*Journal of Animal Science*, 2019, 4598–4607

doi:10.1093/jas/skz290
Advance Access publication September 3, 2019
**Received:** 7 August 2019 and **Accepted:** 30 August 2019
Non Ruminant Nutrition

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# Nutrient digestibility of soybean products in grower-finisher pigs[1]

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## Abstract

Solvent extraction of soybean creates soybean meal (**SBM**), but an array of other soybean products can be created using further processing of SBM or soybean. For accurate inclusion of these products in pig feed, characterization of digestible AA profile and energy value is required. Soybean products from processes such as extrusion (**EX**) of soybean and thermo-mechanical (**TM**) treatment, bioconversion using fermentation or enzymes (**BC**), and ethanol-water extraction (**EW**) of soybean meal were collected together with SBM. These 9 soybean products were tested in cornstarch-based diets together with an N-free diet for a total of 10 diets. Ten ileal-cannulated barrows (30.4 ± 0.7 kg initial BW) were fed 10 diets at 2.8 times maintenance DE for six 9-d periods with a 6 (periods) × 10 (pigs) Youden square. The control SBM contained 47.0% CP, 1.4% ether extract, and ADF 6.0%. The 9 soybean products contained 35.6% to 66.4% CP, 0.9% to 21.6% ether extract, and 4.4% to 8.0% ADF. The EW soybean products were high in CP (>61%), whereas the 2 EX soybean products were low in CP (<36%) but high in ether extract (≥19%). Chemically available Lys ranged from 92.6% to 100% of total Lys, indicating that minor Lys damage occurred during processing. The apparent total tract digestibility (**ATTD**) of energy was lower ($P < 0.05$) for soybean products with greater ether extract and ADF content than SBM, and varied among soybean products. The standardized ileal digestibility (**SID**) did not differ ($P > 0.05$) among soybean products for most AA, except for lower SID of Arg, Ile, Leu, Lys, Phe, and Tyr ($P < 0.05$) for EX2 and BC1 than other soybean products. The DE and predicted NE value did not differ ($P > 0.05$) among soybean products. The greater SID AA content ($P < 0.05$) in EW, BC, and TM1 soybean products than SBM was mainly a result of greater total AA content due to removal of other macronutrients. In conclusion, extrusion of soybean creates soybean products with a greater energy value but lower ATTD of energy and lower SID AA content than SBM. Further processing of SBM creates soybean products with greater CP and SID AA content but similar SID of AA than SBM. Thus, new technologies to process SBM or soybean create high-value ingredients to be included in pig diets, especially for young pigs with high nutritional requirements.

**Key words:** amino acid, digestibility, energy, soybean product, pig

## Introduction

Soybean meal (**SBM**) is a popular feedstuff for swine diets around the world, because SBM is nutritionally superior to many other plant-based protein sources (Shelton et al., 2001), due to a greater protein content and better amino acid balance. In commercial diets fed to young pigs, SBM cannot be included in large quantities because it may cause digestive disturbances due to presence of residual trypsin inhibitors (Lallès, 2000; Woyengo et al., 2017), carbohydrate complexes, and antigens (Li et al., 1990). To avoid negative effects of feeding SBM to young pigs, diets include animal-based protein sources such as dried whey, spray-dried plasma protein, or fish meal; however, those are expensive (Lenehan et al., 2007).

Heat used to dry SBM after oil extraction also reduces antinutritional factors (**ANF**) in SBM, but does not eliminate ANF completely (Baker, 2000). The oil extraction industry introduced new processes while plant genetic companies introduced new cultivars of soybean containing less oligosaccharides (Woyengo et al., 2014a). These novelties enhanced oil extraction and simultaneously created new soybean products, e.g., protein concentrates produced from fermentation and enzyme-treated SBM with reduced ANF that allowed complete substitution of SBM or animal-based protein sources (Lenehan et al., 2007; Yang et al., 2007; Cervantes-Pahm and Stein, 2010). Application of these new soybean products depends on their digestible nutrient profile, ANF, price, and value-attributes such as stimulating feed intake in weaned pigs (Zijlstra et al., 2009). Characterizing the digestible nutrient value of new feedstuffs is an important step for the successful introduction of novel feedstuffs into swine diets (Gunawardena et al., 2010). However, limited information exists about the digestible nutrient profile of a wide array of samples of new soybean products.

We hypothesized that novel soybean products obtained from various processing methods would vary in chemical composition and digestibility of energy and AA. The objective of the present study was to determine the digestible energy (DE) and predicted net energy (NE) values and digestible AA profile of 9 new soybean products in ileal-cannulated grower-finisher pigs.

## Materials and Methods

### Experimental Diets and Design

Soybean products were produced using extrusion **(EX)** of full-fat soybean and thermo-mechanical **(TM)** treatment, bioconversion using fermentation or enzymes **(BC)**, and ethanol-water extraction **(EW)** of SBM. Organized according to processing method (Table 1), test ingredients were SBM (47% CP), **EX1** (Danex soybean; Danis NV, Koolskamp, Belgium), **EX2** (Pigletsoy 2000MSA; SCA Ibérica, Mequinenza, Zaragoza, Spain), **TM1** (HTM-96; SCA Ibérica, Mequinenza, Zaragoza, Spain), **TM2** (Provisoy; Provimi, Brookville, OH), **BC1** (Pepsoygen; Nutraferma, North Sioux City, SD) produced using fermentation, **BC2** (HP-300; Hamlet Protein Inc., Findlay, OH) produced using enzymes, **EW1** (SPC-60-IP; Imcopa, 's-Hertogenbosch, Netherlands), and **EW2** (Soycomil P; Archer Daniels Midland, Decatur, IL). Together with an N-free diet, in total 10 diets were tested using 10 pigs for 6 periods in a 10 × 6 Youden square design (Table 2). Diets contained cornstarch, canola oil, and sucrose as energy sources, and contained 1 of 9 soybean products as sole source of crude protein (CP) and amino acids (AA). The ratio of inclusion among energy sources was identical between soybean product diets and the N-free diet (Stein et al., 2006). Diets were fortified to meet vitamin and mineral requirements (NRC, 2012). As an indigestible marker, $Cr_2O_3$ was included in diets.

### Experimental Procedures

Animal protocols were reviewed and approved by the University of Alberta Animal Care and Use Committee for Livestock and followed guidelines established by the Canadian Council on Animal Care (CCAC, 2009). The experiment was conducted at the Swine Research and Technology Center at the University of Alberta (Edmonton, AB, Canada).

Ten crossbred barrows (initial BW, 30.4 ± 0.7 kg; Duroc sire × Large White/Landrace $F_1$; Genex Hybrid, Hypor, Regina, SK, Canada) were housed in raised individual metabolism pens that allowed freedom of movement (1.2 m wide, 1.2 m long, and 0.9 m high). Pens were equipped with a stainless-steel self-feeder attached to the front of the pen, a cup drinker next to the feeder, plastic walls, and slatted flooring in a temperature-controlled room (22 ± 2.5 °C). During a 10-d preoperative adaptation, barrows had free access to an 18%-CP grower diet. Pigs were then fitted with a simple T-cannula at the distal ileum, circa 5 cm prior to the ileocecal sphincter. The preparation of the cannulas, surgical procedure, and modifications were described previously (Sauer et al., 1983; de Lange et al., 1989). Pre- and post-operative care was done as described previously (Li et al., 1993). After surgery, barrows recovered for 7 d with a gradual increase in feed allowance and were then switched to the experimental diets. Daily feed allowance was adjusted to 2.8 times the maintenance requirement for DE (2.8 × 110 kcal of DE/kg of $BW^{0.75}$; NRC, 2012) that was fed in 2 equal meals at 0800 and 1500 h. Each 9-d experimental period consisted of a 5-d acclimation to experimental diets, followed sequentially by a 2-d collection of feces and a 2-d collection of ileal digesta. Pigs had free access to water throughout the experiment.

Feces were collected using plastic bags attached to the skin around the anus (van Kleef et al., 1994). Digesta samples were collected for 2 d using soft plastic bags (length, 20 cm; i.d., 4 cm) from 0800 to 2000 h containing 15 mL of 5% formic acid that were attached to the opened barrel of the cannula with a rubber band. Tubes were replaced as soon as filled or after 20 min (Li et al., 1993). Collected feces and digesta were pooled for each pig within experimental period and frozen at −20 °C. Prior to analyses, feces and digesta were thawed, homogenized, subsampled, and freeze-dried.

### Chemical Analyses

Diets, test feedstuffs, and lyophilized digesta and feces were ground in a centrifugal mill (model ZM 200; Retsch Co., Newton, PA) through a 1.0-mm sieve. Feedstuffs, diets, feces, and digesta were analyzed for moisture (method 930.15; AOAC, 2006), ash (method 942.05; AOAC, 2006), acid detergent fiber (ADF; method 973.18; AOAC, 2006), crude fiber (method 962.09; AOAC, 2006), and ether extract (method 920.39; AOAC, 2006). Diets, feedstuffs, and digesta were analyzed for CP (method 990.03; AOAC, 2006), for AA by high-pressure liquid chromatography (HPLC; method 982.30E; AOAC, 2006), and for chemically available Lysine (**Lys**; method 975.44; AOAC, 2006). The phosphorus (**P**) and calcium (**Ca**) in feedstuffs were analyzed spectrophotometrically at 400 nm using the vanadate–molybdate method (method 946.06; AOAC, 2006). Starch in feedstuffs was analyzed using the amyloglucosidase and α-amylase method with a final glucose

**Table 1.** Analyzed nutrient content of soybean products (as-is basis)

| | Soybean products[1] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Item, % | SBM | EX1 | EX2 | TM1 | TM2 | BC1 | BC2 | EW1 | EW2 |
| Moisture | 9.0 | 7.4 | 8.1 | 12.5 | 6.5 | 6.0 | 8.2 | 7.0 | 8.4 |
| CP, % | 47.0 | 38.2 | 35.6 | 44.9 | 54.4 | 51.8 | 56.1 | 61.4 | 66.4 |
| GE, Mcal/kg | 4.23 | 5.12 | 4.91 | 4.10 | 4.39 | 4.44 | 4.44 | 4.48 | 4.41 |
| Ether extract, % | 1.4 | 21.6 | 19.0 | 1.7 | 1.1 | 1.2 | 1.9 | 1.4 | 0.9 |
| Ash, % | 6.7 | 5.0 | 5.1 | 5.9 | 7.2 | 6.9 | 7.0 | 6.5 | 6.3 |
| Crude fiber, % | 3.8 | 4.7 | 5.4 | 4.9 | 2.2 | 4.3 | 2.3 | 4.8 | 3.4 |
| ADF, % | 6.0 | 7.3 | 8.0 | 6.3 | 4.5 | 5.6 | 4.4 | 7.7 | 5.4 |
| Starch, % | 1.2 | 0.4 | 1.9 | 2.7 | 0.2 | 0.9 | 0.8 | 0.6 | 0.1 |
| P, % | 0.67 | 0.54 | 0.55 | 0.61 | 0.70 | 0.76 | 0.74 | 0.73 | 0.74 |
| Ca, % | 0.34 | 0.24 | 0.33 | 0.32 | 0.33 | 0.28 | 0.32 | 0.39 | 0.45 |
| Indispensable AA, % | | | | | | | | | |
| Arg | 3.35 | 2.79 | 2.49 | 3.20 | 3.90 | 3.45 | 3.92 | 4.46 | 4.86 |
| His | 1.21 | 0.99 | 0.89 | 1.16 | 1.36 | 1.30 | 1.37 | 1.61 | 1.73 |
| Ile | 2.17 | 2.00 | 1.72 | 2.26 | 2.71 | 2.59 | 2.72 | 3.14 | 3.36 |
| Leu | 3.61 | 3.06 | 2.73 | 3.50 | 4.24 | 4.08 | 4.31 | 4.89 | 5.29 |
| Lys | 2.87 | 2.36 | 2.07 | 2.72 | 3.23 | 3.02 | 3.26 | 3.83 | 4.21 |
| Met | 0.70 | 0.52 | 0.51 | 0.63 | 0.75 | 0.79 | 0.77 | 0.87 | 0.97 |
| Phe | 2.34 | 2.05 | 1.79 | 2.32 | 2.81 | 2.62 | 2.88 | 3.18 | 3.41 |
| Thr | 1.80 | 1.39 | 1.32 | 1.64 | 1.99 | 1.95 | 2.09 | 2.30 | 2.49 |
| Trp | 0.64 | 0.47 | 0.47 | 0.61 | 0.73 | 0.72 | 0.73 | 0.82 | 0.89 |
| Val | 2.32 | 2.02 | 1.80 | 2.34 | 2.75 | 2.69 | 2.75 | 3.20 | 3.47 |
| Dispensable AA, % | | | | | | | | | |
| Ala | 2.00 | 1.63 | 1.50 | 1.91 | 2.30 | 2.27 | 2.38 | 2.64 | 2.82 |
| Asp | 5.17 | 4.30 | 3.84 | 4.97 | 6.09 | 5.67 | 6.12 | 6.90 | 7.49 |
| Cys | 0.80 | 0.67 | 0.69 | 0.64 | 0.90 | 0.85 | 0.85 | 1.03 | 1.01 |
| Glu | 7.60 | 6.19 | 5.57 | 7.44 | 9.08 | 8.22 | 8.97 | 10.14 | 11.20 |
| Gly | 1.94 | 1.60 | 1.47 | 1.90 | 2.21 | 2.24 | 2.24 | 2.55 | 2.74 |
| Pro | 2.21 | 1.78 | 1.65 | 2.13 | 2.55 | 2.46 | 2.61 | 2.95 | 3.22 |
| Ser | 2.07 | 1.55 | 1.50 | 1.90 | 2.32 | 2.25 | 2.47 | 2.59 | 2.82 |
| Tyr | 1.65 | 1.40 | 1.27 | 1.58 | 1.94 | 1.82 | 2.01 | 2.09 | 2.27 |
| Available Lys, % | 2.89 | 2.22 | 2.03 | 2.55 | 3.16 | 2.91 | 3.10 | 3.69 | 3.90 |
| Lys, % of CP | 6.11 | 6.19 | 5.82 | 6.06 | 5.94 | 5.83 | 5.80 | 6.24 | 6.34 |
| Lys availability, % | 100.4 | 94.0 | 98.0 | 93.5 | 97.9 | 96.5 | 95.2 | 96.3 | 92.6 |

[1]SBM = Soybean meal 47; EX1 = Danex soybeans; EX2 = Pigletsoy 2000MSA; TM1 = HTM-96; TM2 = Provisoy; BC1 = Pepsoygen; BC2 = HP-300; EW1 = SPC-60-IP; and EW2 = Soycomil P.

analysis using a spectrophotometer at 510 nm (method 996.11; AOAC, 2006). The gross energy (GE) of diets, feedstuffs, feces, and digesta was analyzed by an adiabatic calorimeter (model AC-300, Leco Corp., St. Joseph, MI). After ashing, $Cr_2O_3$ in diets, feces, and digesta was analyzed spectrophotometrically at 440 nm (Fenton and Fenton, 1979).

## Calculations

Apparent ileal digestibility (**AID**; %) and apparent total tract digestibility (**ATTD**; %) of components in the diet were calculated using the following equation (Adeola, 2001):

$$\text{AID or ATTD, \%} = 100 - [100 \times (\text{marker in diet} \times \text{component in feces or digesta}) / (\text{marker in feces or digesta} \times \text{component in diet})].$$

The basal ileal endogenous loss (**Iend**) of an AA or CP (g/kg of DM intake) was calculated by the equation for the nitrogen (**N**) free diet (Stein et al., 2007):

$$I_{end} = [\text{AA or CP in digesta} \times (\text{marker in diet} / \text{marker in digesta})].$$

Standardized ileal digestibility (SID; %) for each AA was then calculated by correcting the AID for basal ileal endogenous losses by the equation (Stein et al., 2007):

$$\text{SID} = [\text{AID} + (I_{end} \text{of AA} / \text{AA in diet})].$$

Content of SID CP and AA was calculated by multiplying SID measured in digesta by total CP and AA content of soybean products. The DE value of soybean products was calculated by subtracting the DE in the N-free diet that was provided by energy sources from the DE in each of soybean product-containing diets using the difference method (Adeola, 2001).

The NE value of feedstuffs was predicted from the determined DE values (kcal/kg of DM) and analyzed macronutrient (g/kg of DM) of feedstuffs using equation 5 that was developed by Noblet et al. (1994) and adopted by NRC (2012).

## Statistical Analyses

The N-free diet was solely used for calculations and was excluded from statistical analyses. Data were analyzed using the MIXED procedure of SAS version 9.4 (SAS Inst. Inc., Cary, NC). The model included diet or ingredient as fixed effect and pig and period as random effects. The treatment means were reported

**Table 2.** Ingredient composition (as-fed basis) of the experimental diets[1]

| Item, % | Soybean products[1] | | | | | | | | | N-free |
|---|---|---|---|---|---|---|---|---|---|---|
| | SBM | EX1 | EX2 | TM1 | TM2 | BC1 | BC2 | EW1 | EW2 | |
| Cornstarch[2] | 55.15 | 47.29 | 47.29 | 47.29 | 61.17 | 61.17 | 61.17 | 63.48 | 65.80 | 85.50 |
| Soybean meal[3] | 36.50 | – | – | – | – | – | – | – | – | – |
| Danex soybeans[4] | – | 45.00 | – | – | – | – | – | – | – | – |
| Pigletsoy 2000SMA[5] | – | – | 45.00 | – | – | – | – | – | – | – |
| HTM-96[6] | – | – | – | 30.00 | – | – | – | – | – | – |
| Provisoy[7] | – | – | – | – | 30.00 | – | – | – | – | – |
| Pepsoygen[8] | – | – | – | – | – | 30.00 | – | – | – | – |
| HP300[9] | – | – | – | – | – | – | 30.00 | – | – | – |
| SPC-60-IP[10] | – | – | – | – | – | – | – | 27.50 | – | – |
| Soycomil P[11] | – | – | – | – | – | – | – | – | 25.00 | – |
| Sugar, sucrose | 3.25 | 2.79 | 2.79 | 2.79 | 3.59 | 3.59 | 3.59 | 3.73 | 3.86 | 5.00 |
| Solka-Floc[12] | – | – | – | – | – | – | – | – | – | 3.00 |
| Canola oil | 1.30 | 1.12 | 1.12 | 1.12 | 1.44 | 1.44 | 1.44 | 1.49 | 1.54 | 2.00 |
| Limestone | 1.20 | 1.20 | 1.20 | 1.20 | 1.20 | 1.20 | 1.20 | 1.20 | 1.20 | 1.00 |
| Mono-dicalcium phosphate | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 1.20 |
| Salt | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| Vitamin premix[13] | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| Mineral premix[14] | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| $Cr_2O_3$ | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| $K_2CO_3$ | – | – | – | – | – | – | – | – | – | 0.40 |
| MgO | – | – | – | – | – | – | – | – | – | 0.10 |

[1]BC = Bioconversion using fermentation (BC1) or enzymes (BC2); EW = Ethanol-water extraction; EX = Extrusion; SBM = Soybean meal; TM = Thermo-mechanical treatment.
[2]Melojel (National Starch and Chemical Co., Bridgewater, NJ).
[3]47% CP (Commercial supplier).
[4]EX1 = Danex soybeans (Danis NV, Koolskamp, Belgium).
[5]EX2 = Pigletsoy 2000MSA (SCA Ibérica, Mequinenza, Zaragoza, Spain).
[6]TM1 = HTM-96 (SCA Ibérica, Mequinenza, Zaragoza, Spain).
[7]TM2 = Provisoy (Provimi, Brookville, OH).
[8]BC1 = Pepsoygen (Nutraferma, North Sioux City, SD).
[9]BC2 = HP-300 (Hamlet Protein Inc., Findlay, OH).
[10]EW1 = SPC-60-IP (Imcopa, 's-Hertogenbosch, Netherlands).
[11]EW2 = Soycomil P (Archer Daniels Midland, Decatur, IL).
[12]International Fiber Corp., North Tonawanda, NY.
[13]Provided the following per kilogram of diet: vitamin A, 8,250 IU; vitamin $D_3$, 825 IU; vitamin E, 40 IU; niacin, 35 mg; D-pantothenic acid, 15 mg; riboflavin, 5 mg; menadione, 4 mg; folic acid, 2 mg; thiamine, 1 mg; D-biotin 0.2 mg; and vitamin $B_{12}$, 0.025 mg.
[14]Provided the following per kilogram of diet: Zn, 100 mg as $ZnSO_4$; Fe, 80 mg as $FeSO_4$; Cu, 50 mg as $CuSO_4$; Mn, 25 mg as $MnSO_4$; I, 0.5 mg as $Ca(IO_3)_2$; and Se, 0.1 mg as $Na_2SeO_3$.

as least squares means that were separated using the LSD method with the LSMEANS statement and PDIFF option in case treatments effects was significant. Individual pig was considered the experimental unit. Differences were considered significant if $P < 0.05$. To observe associations among chemical composition, digestibility of energy and nutrients, and digestible content of CP and AA of soybean co-products, data were analyzed using the PLS procedure of SAS with chemical composition as predictor variables and digestibility of energy and nutrients, and digestible content of CP and AA as response variables.

## Results

Pigs remained healthy throughout the experiment, and no pigs were removed from the study. No orts were collected as all pigs consumed their daily allotments of feed throughout the experiment.

The CP content of soybean products varied depending on processing technique and averaged 36.9% for EX, 49.6% for TM, 53.9% for BC, and 63.9% for EW with similar patterns for dispensable and indispensable AA (Table 1). Chemically available Lys was 5% units greater for SBM than the other soybean products. The GE value of SBM was 140 kcal/kg lower than the average of soybean products obtained by TM, BC, and EW. With 18.9% units greater ether extract content, soybean products obtained by EX had a 670 kcal/kg greater GE value than the other soybean products. Content of fiber (crude fiber and ADF), P, and Ca was similar among soybean products. Analyzed nutrient composition of the 10 diets followed patterns in accordance with the ingredient nutrient values, indicating proper diet mixing (Table 3).

Among diets, the ATTD of GE was greater ($P < 0.001$; Table 4) for diets containing SBM, TM, BC, or EW than that for diets containing EX1 or EX2. However, diet DE value had a range of 0.12 Mcal/kg of DM and did not differ among soybean products. Among ingredients, the ATTD of GE was greater ($P = 0.01$) for TM1 than EW1, EX1, and EX2, but was intermediate for SBM, TM2, BC1, BC2, and EW2.

The AID of CP ranged from 79.6% to 89.0% and did not differ ($P > 0.05$; Table 5) among diets containing soybean products. Diet AID of Lys was greater ($P < 0.05$) for TM1, TM2, and EW1 than that for EX2 and BC1, and was intermediate for SBM, EX1, BC2, and EW2. Diet AID of Arg, Ile, Leu, Phe, Val, Glu, Tyr, and chemically available Lys differed ($P < 0.05$) among diets. Diet AID of His, Met,

**Table 3.** Analyzed nutrient composition (as-fed basis) of experimental diets containing soybean products

| | Soybean products[1] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Item, % | SBM | EX1 | EX2 | TM1 | TM2 | BC1 | BC2 | EW1 | EW2 | N-free |
| Moisture | 8.2 | 7.9 | 8.2 | 9.7 | 7.8 | 7.6 | 8.1 | 8.1 | 8.5 | 8.1 |
| CP, % | 15.9 | 17.1 | 16.2 | 19.3 | 16.4 | 14.4 | 16.8 | 15.8 | 15.7 | 0.6 |
| GE, Mcal/kg | 3.93 | 4.30 | 4.28 | 3.88 | 3.93 | 3.94 | 3.94 | 3.90 | 3.89 | 3.70 |
| Ether extract, % | 1.31 | 10.50 | 9.26 | 1.36 | 1.42 | 1.50 | 1.37 | 1.07 | 1.60 | 0.75 |
| Ash, % | 4.74 | 4.84 | 4.90 | 5.27 | 4.51 | 4.26 | 4.69 | 3.98 | 3.84 | 2.54 |
| Crude fiber, % | 1.49 | 2.08 | 2.29 | 1.75 | 0.61 | 1.31 | 0.81 | 1.38 | 0.92 | 1.54 |
| Indispensable AA, % | | | | | | | | | | |
| Arg | 1.14 | 1.23 | 1.11 | 1.42 | 1.16 | 0.96 | 1.13 | 1.07 | 1.14 | 0.01 |
| His | 0.42 | 0.44 | 0.40 | 0.51 | 0.41 | 0.37 | 0.41 | 0.39 | 0.41 | 0.00 |
| Ile | 0.77 | 0.80 | 0.72 | 0.92 | 0.82 | 0.69 | 0.81 | 0.75 | 0.77 | 0.01 |
| Leu | 1.25 | 1.36 | 1.23 | 1.54 | 1.31 | 1.15 | 1.29 | 1.22 | 1.28 | 0.03 |
| Lys | 1.00 | 1.05 | 0.93 | 1.21 | 0.99 | 0.85 | 0.96 | 0.96 | 1.00 | 0.01 |
| Met | 0.22 | 0.22 | 0.27 | 0.27 | 0.21 | 0.21 | 0.22 | 0.21 | 0.22 | 0.01 |
| Phe | 0.82 | 0.90 | 0.80 | 1.03 | 0.86 | 0.73 | 0.85 | 0.79 | 0.83 | 0.02 |
| Thr | 0.59 | 0.66 | 0.61 | 0.74 | 0.59 | 0.56 | 0.60 | 0.58 | 0.61 | 0.01 |
| Trp | 0.19 | 0.23 | 0.21 | 0.24 | 0.21 | 0.18 | 0.22 | 0.17 | 0.18 | 0.04 |
| Val | 0.83 | 0.83 | 0.77 | 0.98 | 0.84 | 0.73 | 0.84 | 0.79 | 0.79 | 0.02 |
| Dispensable AA, % | | | | | | | | | | |
| Ala | 0.70 | 0.75 | 0.70 | 0.86 | 0.72 | 0.66 | 0.72 | 0.67 | 0.70 | 0.02 |
| Asp | 1.82 | 1.98 | 1.77 | 2.26 | 1.89 | 1.64 | 1.84 | 1.74 | 1.84 | 0.02 |
| Cys | 0.31 | 0.31 | 0.45 | 0.33 | 0.25 | 0.29 | 0.31 | 0.28 | 0.30 | 0.01 |
| Glu | 2.79 | 2.98 | 2.67 | 3.50 | 2.85 | 2.47 | 2.80 | 2.62 | 2.86 | 0.05 |
| Gly | 0.69 | 0.73 | 0.68 | 0.85 | 0.69 | 0.65 | 0.68 | 0.65 | 0.68 | 0.01 |
| Pro | 0.81 | 0.82 | 0.76 | 1.00 | 0.79 | 0.70 | 0.77 | 0.73 | 0.79 | 0.02 |
| Ser | 0.67 | 0.82 | 0.72 | 0.86 | 0.68 | 0.66 | 0.70 | 0.65 | 0.72 | 0.01 |
| Tyr | 0.52 | 0.58 | 0.53 | 0.67 | 0.51 | 0.45 | 0.52 | 0.43 | 0.47 | 0.01 |
| Available Lys, % | 0.87 | 0.99 | 0.92 | 1.16 | 0.98 | 0.77 | 0.91 | 0.97 | 0.90 | 0.01 |
| Lys, % of CP | 6.25 | 6.12 | 5.74 | 6.27 | 6.03 | 5.91 | 5.75 | 6.05 | 6.38 | 1.82 |
| Lys availability, % | 87.6 | 94.0 | 98.5 | 96.1 | 98.9 | 90.4 | 94.4 | 100.9 | 89.5 | 90.7 |

[1]SBM = Soybean meal 47; EX1 = Danex soybeans; EX2 = Pigletsoy 2000MSA; TM1 = HTM-96; TM2 = Provisoy; BC1 = Pepsoygen; BC2 = HP-300; EW1 = SPC-60-IP; and EW2 = Soycomil P.

**Table 4.** Apparent total tract digestibility (ATTD) of energy of diets and soybean products and diet DE value (DM basis)

| | Soybean products[1] | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Item, % | SBM | EX1 | EX2 | TM1 | TM2 | BC1 | BC2 | EW1 | EW2 | SEM | P |
| ATTD of energy, % | | | | | | | | | | | |
| Diet | 94.1[a] | 86.6[b] | 86.8[b] | 93.5[a] | 94.6[a] | 94.6[a] | 94.5[a] | 92.5[a] | 94.3[a] | 1.31 | < 0.001 |
| Ingredient | 91.0[ab] | 76.4[c] | 76.8[c] | 91.7[a] | 90.1[ab] | 90.1[ab] | 90.3[ab] | 81.9[bc] | 88.7[ab] | 3.68 | 0.010 |
| Diet DE, Mcal/kg | 4.03 | 4.05 | 4.04 | 4.01 | 4.03 | 4.03 | 4.05 | 3.92 | 4.01 | 0.06 | 0.649 |

[1]SBM = Soybean meal 47; EX1 = Danex soybeans; EX2 = Pigletsoy 2000MSA; TM1 = HTM-96; TM2 = Provisoy; BC1 = Pepsoygen; BC2 = HP-300; EW1 = SPC-60-IP; and EW2 = Soycomil P.

Thr, Trp, Ala, Asp, Cys, Gly, Pro, and Ser for soy products did not differ.

The SID of CP ranged from 88.1% to 96.8% and did not differ ($P > 0.05$; Table 6) among soybean products. The SID of Lys was greater ($P < 0.01$) for TM1, TM2, and EW1 than that for EX2 and BC1, and was intermediate for SBM, EX1, BC2, and EW2. The SID of Arg, Ile, Leu, Phe, and Tyr differed ($P < 0.05$) among soybean products and was consistently lower for EX2 ($P < 0.05$). The SID of His, Met, Thr, Trp, Val, Ala, Asp, Cys, Glu, Gly, Ser, and chemically available Lys did not differ ($P > 0.05$) among soybean products.

Ingredient DE value ranged from 3.94 to 4.37 Mcal/kg and NE value ranged from 2.71 to 3.01 Mcal/kg, and did not differ among soybean products (Table 7). The SID content of CP was greatest ($P < 0.05$) for EW1 and EW2, followed by TM2 and BC2, then SBM, TM1, and BC1, and was lowest ($P < 0.05$) for EX1 and EX2, with a similar pattern for SID content of indispensable and dispensable AA.

Using partial least square (**PLS**) analysis, the first two PLS factors explained 71.2% variation in predictor variables (chemical composition and GE) and 59.0% variation in response variables (digestibility and digestible content of nutrients or GE) of the soy co-products (Figure 1). The variation in SID content of CP, Lys, or Thr, and ATTD of GE was explained well with the two PLS factors. The PLS analysis revealed that ATTD of GE was strongly negatively correlated with ADF and crude fiber content. The EX1 and EX2 characterized by greater ether extract content, but that was negatively correlated with the ATTD of GE. The SID content of CP, Lys, and Thr was more

**Table 5.** Apparent ileal digestibility of CP and AA in diets containing soybean meal (SBM) and soy products

| Item, % | Soybean products[1] | | | | | | | | | SEM | P |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | SBM | EX1 | EX2 | TM1 | TM2 | BC1 | BC2 | EW1 | EW2 | | |
| CP | 80.8 | 85.0 | 79.6 | 89.0 | 88.4 | 82.1 | 86.6 | 85.6 | 83.4 | 2.96 | 0.229 |
| Indispensable AA | | | | | | | | | | | |
| Arg | 90.2[b] | 90.3[b] | 84.7[c] | 95.3[a] | 94.6[ab] | 91.1[ab] | 93.6[ab] | 91.9[ab] | 92.5[ab] | 1.70 | 0.007 |
| His | 84.8 | 88.5 | 82.7 | 92.6 | 92.7 | 88.9 | 91.3 | 84.4 | 89.7 | 2.82 | 0.101 |
| Ile | 86.6[cd] | 88.2[bc] | 82.1[d] | 93.0[ab] | 94.4[a] | 88.9[bc] | 92.5[ab] | 89.7[abc] | 90.8[abc] | 2.09 | 0.007 |
| Leu | 85.4[bc] | 88.1[abc] | 82.4[c] | 92.9[a] | 93.8[a] | 88.8[ab] | 92.2[a] | 89.3[ab] | 90.6[ab] | 2.16 | 0.011 |
| Lys | 85.1[ab] | 88.0[ab] | 82.9[b] | 92.7[a] | 93.2[a] | 82.6[b] | 87.2[ab] | 92.1[a] | 89.3[ab] | 2.64 | 0.019 |
| Met | 89.8 | 89.1 | 87.8 | 94.5 | 94.7 | 90.5 | 93.6 | 91.1 | 91.1 | 1.81 | 0.072 |
| Phe | 85.6[cd] | 88.2[bcd] | 82.6[d] | 93.2[ab] | 94.0[a] | 89.1[abc] | 92.9[ab] | 90.1[abc] | 91.4[abc] | 2.11 | 0.005 |
| Thr | 78.0 | 84.8 | 78.9 | 87.4 | 87.4 | 81.5 | 84.8 | 83.4 | 83.2 | 3.35 | 0.332 |
| Trp | 85.3 | 91.1 | 85.1 | 91.1 | 92.9 | 89.0 | 91.1 | 88.8 | 90.7 | 2.29 | 0.178 |
| Val | 83.5[bc] | 86.3[abc] | 80.0[c] | 90.8[a] | 91.9[a] | 85.8[abc] | 89.6[ab] | 87.4[ab] | 88.1[abc] | 2.54 | 0.046 |
| Dispensable AA | | | | | | | | | | | |
| Ala | 81.5 | 86.0 | 80.0 | 89.9 | 89.3 | 82.4 | 87.4 | 84.2 | 85.5 | 2.90 | 0.154 |
| Asp | 82.8 | 86.9 | 81.6 | 89.2 | 90.8 | 85.6 | 87.9 | 85.9 | 82.3 | 2.71 | 0.215 |
| Cys | 80.4 | 88.3 | 88.5 | 86.1 | 88.2 | 85.1 | 87.1 | 85.4 | 85.4 | 3.07 | 0.559 |
| Glu | 86.0[c] | 89.2[abc] | 84.1[c] | 91.5[ab] | 94.3[a] | 87.9[bc] | 91.8[ab] | 89.3[abc] | 90.7[abc] | 2.15 | 0.044 |
| Gly | 69.6 | 79.0 | 70.1 | 82.9 | 79.6 | 73.3 | 76.0 | 73.0 | 71.3 | 5.21 | 0.455 |
| Pro | 65.8 | 69.1 | 65.8 | 80.3 | 55.0 | 72.5 | 75.5 | 78.4 | 62.9 | 8.34 | 0.265 |
| Ser | 82.5 | 87.3 | 80.9 | 90.8 | 90.2 | 85.5 | 88.3 | 87.0 | 87.4 | 2.56 | 0.110 |
| Tyr | 85.4[bc] | 88.0[abc] | 81.8[c] | 92.7[a] | 93.2[a] | 87.4[abc] | 91.0[ab] | 87.8[abc] | 89.3[abc] | 2.27 | 0.024 |
| Available Lys | 84.9[bc] | 88.4[abc] | 83.6[bc] | 92.8[a] | 92.9[a] | 82.6[c] | 86.9[abc] | 89.4[ab] | 88.5[abc] | 2.37 | 0.019 |

[1]SBM = Soybean meal 47; EX1 = Danex soybeans; EX2 = Pigletsoy 2000MSA; TM1 = HTM-96; TM2 = Provisoy; BC1 = Pepsoygen; BC2 = HP-300; EW1 = SPC-60-IP; and EW2 = Soycomil P.
[a–c]Means without a common superscript differ at $P < 0.05$.

**Table 6.** Standardized ileal digestibility of CP and AA in soybean meal (SBM) and soybean products

| Item, % | Soybean products[1,2] | | | | | | | | | SEM | P |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | SBM | EX1 | EX2 | TM1 | TM2 | BC1 | BC2 | EW1 | EW2 | | |
| CP | 89.4 | 93.0 | 88.1 | 95.9 | 96.8 | 91.7 | 94.8 | 94.3 | 92.1 | 2.96 | 0.391 |
| Indispensable AA | | | | | | | | | | | |
| Arg | 95.9[a] | 95.6[a] | 90.6[b] | 99.8[a] | 100.0[a] | 98.0[a] | 99.4[a] | 98.0[a] | 98.2[a] | 1.70 | 0.015 |
| His | 89.5 | 93.0 | 87.6 | 96.3 | 97.4 | 94.3 | 96.1 | 89.4 | 94.4 | 2.78 | 0.133 |
| Ile | 89.4[cd] | 90.9[bcd] | 85.1[d] | 95.3[ab] | 97.0[a] | 92.1[abc] | 95.2[ab] | 92.6[abc] | 93.7[abc] | 2.09 | 0.012 |
| Leu | 88.6[bc] | 91.1[abc] | 85.6[c] | 95.5[a] | 96.9[a] | 92.3[ab] | 95.3[a] | 92.6[ab] | 93.7[ab] | 2.16 | 0.015 |
| Lys | 90.3[ab] | 91.0[ab] | 86.3[b] | 95.3[a] | 96.4[a] | 86.3[b] | 90.5[ab] | 95.4[a] | 92.4[ab] | 2.64 | 0.033 |
| Met | 92.1 | 91.4 | 89.8 | 96.4 | 97.2 | 93.0 | 95.9 | 93.6 | 93.4 | 1.81 | 0.069 |
| Phe | 88.6[cd] | 90.9[bcd] | 85.7[d] | 95.5[ab] | 97.3[a] | 92.5[abc] | 95.8[ab] | 93.2[abc] | 94.4[abc] | 2.11 | 0.007 |
| Thr | 85.2 | 91.3 | 86.0 | 93.1 | 96.4 | 89.1 | 91.9 | 90.8 | 90.1 | 3.35 | 0.444 |
| Trp | 89.8 | 94.7 | 89.1 | 94.4 | 96.9 | 93.7 | 95.0 | 93.6 | 95.4 | 2.29 | 0.254 |
| Val | 88.0 | 90.7 | 84.8 | 94.5 | 96.3 | 90.8 | 94.0 | 92.1 | 92.8 | 2.54 | 0.072 |
| Dispensable AA | | | | | | | | | | | |
| Ala | 89.1 | 93.2 | 87.7 | 96.0 | 96.9 | 90.6 | 94.9 | 92.3 | 93.2 | 2.90 | 0.280 |
| Asp | 86.1 | 89.9 | 85.0 | 91.9 | 94.1 | 89.3 | 91.2 | 89.4 | 85.6 | 2.71 | 0.266 |
| Cys | 85.0 | 92.9 | 91.6 | 90.3 | 93.9 | 90.0 | 91.8 | 90.6 | 90.3 | 3.07 | 0.547 |
| Glu | 88.6 | 91.6 | 86.8 | 93.5 | 96.8 | 90.9 | 94.3 | 92.1 | 93.1 | 2.15 | 0.058 |
| Gly | 88.5 | 97.2 | 89.4 | 98.1 | 98.9 | 93.7 | 95.5 | 93.3 | 90.6 | 5.21 | 0.723 |
| Ser | 88.6 | 92.2 | 86.5 | 95.5 | 96.2 | 91.6 | 94.1 | 93.2 | 93.0 | 2.56 | 0.157 |
| Tyr | 88.7[bc] | 90.9[abc] | 84.4[c] | 95.1[a] | 96.5[a] | 91.1[abc] | 94.2[ab] | 91.7[ab] | 92.9[abc] | 2.27 | 0.032 |
| Available Lys | 88.9 | 92.0 | 87.4 | 95.7 | 96.4 | 87.2 | 90.7 | 93.0 | 92.3 | 2.37 | 0.051 |

[1]SBM = Soybean meal 47; EX1 = Danex soybeans; EX2 = Pigletsoy 2000MSA; TM1 = HTM-96; TM2 = Provisoy; BC1 = Pepsoygen; BC2 = HP-300; EW1 = SPC-60-IP; and EW2 = Soycomil P.
[2]Standardized ileal digestibility of CP and AA was calculated by correcting apparent ileal digestibility of CP and AA with measured basal endogenous losses (g/kg dry matter intake): CP, 14.9; Arg, 0.71; His, 0.21; Ile, 0.24; Leu, 0.44; Lys, 0.34; Met, 0.06; Phe, 0.27; Thr, 0.47; Trp, 0.09; Val, 0.40; Ala, 0.59; Asp, 0.66; Cys, 0.16; Glu, 0.78; Gly, 1.43; Ser, 0.44, and Tyr, 0.18.
[a–c]Means without a common superscript differ at $P < 0.05$.

**Table 7.** The DE and NE value and standardized ileal digestible CP and AA content in soybean products

| | Soybean products[1] | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Item, DM basis | SBM | EX1 | EX2 | TM1 | TM2 | BC1 | BC2 | EW1 | EW2 | SEM | P |
| DE, Mcal/kg | 4.23 | 4.23 | 4.11 | 4.29 | 4.23 | 3.96 | 4.37 | 3.94 | 4.27 | 0.18 | 0.621 |
| NE, Mcal/kg | 2.92 | 2.96 | 2.88 | 2.97 | 2.92 | 2.73 | 3.01 | 2.71 | 2.93 | 0.13 | 0.587 |
| CP, % | 46.2$^{d}$ | 38.3$^{e}$ | 34.2$^{e}$ | 49.2$^{cd}$ | 56.3$^{b}$ | 50.6$^{c}$ | 57.9$^{b}$ | 62.3$^{a}$ | 66.8$^{a}$ | 1.62 | < 0.001 |
| Indispensable AA, % | | | | | | | | | | | |
| Arg | 3.53$^{d}$ | 2.88$^{e}$ | 2.45$^{f}$ | 3.64$^{d}$ | 4.18$^{c}$ | 3.59$^{d}$ | 4.24$^{c}$ | 4.70$^{b}$ | 5.20$^{a}$ | 0.06 | < 0.001 |
| His | 1.19$^{e}$ | 0.99$^{f}$ | 0.85$^{g}$ | 1.28$^{de}$ | 1.42$^{c}$ | 1.30$^{d}$ | 1.44$^{bc}$ | 1.55$^{b}$ | 1.79$^{a}$ | 0.04 | < 0.001 |
| Ile | 2.13$^{e}$ | 1.96$^{f}$ | 1.60$^{g}$ | 2.46$^{d}$ | 2.81$^{c}$ | 2.54$^{d}$ | 2.81$^{c}$ | 3.13$^{b}$ | 3.44$^{a}$ | 0.05 | < 0.001 |
| Leu | 3.52$^{e}$ | 3.01$^{f}$ | 2.55$^{g}$ | 3.81$^{d}$ | 4.40$^{c}$ | 4.00$^{d}$ | 4.48$^{c}$ | 4.87$^{b}$ | 5.41$^{a}$ | 0.09 | < 0.001 |
| Lys | 2.85$^{d}$ | 2.32$^{e}$ | 1.96$^{f}$ | 2.96$^{d}$ | 3.33$^{c}$ | 2.77$^{d}$ | 3.21$^{c}$ | 3.93$^{b}$ | 4.26$^{a}$ | 0.09 | < 0.001 |
| Met | 0.70$^{d}$ | 0.51$^{e}$ | 0.50$^{e}$ | 0.69$^{d}$ | 0.78$^{c}$ | 0.78$^{c}$ | 0.81$^{c}$ | 0.88$^{b}$ | 0.99$^{a}$ | 0.01 | < 0.001 |
| Phe | 2.28$^{e}$ | 2.02$^{f}$ | 1.68$^{g}$ | 2.53$^{d}$ | 2.92$^{c}$ | 2.58$^{d}$ | 3.01$^{c}$ | 3.19$^{b}$ | 3.51$^{a}$ | 0.06 | < 0.001 |
| Thr | 1.69$^{e}$ | 1.37$^{f}$ | 1.24$^{f}$ | 1.75$^{e}$ | 2.01$^{cd}$ | 1.85$^{de}$ | 2.09$^{bc}$ | 2.25$^{ab}$ | 2.45$^{a}$ | 0.07 | < 0.001 |
| Trp | 0.63$^{d}$ | 0.48$^{e}$ | 0.45$^{e}$ | 0.65$^{d}$ | 0.76$^{c}$ | 0.72$^{c}$ | 0.75$^{c}$ | 0.83$^{b}$ | 0.93$^{a}$ | 0.02 | < 0.001 |
| Val | 2.24$^{e}$ | 1.97$^{f}$ | 1.67$^{g}$ | 2.52$^{d}$ | 2.83$^{c}$ | 2.60$^{d}$ | 2.82$^{c}$ | 3.17$^{b}$ | 3.52$^{a}$ | 0.07 | < 0.001 |
| Dispensable AA, % | | | | | | | | | | | |
| Ala | 1.95$^{e}$ | 1.64$^{f}$ | 1.43$^{g}$ | 2.09$^{de}$ | 2.38$^{c}$ | 2.19$^{d}$ | 2.46$^{bc}$ | 2.62$^{b}$ | 2.87$^{a}$ | 0.07 | < 0.001 |
| Asp | 4.89$^{d}$ | 4.18$^{e}$ | 3.57$^{f}$ | 5.21$^{cd}$ | 6.13$^{b}$ | 5.39$^{c}$ | 6.08$^{b}$ | 6.63$^{a}$ | 7.00$^{a}$ | 0.16 | < 0.001 |
| Cys | 0.74$^{d}$ | 0.68$^{de}$ | 0.68$^{de}$ | 0.66$^{e}$ | 0.90$^{b}$ | 0.81$^{bc}$ | 0.85$^{bc}$ | 1.00$^{a}$ | 1.00$^{a}$ | 0.03 | < 0.001 |
| Glu | 7.39$^{e}$ | 6.13$^{f}$ | 5.27$^{g}$ | 7.94$^{d}$ | 9.41$^{c}$ | 7.95$^{d}$ | 9.21$^{c}$ | 10.04$^{b}$ | 11.40$^{a}$ | 0.19 | < 0.001 |
| Gly | 1.89$^{cd}$ | 1.68$^{de}$ | 1.44$^{e}$ | 2.12$^{bc}$ | 2.33$^{ab}$ | 2.24$^{b}$ | 2.33$^{ab}$ | 2.55$^{a}$ | 2.72$^{a}$ | 0.12 | < 0.001 |
| Pro | 2.86$^{bcd}$ | 2.45$^{cd}$ | 2.01$^{d}$ | 3.00$^{abc}$ | 3.20$^{abc}$ | 3.43$^{ab}$ | 3.41$^{ab}$ | 3.79$^{a}$ | 3.69$^{ab}$ | 0.35 | 0.012 |
| Ser | 2.02$^{e}$ | 1.54$^{f}$ | 1.42$^{f}$ | 2.07$^{de}$ | 2.38$^{c}$ | 2.19$^{d}$ | 2.53$^{bc}$ | 2.60$^{b}$ | 2.86$^{a}$ | 0.06 | < 0.001 |
| Tyr | 1.79$^{c}$ | 1.40$^{d}$ | 1.22$^{e}$ | 1.76$^{c}$ | 2.12$^{b}$ | 1.84$^{c}$ | 2.16$^{ab}$ | 2.25$^{a}$ | 2.32$^{a}$ | 0.05 | < 0.001 |
| Available Lys | 2.82$^{c}$ | 2.21$^{d}$ | 1.94$^{e}$ | 2.78$^{c}$ | 3.26$^{b}$ | 2.70$^{c}$ | 3.06$^{b}$ | 3.69$^{a}$ | 3.94$^{a}$ | 0.08 | < 0.001 |

[1]SBM = Soybean meal 47; EX1 = Danex soybeans; EX2 = Pigletsoy 2000MSA; TM1 = HTM-96; TM2 = Provisoy; BC1 = Pepsoygen; BC2 = HP-300; EW1 = SPC-60-IP; and EW2 = Soycomil P.

[a-f]Means without a common superscript differ at $P < 0.05$.

correlated with total content of CP, Lys, and Thr than SID of CP, Lys, and Thr. The SID of Lys did not correlate with Lys availability. The EW1 was far from and in an opposite direction to the DE and NE loading.

## Discussion

The present study was focused on novel soybean products that were produced by processing soybean or SBM using various technologies. Consequently, these soybean products varied in macronutrient composition especially for ether extract, CP, and fiber. Changes in macronutrients and in factors that restrict digestibility resulted in differences in digestibility of energy and AA.

### Composition of Ingredients

The GE value and CP and AA content of SBM in the present study were similar to the published data for SBM (NRC, 2012; Yáñez et al., 2014). The EX1 and EX2 soybean products from extrusion of full fat soybean had ether extract, CP, and AA profile close to the previously reported for full fat soybeans (Cervantes-Pahm and Stein, 2008; NRC, 2012). However, novel cultivars of full fat soybeans may contain high protein or low oligosaccharide and may contain slightly more ether extract (NRC, 2012). Because soybean oil was not extracted, the EX1 and EX2 contained more ether extract than SBM and other soybean products, and thus had a greater GE value. Processed using a thermo-mechanical treatment to increase nutrient digestibility of SBM, the TM soybean products contained CP and AA in average similar to regular SBM with 47% CP. The BC process uses either fermentation (BC1) or enzymes (BC2) to hydrolyze carbohydrates and protein from SBM (Rosenthal et al., 1996). Consequently, the BC soybean products had ether extract, CP, and AA profile similar to fermented SBM and enzyme-treated SBM (Cervantes-Pahm and Stein, 2010; NRC, 2012). The EW process uses SBM as starting material, which is then under liquid–solid extraction, removal and recovery of solvent from liquid extract, removal and recovery of solvent from extracted flakes, and drying and grinding of flakes to extract the soluble sugar fraction of defatted SBM without solubilizing its proteins (Berk, 1992). Little is known about the nutrient composition of soybean products processed using EW, but they are expected to be similar to soybean protein concentrates due to their greater CP content (NRC, 2012). In the present study, soybean products that had low fat content contained more CP. The processes used to create the soybean products in the present study may reduce ANF, such as trypsin inhibitors, oligosaccharides, and allergenic proteins, which are not tolerated well by young pigs (Sissons et al., 1982; Cromwell, 2000; Cervantes-Pahm and Stein, 2010). Removal or reduction of these ANF may increase digestibility of energy and nutrients. Consequently, novel soybean products with low ANF might be attractive for inclusion in diets for young pigs (Jones et al., 2010; Kim et al., 2010).

### Digestibility of Energy

In the present study, full-fat soybean had lower energy digestibility than SBM (Kim et al., 2013), which could be due to its fat within a fibrous matrix and its external hull that may hinder energy digestibility (Dilger et al., 2004). The extrusion step in EX1 and EX2 may open the fibrous matrix (Lundblad et al., 2011). However, energy digestibility remained lower for EX than

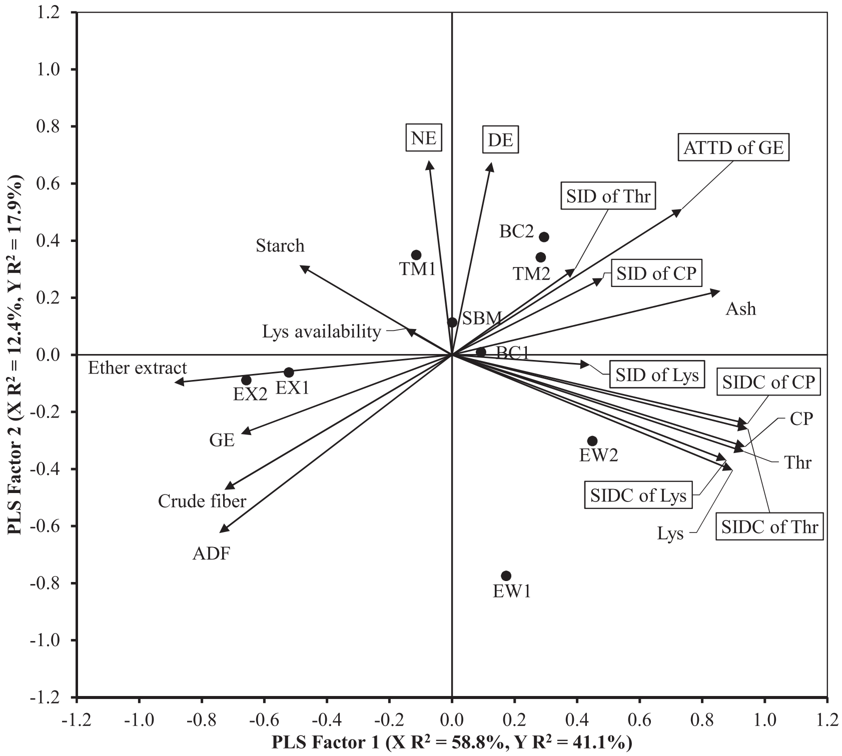


**Figure 1.** Correlation loading plot of chemical components (predictor variables; without box) and digestibility of energy and nutrients and digestible content of crude protein and amino acids (response variables; labeled with solid-line boxes) following PLS analyses. The 9 soybean products were labeled with solid round dots. Lines pointing in similar direction with sharp angles indicate that variables were strongly correlated, but lines in opposite directions indicate that variables were strongly negatively correlated, whereas lines perpendicular to each other indicate that variables were not correlated. Placing of soybean products closer to each other or to predictor or response variables indicates a stronger association. SBM = Soybean meal 47; EX1 = Danex soybeans; EX2 = Pigletsoy 2000MSA; TM1 = HTM-96; TM2 = Provisoy; BC1 = Pepsoygen; BC2 = HP-300; EW1 = SPC-60-IP and EW2 = Soycomil P; and SIDC = SID content.

for SBM. Following dehulling and oil extraction, SBM contains less fiber than full-fat soybean. Energy digestibility and energy value of dehulled-expelled SBM have been well established. In the present study, energy value of SBM was similar to NRC (2012) values of DE at 4.21 Mcal/kg and NE at 2.60 Mcal/kg, and other reported values (Baker and Stein, 2009), but greater than the reported 3.38 Mcal DE/kg (van Kempen et al., 2006). Fiber analyses used in the present study especially measure insoluble fiber and not soluble fiber (Goering and van Soest, 1970). Treatments used to process SBM in the present study may cause marginal changes in insoluble fiber content among the soy products; however, these changes were associated with changes of ATTD of energy compared with SBM. Treatments used in BC and EW of SBM may cause changes in soluble fiber and especially the oligosaccharides content (Cervantes-Pahm and Stein, 2010). However, these potential changes did not alter ATTD of energy too much when comparing with SBM in the present study, likely because soluble fiber components in SBM were fermented well within the gastrointestinal tract (Jha and Berrocoso, 2016). Overall, similar GE with similar ATTD of GE or greater GE with lower ATTD of GE for soybean products in the present study resulted in similar DE and predicted NE value among soybean products.

## Digestibility of Amino Acids

Soybean products are rich in protein overall, and thus their protein quality is important (Sauer and Ozimek, 1986). In the present study, soybean products varied substantially in protein content and differed in AID and SID of AA, similar to previous studies (e.g., Stein et al., 2007). Some ingredient factors may have influenced AA digestibility. For example, the fiber-rich soybean hulls reduce digestibility of AA (Dilger et al., 2004). The ANF in raw soybean or remaining ANF in processed soybean can reduce digestibility of AA (Qin et al., 1996). Finally, excessive heat processing may reduce digestibility and availability of AA (Fontaine et al., 2007). As an indicator of protein quality, Lys chemical-availability was slightly lower than 100% for soybean products other than SBM in the present study, indicating heat damage to protein was minor, similar to soybean products such as dry extruded-expelled SBM (Opapeju et al., 2006).

In full-fat soybean and other oilseeds, AA might be trapped in the protein–fiber–fat matrix that may make digestion of AA difficult and thereby reduce digestibility of AA (Woyengo et al., 2014b; Park et al., 2017). Increased fat in diets may reduce passage rate, thereby allowing for more time for AA digestion and absorption (Albin et al., 2001); however, the effect on increasing AA digestibility was not apparent for the EX soybean products containing the extra oil likely because the oil was contained within the ingredient matrix and not free oil. Due to greater oil and fiber content, AA content in EX soybean products was lower; therefore, SID AA content was lower in EX soybean products than SBM, similar to the previously reported (Cervantes-Pahm and Stein, 2008).

The novel technologies used to process SBM may remove components that reduce digestibility of AA including fibrous components (Cromwell, 2000). Consequently, novel soybean products with lower ANF may be included to diets for monogastric species, especially for young pigs, to meet their high requirements for digestible AA. These novel soybean products might therefore substitute animal origin protein sources. In the present study, digestibility of the first- to fourth-limiting AA did not differ between SBM and novel soybean products. However, digestibility of branched-chain AA was greater in novel soybean products processed from SBM. With the increased growth rate of young pigs, meeting the requirements of the fifth- to seventh-limiting AA such as the branched-chain AA is becoming increasingly important (NRC, 2012). Therefore, these novel soybean meal products are attractive for inclusion into diets for young pigs. Moreover, the novel processing procedures such as treatments using solvents, fermentation, or enzymes increase the digestible content of essential AA in the novel soybean products compared with SBM. Principally, these treatments open the protein matrix, reduce ANF, or enhance access to digestive enzymes, thereby making these novel soybean products interesting feedstuffs to consider in diets for young pigs (Cervantes-Pahm and Stein, 2008; Oliveira and Stein, 2016).

In conclusion, soybean products developed from soybean had unique chemical characteristics. Soybean products with high residual oil increased GE value, but not DE or NE value. Finally, soybean products with enriched CP through removing fractions other than CP would provide greater SID CP content to pigs.

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