.

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

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

Table 3. Composition (as-fed basis) of experimental diets, Exp. 2

	Diet[1]					
Item	Corn	Soybean meal	SPC-70	SPC-180	SPC-700	Fish meal
Ingredient, %						
Corn	96.7	67.1	76.0	76.0	76.0	77.3
Soybean meal	–	30.0	–	–	–	–
SPC-70	–	–	21.0	–	–	–
SPC-180	–	–	–	21.0	–	–
SPC-700	–	–	–	–	21.0	–
Fish meal	–	–	–	–	–	22.0
Ground limestone	0.8	0.9	0.9	0.9	0.9	–
Dicalcium phosphate	1.8	1.3	1.4	1.4	1.4	–
Sodium chloride	0.4	0.4	0.4	0.4	0.4	0.4
Vitamin mineral premix[2]	0.3	0.3	0.3	0.3	0.3	0.3
Analyzed composition						
DM, %	80.9	87.2	88.0	88.1	88.3	87.3
GE, kcal/kg	3,660	3,819	3,860	3,846	3,847	3,886

[1]SPC-70, SPC-180, and SPC-700 indicates soy protein concentrate ground to 70, 180, or 700 µm.

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

meal, fish meal, and SPC ground to 70, 180, or 700 µm. Thirty-six barrows (13.70 ± 1.86 kg BW) were allotted to a randomized complete block design with 6 diets and 6 replicate pigs per diet. Pigs were placed in individual metabolism crates that were equipped with a self-feeder, a nipple waterer, and slatted floors to allow for the total, but separate, collection of urine and fecal materials from each pig.

A corn diet was formulated by mixing 96.7% corn and vitamins and minerals, and 5 additional diets were based on a mixture of corn and each source of protein (Table 3).

All diets were fed in meal form. Pigs were fed at 3 times the energy requirement for maintenance (i.e., 197 kcal ME per kg $BW^{0.60}$; NRC, 2012), which was provided daily in 2 equal meals at 0800 and 1500 h. Throughout the experiment, pigs had free access to water. Feed intake was recorded daily and diets were fed for 12 d.

The initial 7 d was the adaptation period to the diet, whereas urine and fecal materials were collected during the following 5 d according to standard procedures using the marker to marker approach (Baker and Stein, 2009; Kim et al., 2009). 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 (Kim et al., 2009). Fecal samples were thawed and mixed within pig and diet, and then dried in a forced-air drying oven at 65°C, and finely ground using a laboratory mill (Model 4, Thomas-Wiley with a 1.0-mm sieve; Thomas Scientific).

Experiment 3: Growth Performance

Experiment 3 was designed to determine effects on growth performance and blood characteristics of including SPC-180 in diets fed to weanling pigs at the expense of spray dried protein plasma or fish meal or both spray dried protein plasma and fish meal. A total of 160 pigs (initial BW: 7.06 ± 1.07 kg) were used. There were 4 dietary treatments and 8 pens per treatment for a total of 32 pens with 5 pigs per pen.

The same batches of soybean meal, fish meal, and SPC-180 as used in Exp. 1 and 2 were used in this experiment. A 2-phase feeding program was used, with weeks 1 and 2 as phase 1 and weeks 3 and 4 as phase 2. Pigs were fed one of 4 diets during phase 1, whereas all pigs were fed a common diet in phase 2. Therefore, a total of 5 diets were formulated (Table 4). The 4 dietary treatments used in phase 1 included a control diet containing 5% fish meal, 5% spray dried protein plasma, and no SPC. Diet 2 contained 5% fish meal, 8% SPC-180, and no spray-dried protein plasma. Diet 3 contained 5% spray-dried protein plasma, 5.25% SPC-180, and no fish meal, and diet 4 contained no spray dried protein plasma, no fish meal, but 13.25% SPC-180. The inclusion of SPC-180 in diets 2, 3, and 4 was calculated to replace an equivalent amount of standardized ileal digestible Lys as provided by the spray dried protein plasma, the fish meal, or both spray-dried protein plasma and fish meal in the control diet. All diets were formulated to meet current estimates for nutrient requirements for weanling pigs (NRC, 2012). Pigs were weighted at the beginning of the experiment and at the conclusion of each phase and daily feed allotments were recorded. The quantities of feed left in the feeders were recorded at the end of each phase.

On the last d of phase 1, the pig in each pen with a BW that was closest to the pen average was identified. Two blood samples were collected from the jugular vein of this pig. Samples were collected in vacutainers containing EDTA and centrifuged at 1500 × *g* at 4°C for 15 min to collect plasma. All samples were then stored at −20°C until analyzed.

Table 4. Ingredient and analyzed composition (as-fed basis) of experimental diets containing soy protein concentrate (SPC), Exp. 3[1]

Item	Phase 1 diet: No SPC	No plasma	No fish meal	SPC-180[2]	Phase-2
Ingredient, %					
Corn	46.55	46.35	48.22	48.65	52.13
Whey powder	15.00	15.00	15.00	15.00	10.00
Soybean meal	23.24	20.00	20.00	16.00	29.00
SPC-180	–	8.00	5.25	13.25	–
Fish meal	5.00	5.00	–	–	3.00
Spray dried protein plasma	5.00	–	5.00	–	–
Choice white grease	3.00	3.22	3.38	3.65	3.00
Limestone	1.20	1.00	1.25	1.05	0.90
Dicalcium phosphate	0.15	0.36	0.86	1.10	0.70
L-Lys HCl	0.10	0.22	0.21	0.35	0.36
DL-Met	0.06	0.13	0.12	0.18	0.12
L-Thr	–	0.02	0.01	0.07	0.09
Sodium chloride	0.40	0.40	0.40	0.40	0.40
Vitamin mineral premix[3]	0.30	0.30	0.30	0.30	0.30
Analyzed composition					
GE, kcal/kg	4023	4069	4042	4062	3995
DM, %	88.93	89.08	88.81	89.75	87.83
Ash, %	6.35	6.23	5.60	5.92	5.63
CP, %	22.90	23.02	22.43	22.26	21.10
ADF, %	2.92	4.01	3.72	5.23	3.51
NDF, %	7.40	6.42	7.27	7.59	7.36

[1]All diets were formulated to contain between 3,424 and 3,490 kcal ME per kilogram, and at least the following quantities of standardized ileal digestible AA per kilogram diet: Lys, 1.43%; Met, 0.41%; Thr, 0.79%; Trp, 0.23%.

[2]SPC-180 = soy protein concentrate ground to 180 μm.

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

Chemical Analysis

The 3 batches of SPC and fish meal and soybean meal were analyzed in duplicate for DM (Method 930.05; AOAC, 2007), ash (Method 942.05, AOAC, 2007), AA [Method 982.30 95 E (a, b, c); AOAC, 2007], Ca, and P (Method 985.01; AOAC, 2007). Crude protein in these samples was determined by the combustion procedure (Method 990.03; AOAC, 2007) using an Elementar Rapid N-cub Protein/Nitrogen apparatus (Elementar Americas Inc., Mt Laurel, NJ), and acid hydrolyzed ether extract was determined using the acid hydrolysis filter bag technique (Ankom HCl Hydrolysis System; Ankom Technology, Macedon, NY) followed by fat extraction (Ankom XT-15 Extractor; Ankom Technology, Macedon, NY). Ingredients also were analyzed in duplicate for GE using an isoperibol bomb calorimeter (Model 6300; Parr Instruments, Moline, IL) with benzoic acid as the standard for calibration, and for ADF and NDF using Ankom Technology methods 12 and 13, respectively (Ankom 2000 Fiber Analyzer; Ankom Technology, Macedon, NY). Soy protein concentrate, soybean meal, and corn were also analyzed for insoluble dietary fiber (**IDF**) and soluble dietary fiber (**SDF**) according to method 991.43 (AOAC, 2007) using the Ankom[TDF] Dietary Fiber Analyzer (Ankom Technology, Macedon, NY). Total dietary fiber (**TDF**) was calculated as the sum of insoluble and soluble dietary fiber. In addition, soybean meal and SPC were analyzed for fructose, glucose, sucrose, maltose, lactose, stachyose, and raffinose (Janauer and Englmaier, 1978). Particle size of each source of SPC and of soybean meal, corn, and fish meal was determined using 50 g of the ingredient that was placed on top of test sieves and placed in a vibratory sieve shaker for 10 min. The weight of the feedstuff material in each of the test sieves was recorded for calculation of mean particle size (ANSI/ASAE, 2008). Soybean meal and SPC were also analyzed for trypsin inhibitors (Method Ba 12–75: AOCS, 2006).

Diets and ileal digesta samples that were collected in Exp. 1 were analyzed for CP, DM, and AA as explained for ingredients, and these samples were also analyzed for chromium (Method 990.08; AOAC, 2007). Likewise, diets and fecal samples from Exp. 2 were analyzed for GE and DM as described for ingredients. Urine samples were also analyzed for GE using the same procedure after being mixed with cotton and lyophilized as previously described (Kim et al., 2009).

Diets used in Exp. 3 were also analyzed for GE, DM, ash, CP, ADF, and NDF as explained for ingredients. One of the plasma samples collected in Exp. 3 was analyzed for tumor necrosis factor- α (**TNF- α**), IgG, and peptide YY (**PYY**) using ELISA kits according to recommendations from the manufacturer (R&D Systems, Inc., Minneapolis, MN; Bethyl Laboratories, Inc., Montgomery, TX; and Phoenix Pharmaceuticals Inc., Burlingame, CA, respectively). All samples were analyzed in duplicate. The other plasma sample collected in Exp. 3 was analyzed for blood urea nitrogen (**BUN**), albumin, and total protein using a Beckman Coulter Clinical Chemistry AU analyzer (Beckman Coulter, Inc., Brea, CA).

Calculations and Data Analyses

Values for AID and SID of AA in each diet used in Exp. 1 were calculated (Stein et al., 2007). The amount of energy lost in the feces and in the urine, respectively, was determined, and the quantities of DE and ME in each of the 6 diets used in Exp. 2 were calculated (Baker and Stein, 2009; Kim et al., 2009). The DE and ME in corn were calculated by dividing the DE and ME values for the corn diet by the inclusion rate of corn in this diet and the contribution of corn to the DE and ME in the diets containing soybean meal, SPC-70, SPC-180, SPC-700, or fish meal was calculated. The DE and ME in soybean meal, SPC-70, SPC-180, SPC-700, and fish meal were then calculated by difference as previously explained (Baker and Stein, 2009; Kim et al., 2009). Data for ADG, ADFI, and G:F for each treatment in Exp. 3 were calculated based on the recorded pig weights and data for feed disappearance.

Data from all 3 experiments were analyzed by ANOVA using the PROC MIXED procedure of SAS (SAS Inst. Inc., Cary, NC) with the pig as the experimental unit in Exp. 1 and 2 and pen as the experimental unit in Exp. 3. Normality of data was verified, and outliers were identified as values that deviated from the treatment mean by more than 3 times the interquartile range using the UNIVARIATE procedure in SAS. The statistical model in Exp. 1 included diet as the main effect and pig and period as random effects. Treatment means were separated using the LSMEANS statement and the PDIFF option of PROC MIXED. Statistical significance and tendencies were considered at $P < 0.05$ and $0.05 \leq P < 0.10$, respectively. Data for Exp. 2 and 3 were analyzed using the same procedures with the exception that pig was the only random effect in Exp. 2 and pen was the random effect in Exp. 3.

Table 5. Apparent ileal digestibility (%) of CP and AA in soybean meal, soy protein concentrate ground to a mean particle size of 70, 180, or 700 μm (SPC-70, SPC-180, and SPC-700, respectively), and fish meal by weanling pigs[1]

Item	Soybean meal	SPC-70	SPC-180	SPC-700	Fish meal	SEM	*P*-value
CP	76.4[b]	82.5[a]	83.6[a]	79.9[ab]	76.7[b]	1.83	0.0236
Indispensable AA							
Arg	91.4[b]	94.0[a]	94.4[a]	91.5[b]	87.9[c]	1.01	0.006
His	83.4	87.4	88.6	85.5	82.9	1.53	0.052
Ile	83.0[c]	86.9[ab]	88.1[a]	85.2[abc]	84.1[bc]	1.25	0.048
Leu	82.4[b]	86.7[a]	87.9[a]	86.2[a]	85.2[ab]	1.14	0.041
Lys	81.6	86.3	88.5	84.8	87.4	1.79	0.100
Met	85.1	87.5	86.4	84.2	87.8	1.38	0.153
Phe	82.4[b]	88.2[a]	89.1[a]	86.5[a]	81.8[b]	1.12	< 0.001
Thr	74.1	77.6	79.3	75.2	79.5	2.10	0.218
Trp	82.4[b]	88.7[a]	89.4[a]	82.6[b]	83.0[b]	1.47	0.003
Val	80.5	84.2	85.7	83.9	82.1	1.39	0.134
Mean	83.0	87.1	88.1	85.1	84.7	1.33	0.065
Dispensable AA							
Ala	76.6	81.0	82.1	79.4	81.9	1.85	0.202
Asp	80.4	80.0	82.6	78.0	79.4	1.73	0.324
Cys	63.2	66.9	68.1	59.4	58.7	4.20	0.302
Glu	80.4	86.8	87.9	84.4	84.8	2.08	0.135
Gly	64.8	72.6	75.1	72.4	71.9	3.57	0.355
Pro	79.6	82.5	84.8	83.6	80.3	2.28	0.393
Ser	82.2[b]	86.6[a]	87.5[a]	83.5[ab]	81.0[b]	1.46	0.024
Tyr	83.0[c]	88.2[ab]	89.1[a]	85.6[bc]	82.3[c]	1.28	0.002
Mean	78.5	82.8	84.3	80.3	80.1	2.01	0.238
All AA	80.7	84.8	86.1	82.5	82.4	1.67	0.147

[a–c]Within a row, means followed by the same or no superscript letter are not different ($P > 0.05$).

[1]Each least squares mean represents 5 or 6 observations.

RESULTS

Experiment 1: Amino Acid Digestibility

The AID of Arg and Trp in SPC-70 and SPC-180 was greater ($P < 0.05$) than in SPC-700, and the AID of Tyr in SPC-180 was greater ($P < 0.05$) than in SPC-700, but for CP and all other AA, no differences among SPC-70, SPC-180, and SPC-700 were observed (Table 5). The AID of CP, Arg, Phe, Trp, Ser, and Tyr were greater in SPC-70 and SPC-180 than in soybean meal and fish meal, and the AID of Ile and Leu were greater ($P < 0.05$) in SPC-70 and SPC-180 than in soybean meal. The AID of Ile in SPC-180 was also greater ($P < 0.05$) than in fish meal.

The SID of Arg was greater ($P < 0.05$) in SPC-70 and SPC-180 than in SPC-700, and the SID of Trp and Tyr was greater in SPC-180 than in SPC-700, but for CP and all other AA, no differences among the 3 sources of SPC were observed (Table 6). The SID of Leu was less ($P < 0.05$) in soybean meal than in the other ingredients and the SID of Arg and Tyr was greater ($P < 0.05$) in SPC-70 and SPC-180 than in soybean meal and fish meal. Likewise, the SID of Trp was greater ($P < 0.05$) in SPC-70, SPC-180, and fish meal than in soybean meal. The SID of His, Lys, and Thr also tended to be greater in SPC-180 than in soybean meal ($P = 0.090$, 0.078, and 0.097, respectively).

Experiment 2: Energy Measurements

Pigs fed the SPC-70 diet had greater ($P < 0.01$) dry feces output than pigs fed the SPC-180 diet, and pigs fed the SPC-700 diet had greater ($P < 0.05$) urine output than pigs fed the SPC-70 or the SPC-180 diets (Table 7). However, for ATTD of GE and DE and ME values, no differences among SPC-70, SPC-180, and SPC-700 diets were observed.

There were no differences in DE and ME among the 3 sources of SPC, but on an as-fed basis, SPC-180 contained more ($P < 0.05$) DE than corn, soybean meal, and fish meal (Table 8). There were, however,

Table 6. Standardized ileal digestibility (SID) of CP and AA in soybean meal, soy protein concentrate ground to a mean particle size of 70, 180, or 700 µm (SPC-70, SPC-180, and SPC-700, respectively), and fish meal by weanling pigs[1,2]

Item	Soybean meal	SPC-70	SPC-180	SPC-700	Fish meal	SEM	P-value
CP	83.9[c]	90.5[ab]	91.5[a]	87.4[abc]	85.9[bc]	1.83	0.029
Indispensable AA							
Arg	94.4[b]	97.4[a]	97.8[a]	94.8[b]	92.7[b]	1.01	0.004
His	87.8	92.3	93.4	90.1	89.5	1.53	0.090
Ile	87.1[b]	91.4[a]	92.5[a]	89.5[ab]	90.0[ab]	1.25	0.049
Leu	86.8[b]	91.5[a]	92.6[a]	90.8[a]	91.3[a]	1.14	0.029
Lys	85.3	90.3	92.7	89.9	91.1	1.74	0.078
Met	89.4	92.1	91.0	88.8	90.3	1.38	0.254
Phe	86.4[c]	92.6[a]	93.4[a]	90.7[ab]	88.7[bc]	1.12	0.001
Thr	84.7	88.9	90.9	88.3	91.9	1.82	0.097
Trp	87.3[c]	93.6[ab]	94.5[a]	89.8[bc]	92.9[ab]	1.42	0.011
Val	86.1	90.5	91.5	88.5	89.6	1.49	0.118
Mean	87.7	92.2	93.1	90.0	90.8	1.33	0.052
Dispensable AA							
Ala	82.7	87.8	88.8	86.0	87.5	1.85	0.174
Asp	84.2	84.2	86.7	82.1	85.6	1.73	0.276
Cys	75.0	79.9	81.0	72.3	83.9	4.20	0.216
Glu	83.2	90.0	91.3	88.6	89.7	2.05	0.095
Gly	79.2	88.7	90.9	87.9	83.1	3.57	0.183
Pro	92.2	96.4	101.6	96.7	96.7	1.95	0.057
Ser	89.1	93.5	94.3	91.8	89.9	1.33	0.051
Tyr	87.7[c]	93.4[ab]	94.3[a]	90.7[bc]	89.6[c]	1.28	0.006
Mean	84.5	89.3	90.7	86.5	88.4	2.01	0.200
All AA	86.0	90.7	91.8	88.2	89.6	1.67	0.119

[a–c]Within a row, means followed by the same or no superscript letter are not different ($P > 0.05$).

[1]Each least squares mean represents 5 or 6 observations.

[2]Values for standardized ileal digestibility were calculated by correcting apparent ileal digestibility values for basal endogenous losses. Basal endogenous losses were determined using pigs fed the N-free diets as (g/kg DMI) CP, 19.36; Arg, 0.56; His, 0.30; Iso, 0.53; Leu, 0.90; Lys, 0.60; Met, 0.14; Phe, 0.55; Thr, 1.00, Trp, 0.16; Val 0.76; Ala, 0.71; Asp, 1.13; Cys, 0.39; Glu, 1.34; Gly, 1.62, Pro, 1.69; Ser, 0.69; Tyr, 0.39.

no differences in ME calculated on an as-fed basis or DE and ME (DM basis) among the 6 ingredients.

Experiment 3: Growth Performance

During phase 1, ADFI, ADG, G:F, and final BW were not affected by experimental diets (Table 9). Likewise, replacement of spray-dried plasma protein and fish meal with SPC-180 in diets fed during phase 1 had no effect on growth performance during phase 2 or during the overall experimental period.

The concentration of TNF-α, PYY, IgG, and BUN were not affected by dietary treatments (Table 10). However, the concentration of total protein had a tendency ($P = 0.078$) to be greater in plasma from pigs fed diets containing 13.25% SPC-180 than in plasma from pigs fed the control diet. The concentration of albumin in plasma also had a tendency ($P = 0.082$) to be greater in pigs fed the diet with 13.25% SPC-180 compared with pigs fed the diet with 8% SPC-180.

DISCUSSION

The measured particle sizes were slightly greater than planned and SPC-70, SPC-180, and SPC-700 had actual mean particle sizes of 122, 209, and 745 µm, respectively (Table 1). Thus, the expected differences among the 3 sources of SPC were obtained. The concentration of CP in the soybean was greater than reported by Sauvant et al. (2004), NRC (2012), and Rostagno et al. (2011). Soybean meal used in this experiment was from Brazil, and previous reports indicate that the concentration of CP in Brazilian soybean meal is greater than in soybean meal from other origins (Ravindran et al., 2014; García-Rebollar et al., 2016). Concentration of acid hydrolyzed ether extract acid hydrolyzed ether extract was lower than values reported by NRC (2012) and Sauvant et al. (2004). The concentrations of ADF and NDF in soybean meal concurs with values reported by NRC (2012), but were lower than values reported by Rostagno et al. (2011). The analyzed composition of fish meal concurs with previous reports (NRC, 2012; Rojas and Stein, 2013). The composition of the 3 sources of SPC was not different, and concentrations of CP and AA were in agreement with values reported by Rostagno et al. (2011) and Cervantes-Pahm and Stein (2008), but less than values reported by NRC (2012) and Sauvant et al. (2004). The concentration of Lys was 6.28% of CP on soybean meal and approximately 6.26 in the 3 sources of SPC, which indicates that these protein sources were not heat damaged (Gonzalez-Vega et al., 2011). The concentrations of AEE, ADF, NDF, and stachyose in SPC were greater than previous values (Cervantes-Pahm and Stein, 2008; NRC, 2012; Guzmán et al., 2016). The manufacturing process of SPC is based on extraction of the most soluble carbohydrates from defatted soybean flakes. This process is influenced by oil extraction method, meal age, temperature, and solvent to meal ratio, which is the reason for variation among different sources of SPC (Ohren, 1981).

The SID of CP and AA in soybean meal was within the range of values reported previously (Rostagno et al., 2011; NRC, 2012). Likewise, the SID of CP and most AA in SPC-70 and SPC-180 were in agreement with previous values (Fastinger and Mahan, 2003; Cervantes-Pahm and Stein, 2008; Rostagno et al., 2011; NRC, 2012; Cotten et al., 2016; Oliveira and Stein, 2016). The observation that particle size of SPC had no effect on the SID of CP and AA contrasts with results for soybean

Table 7. Apparent total tract digestibility (ATTD) of GE and concentrations of DE and ME in diets containing corn or corn and soybean meal, corn and soy protein concentrate ground to a mean particle size of 70, 180, or 700 μm (SPC-70, SPC-180, and SPC-700, respectively), or corn and fish meal (as-fed basis)[1,2]

	Diet							
Item	Corn	Soybean meal	SPC-70	SPC-180	SPC-700	Fish meal	SEM	*P*-value
Total feed intake, kg/5d	3.38[c]	4.71[a]	4.63[a]	4.49[a]	4.61[a]	4.19[b]	0.12	< 0.001
GE intake, kcal /5d	12,465[c]	18,012[a]	17,862[a]	17,253[ab]	17,723[a]	16,244[b]	482	< 0.001
Dry feces output, kg/5d	0.250[c]	0.422[ab]	0.454[a]	0.378[b]	0.393[ab]	0.377[b]	0.04	< 0.001
GE in dry feces, kcal/kg	4,538	4,586	4,523	4,572	4,555	45,80	80	0.895
Fecal GE output, kcal/5d	1,152[b]	1,954[a]	2,073[a]	1,749[a]	1,815[a]	1,748[a]	167	< 0.001
ATTD, GE %	90.3	88.6	87.8	89.4	88.4	88.5	1.31	0.315
DE in diet, kcal/kg	3,306[b]	3,384[ab]	3,389[ab]	3,438[a]	3,438[a]	3,436[a]	50	< 0.017
Urine output, kg/5 d	6.76[c]	25.51[ab]	17.68[bc]	12.23[c]	37.24[a]	12.09[c]	4.43	< 0.001
GE in urine, kcal/kg	26.20	24.70	20.10	36.36	12.94	25.78	5.1	0.065
Urinary GE output, kcal/5d	159[c]	527[a]	362[ab]	392[ab]	440[ab]	295[bc]	76	< 0.001
ME in diet, kcal/kg	3,252	3,256	3,303	3,340	3,331	3,359	56	0.161

[a-c]Within a row, means without a common superscript letter are different ($P < 0.05$).

[1]Each least squares mean represents 5 or 6 observations.

[2]Diet intake, fecal output, and urine output were based on 5 d of collection.

meal (Fastinger and Mahan, 2003). It is possible that the reason for this observation is that a wider range of particle sizes in soybean meal were used by Fastinger and Mahan (2003), but it is also possible that the alcohol extraction that is used in the production of SPC makes the protein more digestible and further improvements due to particle size reduction are, therefore, not obtained. Recent results for corn grain indicate that there is no difference in SID of AA among corn grains ground to different particle sizes (Rojas and Stein, 2015). It thus appears that there is not always an increase in SID of AA if particle size is reduced. However, the reduced SID of CP and most AA in soybean meal compared with SPC-70 and SPC-180 is in agreement with previous data (Sohn et al., 1994; Cervantes-Pahm and Stein, 2008; NRC, 2012), and is most likely a result of lower concentrations of trypsin inhibitors and oligosaccharides in SPC than in soybean meal (Li et al., 1991).

The concentration of DE and ME in corn were close to previous values (Rostagno et al., 2011; NRC, 2012; Rojas and Stein, 2013), whereas the concentration of DE and ME in soybean meal were less than values reported for U.S. soybean meal by Sotak-Peper et al. (2015), but in agreement with the values reported for Brazilian soybean meal by Rostagno et al. (2011). It is possible that the reduced concentration of acid hydrolyzed ether extract and the greater concentration of stachyose and raffinose in the soybean meal used in this experiment compared with the meal used by Sotak-Peper et al. (2015) may explain these differences (van Kempen et al., 2006). When fed to broiler chickens, it was also demonstrated that U.S. soybean meal contains more ME than soybean meal from Brazil (Ravindran et al., 2014). The concentration of ME in fish meal concurs with NRC (2012), but is greater than reported by Rojas and Stein (2013). The DE and ME in the SPC used in this experiment were less than previous values (Rostagno et al., 2011; NRC, 2012; Zhang et al., 2013), which is likely a result of the greater concentration of oligosaccharides and NDF in the SPC used in

Table 8. Concentration of DE and ME in corn, soybean meal, soy protein concentrate ground to a mean particle size of 70, 180, or 700 μm (SPC-70, SPC-180, and SPC-700, respectively), and fish meal[1]

	Ingredient							
Item	Corn	Soybean meal	SPC-70	SPC-180	SPC-700	Fish meal	SEM	*P*-value
As-fed basis								
DE, kcal/kg	3,407[b]	3,618[b]	3,750[ab]	3,985[a]	3,985[a]	3,593[b]	122	0.008
ME, kcal/kg	3,346	3,305	3,528	3,704	3,658	3,424	144	0.291
DM basis								
DE, kcal/kg	3,990	4,021	3,914	4,198	4,233	3,949	132	0.410
ME, kcal/kg	3,919	3,672	3,683	3,903	3,886	3,763	156	0.758

[a,b]Within a row, means without a common superscript letter are different ($P < 0.05$).

[1]Each least squares mean represents 5 or 6 observations.

Table 9. Effects of spray dried plasma protein, fish meal, and soy protein concentrate (SPC) on growth performance of weanling pigs[1,2]

Item	No SPC	No plasma	No fish meal	SPC-180	SEM	*P*-value
Phase 1, d 0–14						
Initial BW, kg	7.05	7.06	7.09	7.06	0.401	0.999
Final BW, kg	9.11	9.11	9.00	9.03	0.403	0.996
ADG, kg/d	0.146	0.149	0.135	0.140	0.009	0.744
ADFI, kg/d	0.213	0.204	0.193	0.208	0.008	0.424
G:F	0.689	0.726	0.699	0.673	0.033	0.722
Phase 2, d 14- 28						
Initial BW, kg	9.11	9.11	9.00	9.03	0.403	0.996
Final BW, kg	16.16	16.83	16.11	16.39	0.620	0.842
ADG, kg/d	0.504	0.546	0.507	0.525	0.022	0.524
ADFI, kg/d	0.661	0.728	0.686	0.702	0.024	0.303
G:F	0.761	0.736	0.738	0.746	0.012	0.553
Overall, d 0- 28						
ADG, kg/d	0.325	0.347	0.321	0.332	0.014	0.593
ADFI, kg/d	0.437	0.469	0.443	0.455	0.015	0.453
G:F	0.743	0.741	0.725	0.728	0.016	0.829

[1]The soy protein concentrate used in this experiment was ground to a particle size of 180µm.

[2]Each least squares mean represents 8 observations.

Table 10. Effects of spray dried plasma protein, fish meal, and soy protein concentrate (SPC) on blood parameters of weanling pigs [1,2]

Item	No SPC	No plasma	No fish meal	SPC-180	SEM	*P*-value
TNF-α[3], pg/mL	80.42	63.40	77.36	86.42	13.11	0.646
PYY, ng/mL	2.53	4.22	4.04	2.40	0.74	0.167
IgG, mg/mL	229	205	227	188	25.13	0.623
BUN, mg/dL	15.00	13.25	14.87	13.42	1.32	0.570
Total protein, g/dL	4.50	4.75	4.62	4.95	0.12	0.078
Albumin, g/dL	2.85	2.98	2.73	3.10	0.10	0.082

[1]The soy protein concentrate used in this experiment was ground to a particle size of 180µm.

[2]Each least squares mean represents 8 observations.

[3]TNF-α = tumor necrosis factor-α; PYY = peptide YY; BUN = blood urea nitrogen.

this experiment. However, the values obtained in this experiment concur with those reported by Ruiz et al. (2012). The greater ADF and NDF in the SPC used in this experiment may also have contributed to the lack of a difference in ME between SPC and soybean meal.

Animal proteins are commonly included in diets for weanling pigs to stimulate feed intake and avoid the antinutritional factors in soybean meal (Lenehan et al., 2007). However, SPC contains less antigenic and antinutritional factors than soybean meal, and inclusion of SPC in diets for weanling pigs may improve the morphology of the small intestine resulting in improved growth performance compared with pigs fed soybean meal (Li et al., 1991; Sohn et al., 1994). Based on the results of the AA digestibility experiment, it was decided to use SPC-180 in the growth performance experiment because the SID of some AA was greater in SPC-180 than in SPC-700, but there appeared to be no additional benefit of reducing the particle size further. Results of the growth performance experiment indicated that phase 1 diets based on soybean meal and SPC may be fed to weanling pigs without negative effects on growth performance during the initial 4 wk postweaning. The lack of effects on the concentrations of TNF-α and IgG when SPC replaced spray-dried plasma protein or fish meal, or both ingredients, indicates that the inflammatory immune response was not affected when pigs were fed diets containing SPC, which may be a result of reduced concentration of antigenic factors in SPC. Peptide YY is secreted in the lower gastrointestinal tract, reduces feed intake, and affects the homeostasis of energy (Holzer et al., 2012). The concentration of PYY in plasma of pigs allowed ad libitum intake of feed was 2.2 ± 0.2 ng/mL (Ito et al., 2006), and concentrations of PYY in plasma observed in this experiment were in agreement with values previously reported. The observation that the values for PYY were not different among diets indicates that feed intake and energy metabolism were not negatively affected by SPC in the diets. Although concentrations of total protein and albumin had a tendency to increase in pigs fed diets without plasma and fish meal, the values were within the normal physiological ranges (Tumbleson and Kalish, 1972) further indicating that diets based on soybean meal and SPC-180 may be used during the initial 2 wk postweaning.

In conclusion, the SID of most indispensable AA in SPC-70 and SPC-180 were greater than in soybean meal, and the SID of some AA in SPC-180 was also greater than in fish meal. It appears that grinding SPC to approximately 180 µm may maximize digestibility of indispensable AA. However, no effects of particle size of SPC on DE and ME were observed. Results indicate that diets based on soybean meal and SPC ground to 180 µm may be used during the initial 14 d postweaning without affecting growth performance or plasma concentrations of indicators of pro-inflammatory immune responses.

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