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Non Ruminant Nutrition

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Digestibility of amino acids and concentrations of metabolizable energy and net energy are greater in high-shear dry soybean expellers than in soybean meal when fed to growing pigs

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Abstract

Soybean expellers may be produced by dry extrusion and mechanical oil pressing of soybeans, but there is limited information about the nutritional value of expellers produced via this procedure. Therefore, 2 experiments were conducted to test the hypothesis that standardized ileal digestibility (**SID**) of CP and amino acids (**AA**), apparent total tract digestibility (**ATTD**) of energy and total dietary fiber (**TDF**), and concentrations of DE, ME, and NE are greater in soybean expellers than in soybean meal (**SBM**) when fed to growing pigs. Pigs were the offspring of Line 359 boars mated to Camborough females (Pig Improvement Company, Hendersonville, TN). In experiment 1, nine growing barrows (initial BW: 55.98 kg ± 13.75 kg) with T-cannulas installed in the distal ileum were allotted to 1 of 3 diets using a triplicated 3 × 3 Latin square design with 3 periods. Two diets were formulated to contain 35% soybean expellers or 33% SBM as the sole source of AA. A N-free diet was used to determine basal endogenous losses of AA. Ileal digesta were collected on days 6 and 7 of each 7-d period. Results indicated that the SID of most indispensable and dispensable AA were greater ($P < 0.05$) or tended ($P < 0.10$) to be greater in soybean expellers than in SBM. In experiment 2, a corn-based diet and 2 diets based on corn and each of the 2 soybean products were formulated. Twenty-four growing barrows (initial BW: 44.88 kg ± 2.17 kg) were allotted to 1 of the 3 diets with 8 pigs per diet. Urine and fecal samples were collected for 4 d after 5 d of adaptation. Results indicated that the ATTD of energy and TDF was not different between soybean expellers and SBM, but the ATTD of TDF in the 2 soybean products was greater ($P < 0.05$) than in corn. Concentrations of DE and ME in soybean expellers were greater ($P < 0.05$) compared with corn or SBM. Soybean expellers had greater ($P < 0.05$) calculated NE compared with SBM, but there was no difference in NE between corn and soybean expellers. In conclusion, values for SID of most AA and DE, ME, and NE in soybean expellers were greater than in SBM.

Key words: extrusion, oil extraction, pigs, soybean expellers, soybean meal

Introduction

Soybean products are used as a source of amino acids (**AA**) in diets for animals and the global production of soybeans contributes ~60% to total global oilseed production (USDA, 2019). Due to increased global production of livestock and poultry, the annual production of soybeans has increased more than three times in the past 30 yr (USDA, 2019). Most soybeans are dehulled and crushed using a solvent to extract soy oil

Abbreviations

AA	amino acids
AEE	acid hydrolyzed ether extract
AID	apparent ileal digestibility
ATTD	apparent total tract digestibility
CP	crude protein
DE	digestible energy
DM	dry matter
GE	gross energy
ME	metabolizable energy
ND	not detectable
NE	net energy
SBM	soybean meal
SID	standardized ileal digestibility
TDF	total dietary fiber

and the resulting coproduct is soybean meal (**SBM**). SBM is the most widely used plant source of protein in pig and poultry diets because of its wide availability and excellent AA profile (Stein et al., 2008). Alternatively, oil may also be removed from soybeans using the extrusion-expeller method, which results in production of soy oil and soybean expellers (Wang and Johnson, 2001). Unlike in production of conventional SBM, soybeans are usually not dehulled if being used in the extrusion-expeller method, and therefore, the concentration of total dietary fiber (**TDF**) is greater than in solvent-extracted dehulled SBM, which may affect the digestibility of nutrients and energy (Baker and Stein, 2009). The expelling procedure is less efficient than solvent extraction in removing oil from the beans and soybean expellers, therefore, contain more residual oil than SBM.

Soybean expellers may be produced using different technologies, and a novel procedure involving a patented high shear dry extrusion is one procedure that may be used (Zhang et al., 1993; Webster et al., 2003). This procedure results in continuous pressing of oil and production of soybean expellers that contain 6% to 8% fat. Because of the dry extrusion process and the constant higher shear, the extrusion-expeller procedure may prevent Maillard reactions and rupture cell walls, which may increase nutrient utilization. In addition, a greater concentration of oil in feed ingredients results in increased digestibility of AA and energy (Cervantes-Pahm and Stein, 2008; Baker and Stein, 2009) and soybean expellers may, therefore, have greater digestibility of AA and greater concentration of ME than SBM. However, limited data regarding the nutritional value of soybean expellers produced from the high shear dry extrusion process have been reported. Therefore, the objective of this research was to test the hypothesis that the apparent ileal digestibility (**AID**) and the standardized ileal digestibility (**SID**) of crude protein (**CP**) and AA, as well as the apparent total tract digestibility (**ATTD**) of gross energy (**GE**) and TDF, and the digestible energy (**DE**), ME, and net energy (**NE**) in soybean expellers that are produced using the high shear dry extrusion-expelling process are greater than in SBM when fed to growing pigs.

Materials and Methods

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocols for 2 experiments prior to initiation of the experiments. Pigs that were the offspring of Line 359 boars mated to Camborough females (Pig Improvement Company, Hendersonville, TN) were used in both experiments. Soybean expellers (ExPress®, Insta-Pro International, Grimes, IA) and SBM used in both experiments were sourced from Insta-Pro International, Grimes, IA, and the high shear dry extrusion-pressing procedure was used to produce the soybean expellers. The extruder was a single screw extruder and extrusion temperature in the final chamber was 160 °C. The material was exposed to this temperature for only 15 to 20 s before exciting the extruder. The soybeans used to produce the soybean expellers and the beans used to produce SBM were from the same batch (Table 1). The soybeans were dehulled to produce SBM, but non-dehulled soybeans were used to produce soybean expellers.

Table 1. Nutrient composition of corn, soybean expellers, and SBM, as-fed basis

Item	Soybean expellers[1]	SBM	Corn
DM, %	93.28	92.42	88.26
GE, kcal/kg	4,631	4,141	3,887
AEE, %	5.54	0.93	3.02
Ether extract, %	5.50	0.59	2.40
Ash, %	6.15	6.97	0.94
Acid detergent fiber, %	5.99	5.19	2.46
TDF[2], %	19.5	20.6	12.2
Soluble dietary fiber, %	3.7	3.3	1.1
Insoluble dietary fiber, %	15.8	17.3	11.1
CP, %	43.37	47.60	7.17
Lys to CP, %	6.27	6.05	3.21
Indispensable AA, %			
Arg	3.13	3.27	0.32
His	1.12	1.19	0.20
Ile	2.06	2.18	0.25
Leu	3.35	3.57	0.77
Lys	2.72	2.88	0.25
Met	0.58	0.62	0.13
Phe	2.25	2.39	0.32
Thr	1.70	1.83	0.24
Trp	0.60	0.62	0.05
Val	2.15	2.26	0.33
Dispensable AA, %			
Ala	1.87	1.99	0.48
Asp	4.88	5.16	0.46
Cys	0.63	0.66	0.16
Glu	7.61	8.25	1.18
Gly	1.85	1.92	0.27
Pro	2.10	2.22	0.63
Ser	1.90	2.17	0.29
Tyr	1.68	1.73	0.18
Carbohydrates, %			
Starch	ND[3]	ND	63.19
Glucose	ND	ND	0.19
Fructose	ND	0.06	0.21
Maltose	ND	ND	ND
Sucrose	5.86	7.03	1.73
Stachyose	4.86	5.48	ND
Raffinose	1.21	1.18	0.19
Trypsin inhibitors, unit/mg	4.60	3.40	—
Particle size, μm	504	744	470

[1]Insta-Pro International, Grimes, IA.
[2]TDF was calculated as the sum of soluble dietary fiber and insoluble dietary fiber.
[3]ND = not detectable.

Experiment 1: AA digestibility

Experiment 1 was conducted to determine the AID and SID of CP and AA in soybean expellers and SBM. Nine barrows (initial BW: 55.98 ± 13.75 kg) that had T-cannulas installed in the distal ileum (Stein et al., 1998) were allotted to 1 of 3 diets using a triplicated 3 × 3 Latin square design with 3 diets and 3 periods. There were, therefore, a total of 9 observations per treatment. Pigs were housed in individual pens (1.2 m × 1.5 m) in an environmentally controlled room. Pens were equipped with a self-feeder, a nipple waterer, and a slatted tri-bar floor.

Three diets were formulated (Tables 2 and 3). One diet contained 35% soybean expellers as the sole source of AA and a second diet contained 33% SBM as the sole source of AA. A N-free diet was used to determine basal endogenous losses of CP and AA. Vitamins and minerals were included in all diets to meet or exceed current requirement estimates (NRC, 2012). All diets contained 0.40% chromic oxide as an indigestible marker. Pigs were limit-fed to 3.3 times the estimated energy requirement for maintenance (i.e., 197 kcal ME per $kg^{0.60}$; NRC, 2012) and water was available at all times. Pig weights were recorded at the beginning of each period and at the conclusion of the experiment. Each period lasted 7 d. The initial 5 d of each period was considered an adaptation period to the diet. Ileal digesta were collected for 8 h on days 6 and 7 using standard procedures (Stein et al., 1998). Digesta flowing into the bag were collected and bags were replaced whenever they were full or at least once every 30 min. All samples were stored at −20 °C after collection. After the completion of one experimental period, animals were deprived of feed overnight, and the following morning, a new experimental diet was offered. After the experiment, ileal digesta samples were thawed and mixed within animal and diet, and a sub-sample was lyophilized and finely ground.

Values for AID of CP and AA were calculated using analyzed Cr, CP, and AA in diets and ileal digesta samples, and AID values were then corrected for basal endogenous losses to calculate SID of CP and AA (Stein et al., 2007). Data were analyzed using the MIXED procedure of SAS (SAS Inst. Inc., Cary, NC). Homogeneity of the variances was confirmed using the UNIVARIATE procedure. The statistical model included diet as the fixed effect, and square, pig nested within square, and period as the random effects. Statistical significance and tendencies were considered at $P \leq 0.05$ and $0.05 < P < 0.10$, respectively.

Experiment 2: Digestibility of energy and fiber and concentrations of DE and ME

Experiment 2 was conducted to determine the ATTD of GE and TDF, as well as concentrations of DE, ME, and NE in soybean expellers and SBM. Twenty-four growing barrows (initial BW: 44.88 ± 2.17 kg) were allotted to 1 of 3 diets using a randomized complete block design with BW as the block and 8 replicate pigs per diet. Pigs were housed individually in metabolism crates that were equipped with a self-feeder, a nipple drinker, a slatted floor, and a urine tray to allow for the total, but separate, collection of urine and fecal materials. A corn-based basal diet and two diets containing corn and soybean expellers or corn and SBM were formulated (Table 4). Vitamins and minerals were included in all diets to meet or exceed the estimated nutrient requirements for growing pigs (NRC, 2012).

All diets were fed in meal form. Pigs were fed at 3.2 times the energy requirement for maintenance (i.e., 197 kcal ME per $kg^{0.60}$; NRC, 2012), and feed was provided each day in two equal meals at 0800 and 1600 hours. Throughout the study, pigs had free access to water. Feed provisions and feed refusals were recorded daily and orts were collected during the collection period to calculate the exact feed intake of pigs. Diets were fed for 12 d. The initial 5 d were the adaptation period to the diet. Start and

Table 2. Ingredient composition of experimental diets, experiment 1

Ingredient, %	Soybean expellers[1]	SBM	N-free
Corn starch	42.40	42.35	68.35
Soybean expellers	35.00	—	—
Soybean meal	—	33.00	—
Soybean oil	—	2.00	4.00
Sucrose	20.00	20.00	20.00
Ground limestone	0.65	0.65	0.40
Dicalcium phosphate	1.00	1.05	1.80
Magnesium oxide	—	—	0.10
Potassium carbonate	—	—	0.40
Solka floc[2]	—	—	4.00
Sodium chloride	0.40	0.40	0.40
Chromic oxide	0.40	0.40	0.40
Vitamin-mineral premix[3]	0.15	0.15	0.15

[1]Insta-Pro International, Grimes, IA.
[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, 11,150 IU; vitamin D_3 as cholecalciferol, 2,210 IU; vitamin E as selenium yeast, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.42 mg; thiamin as thiamine mononitrate, 1.10 mg; riboflavin,6.59 mg; pyridoxine as pyridoxine hydrochloride, 1.00 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.6 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 125 mg as iron sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese hydroxychloride; Se, 0.30 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc hydroxychloride.

Table 3. Analyzed nutrient composition of experimental diets, as-fed basis (experiment 1)

Ingredient, %	Soybean expellers[1]	SBM	N-free
DM	93.42	91.92	92.53
CP	15.17	16.45	0.36
AEE	2.87	3.07	3.48
Indispensable AA			
Arg	1.29	1.08	0.01
His	0.48	0.41	0.01
Ile	0.88	0.75	0.01
Leu	1.43	1.23	0.02
Lys	1.15	0.98	0.01
Met	0.25	0.21	0.01
Phe	0.94	0.81	0.01
Thr	0.71	0.62	0.00
Trp	0.22	0.24	0.02
Val	0.92	0.78	0.01
Dispensable AA			
Ala	0.81	0.69	0.01
Asp	2.06	1.80	0.01
Cys	0.27	0.23	0.01
Glu	3.32	2.83	0.02
Gly	0.79	0.67	0.01
Pro	0.93	0.80	0.02
Ser	0.81	0.69	0.01
Tyr	0.59	0.52	0.02

[1]Insta-Pro International, Grimes, IA.

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

Ingredient, %	Corn	Soybean expellers[1]	SBM
Ground corn	97.15	65.70	67.60
Soybean expellers	—	32.00	—
SBM	—	—	30.00
Monocalcium phosphate	1.20	0.65	0.80
Ground limestone	1.10	1.10	1.05
Sodium chloride	0.40	0.40	0.40
Vitamin-mineral premix[2]	0.15	0.15	0.15
Analyzed composition			
DM, %	91.88	92.12	93.16
GE, kcal/kg	3,773	4,012	3,774
TDF, %	12.6	14.7	16.3
Calculated composition[3]			
ME, kcal/kg	3,300	3,350	3,300
TDF, %	11.9	14.3	14.4

[1]Insta-Pro International, Grimes, IA.
[2]Provided the following quantities of vitamins and micro minerals per kg of complete diet: vitamin A as retinyl acetate, 11,150 IU; vitamin D_3 as cholecalciferol, 2,210 IU; vitamin E as selenium yeast, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.42 mg; thiamin as thiamine mononitrate, 1.10 mg; riboflavin,6.59 mg; pyridoxine as pyridoxine hydrochloride, 1.00 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.6 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 125 mg as iron sulfate; I, 1.26mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese hydroxychloride; Se, 0.30mg as sodium selenite and selenium yeast; and Zn, 125.1mg as zinc hydroxychloride.
[3]Values for ME were calculated from NRC (2012) and values for TDF were calculated from Table 1.

stop markers were fed in the morning meals on days 6 and 10, respectively, and urine and fecal materials were collected from the feed provided from days 6, 7, 8, and 9 according to standard procedures using the marker-to-marker approach (Adeola, 2001). Urine was collected in 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 dripped onto cotton balls that were placed in a plastic bag and lyophilized (Kim et al., 2009). Fecal samples were thawed and mixed within pig and diet, and then dried for 7 d in a 50 °C forced-air drying oven (Model 8; Metalab Equipment Corporation, Hicksville, Long Island, NY) to reduce moisture to <10%. Samples were then ground through a 1-mm screen using a Wiley mill (Model 4; Thomas Scientific, Swedesboro, NJ).

Following analysis, values for the ATTD of GE and TDF were calculated for each diet. The DE and ME were also calculated for each diet, and the DE and ME in soybean expellers and SBM were calculated by subtracting the contribution from corn to the mixed diets using the difference procedure (Adeola, 2001). The ATTD of GE and TDF in soybean expellers and SBM was also calculated using the different procedure. NE in corn, soybean expellers, and SBM was predicted from ME and analyzed nutrient composition by using the following equation (Noblet et al., 1994):

$$\begin{aligned} NE &= (0.726 \times ME) + (1.33 \times \text{ether extract}) \\ &+ (0.39 \times \text{starch}) - (0.62 \times CP) \\ &- (0.83 \times \text{acid detergent fiber}) \end{aligned}$$

where NE is expressed as kcal/kg DM and all nutrient contents are expressed as g/kg DM.

Data were analyzed using the MIXED procedure of SAS (SAS Inst. Inc., Cary, NC) and pig was the experimental unit. Homogeneity of the variances was confirmed as explained for experiment 1. In the statistical model, diet or ingredient was the fixed effect and block was the random effect. Least squares means were calculated, and the PDIFF statement with Tukey's adjustment was used to separate means if significant differences were detected. Results were considered significant or a tendency at $P \le 0.05$ and $0.05 < P \le 0.10$, respectively.

Chemical analysis

Samples of ingredients, diets, ileal digesta, and feces were analyzed for DM (method 930.15; AOAC Int., 2007). Crude protein in ingredients, diets, and ileal digesta samples from experiment 1 were calculated as $N \times 6.25$ and N was measured using a LECO FP628 Nitrogen Analyzer (method 990.03; AOAC Int., 2007; LECO Corp., Saint Joseph, MI). Ingredient, diet, and ileal digesta samples were also analyzed for AA using a Hitachi AA Analyzer (Model No. L8800; Hitachi High Technologies America, Inc., Pleasanton, CA) using ninhydrin for postcolumn derivatization and norleucine as the internal standard [method 982.30 E(a, b, c); AOAC Int., 2007]. Diets and ileal digesta samples from experiment 1 were also analyzed for Cr using an inductive coupled plasma atomic emission spectrometric method (method 990.08; AOAC Int., 2007) after digestion with nitric acid–perchloric acid [method 968.08D(b); AOAC Int., 2007]. Ingredient samples were analyzed for ash (method 942.05; AOAC Int., 2007), and acid hydrolyzed ether extract (**AEE**) in ingredient and diet samples from experiment 1 was analyzed by acid hydrolysis using 3 N HCl (Ankom HCl Hydrolysis System, Ankom Technology, Macedon, NY) followed by fat extraction (Ankom XT-15 Extractor, Ankom Technology, Macedon, NY). Ether extract in corn, SBM, and soybean expellers was also analyzed without prior acid hydrolysis. Diets, ingredients, ground fecal samples, and lyophilized urine samples from experiment 2 were analyzed for GE using bomb calorimetry (Model 6400; Parr Instruments, Moline, IL). Ingredients were analyzed for acid detergent fiber using Ankom Technology methods 12 (Ankom 2000 Fiber Analyzer, Ankom Technology, Macedon, NY). Total dietary fiber in ingredients, diets, and fecal samples from experiment 2 were analyzed according to method 991.43 (AOAC Int., 2007) using the Ankom[TDF] Dietary Fiber Analyzer (Ankom Technology, Macedon, NY). Insoluble and soluble dietary fiber in ingredient samples were also analyzed as described for TDF. Ingredients were analyzed for sugars including glucose, fructose, maltose, sucrose, stachyose, and raffinose (method 977.2, AOAC Int., 2007), and fructooligosaccharides using refractive index high-performance liquid chromatography (Campbell et al., 1997). Starch was analyzed in corn and each soybean product using the glucoamylase procedure (method 979.10; AOAC Int., 2007). Trypsin inhibitor concentrations were analyzed in SBM and in soybean expellers (method Ba 12-75; AOCS, 2006).

Results

In both experiments, pigs remained healthy and readily consumed their assigned diets.

Experiment 1. AA digestibility

The AID of CP did not differ between soybean expellers and SBM, but the SID of CP in soybean expellers tended to be greater compared with SBM ($P < 0.10$; Table 5). The AID of all indispensable AA was greater ($P < 0.05$) in soybean expellers compared with SBM, with the exception that the AID of Trp was not different between the 2 soybean products. Values for the AID of all dispensable AA except Cys were also greater ($P < 0.05$) in soybean expellers compared with SBM. The SID of all indispensable and dispensable AA was greater ($P < 0.05$) in soybean expellers compared with SBM, with the exception that the SID of Lys and Trp in soybean expellers only tended to be greater ($P < 0.10$) than in SBM, and no difference in the SID of Cys between the 2 soybean products was observed.

Experiment 2: Digestibility of energy and fiber and concentrations of DE and ME

Because of a greater amount of orts, pigs fed the corn diet had reduced ($P < 0.05$) feed and GE intake compared with pigs fed diets containing soybean expellers or SBM (Table 6). Likewise, pigs fed the soybean expellers or SBM diet had greater ($P < 0.05$) fecal and urine excretion of GE compared with pigs fed the corn diet. The ATTD of GE was not different among pigs fed the 3 diets. Concentrations of DE and ME did not differ between the corn diet and the SBM diet, but corn and SBM diets contained less ($P < 0.05$) DE and ME than the soybean expellers diet. Intake of TDF was greatest ($P < 0.05$) if pigs were fed the diet containing soybean expellers followed by the diet containing SBM and the diet containing only corn. There was no difference in fecal excretion of TDF among pigs fed the 3 diets, but the ATTD of TDF was greater ($P < 0.05$) if pigs were fed the diets containing soybean expellers or SBM than the diet containing only corn.

The ATTD of GE was not different among corn, soybean expellers, and SBM (Table 7). Values for the ATTD of TDF in the 2 soybean products were greater ($P < 0.05$) than in corn, but there was no difference in the ATTD of TDF between the 2 soybean products. Concentrations of DE and ME in soybean expellers were greater ($P < 0.05$) compared with SBM or corn. Soybean expellers had greater ($P < 0.05$) NE compared with SBM, but there was no difference in NE between corn and soybean expellers. The ME to DE ratio was not different between the 2 soybean products, but the ME to DE ratio in corn was greater ($P < 0.05$) than in SBM. The ME to GE ratio in corn tended to be greater ($P < 0.10$) than in SBM. The NE to ME ratio was greater ($P < 0.05$) in corn than in the 2 soybean products and the NE to ME ratio in soybean expellers was greater ($P < 0.05$) than in SBM.

Discussion

The analyzed concentrations of GE, AEE, CP, and AA in soybean expellers and SBM are in agreement with reported values (NRC, 2012). During production of soybean expellers, heat is generated when the defatted beans are passing through the extruder (Zhang et al., 1993), and this may result in Maillard reaction and formation of sugar-AA complexes. Products of Maillard reaction reduce concentrations of AA and AA digestibility with Lys being the most sensitive AA (González-Vega et al., 2011; Kim et al., 2012). However, the Lys to CP ratio in the soybean expellers used in this experiment was 6.27%, which indicates

Table 5. AID, and SID of CP and AA in soybean expellers and SBM, experiment 1[1]

Item, %	AID				SID			
	Soybean expellers[2]	SBM	SEM	P-value	Soybean expellers	SBM	SEM	P-value
CP	81.6	79.8	1.07	0.215	91.2	88.5	1.07	0.078
Indispensable AA								
Arg	93.1	89.2	0.79	<0.001	97.6	94.4	0.79	0.002
His	91.4	87.7	0.66	0.001	94.4	91.2	0.66	0.003
Ile	90.8	86.4	1.04	0.012	93.4	89.5	1.04	0.019
Leu	90.5	86.2	0.88	0.008	93.4	89.6	0.88	0.013
Lys	89.1	85.3	1.18	0.037	92.0	88.6	1.18	0.059
Met	91.4	87.8	0.97	0.019	93.8	90.7	0.97	0.034
Phe	91.1	86.5	0.90	0.006	94.1	90.0	0.90	0.010
Thr	84.8	80.3	1.20	0.020	91.4	87.7	1.20	0.045
Trp	91.4	90.4	0.65	0.200	94.9	93.6	0.65	0.092
Val	87.9	83.0	1.11	0.010	92.6	88.4	1.11	0.021
Total	90.1	86.0	0.78	0.002	93.8	90.2	0.78	0.005
Dispensable AA								
Ala	84.7	78.8	1.14	0.002	90.9	86.0	1.14	0.008
Asp	89.3	84.3	0.82	0.003	92.3	87.8	0.82	0.004
Cys	83.1	79.6	1.48	0.101	88.9	86.3	1.48	0.202
Glu	92.3	88.7	0.72	0.002	94.6	91.4	0.72	0.004
Gly	73.5	65.6	2.55	0.001	91.1	86.0	2.55	0.014
Ser	88.9	84.4	0.76	0.003	94.0	90.3	0.76	0.008
Tyr	89.4	85.5	0.90	0.015	93.1	89.6	0.90	0.025
Total	84.4	78.3	1.53	0.001	93.8	89.0	1.53	0.005
Total AA	87.1	81.9	0.93	0.002	93.8	89.6	0.93	0.005

[1]Each least squares mean represents nine observations. Values for SID of CP and AA were calculated by correcting the values for AID of CP and AA for basal ileal endogenous losses of CP and AA. Basal ileal endogenous losses were determined (g/kg of DMI) as CP, 15.60; Arg, 0.61; His, 0.15; Ile, 0.25; Leu, 0.45; Lys, 0.35; Met, 0.07; Phe, 0.31; Thr, 0.50; Trp, 0.08; Val, 0.46; Ala, 0.54; Asp, 0.68; Cys, 0.17; Glu, 0.81; Gly, 1.49; Ser, 0.44; and Tyr, 0.23.
[2]Insta-Pro International, Grimes, IA.

Table 6. ATTD of GE and TDF, and concentrations of DE and ME in experimental diets, as-fed basis[1] (experiment 2)

Item	Corn	Soybean expellers[2]	SBM	SEM	P-value
Intake					
Feed, g/d	1,296[b]	1,761[a]	1,682[a]	68	<0.001
GE, kcal/d	4,893[b]	7,066[a]	6,446[a]	257	<0.001
TDF, g/d	163.5[c]	287.1[a]	247.3[b]	8.9	<0.001
Fecal excretion					
Dry feces output, g/d	147[b]	201[a]	195[a]	13	0.017
GE, kcal/d	682[b]	927[a]	898[a]	59	0.018
TDF, g/d	67.1	84.6	75.4	5.5	0.105
Urinary excretion					
Urine output, g/d	3,521	6,344	7,390	1,118	0.057
GE, kcal/d	104[b]	187[a]	196[a]	15	0.001
ATTD, %					
GE	86.1	86.8	86.1	0.7	0.663
TDF	58.9[b]	70.4[a]	69.6[a]	1.7	<0.001
Energy values, kcal/kg					
DE	3,249[b]	3,484[a]	3,300[b]	27	<0.001
ME	3,156[b]	3,367[a]	3,170[b]	30	<0.001

[1]Each least squares mean represents eight observations, with the exception that corn diet only had seven observations because one of the collected samples was an outlier.
[2]Insta-Pro International, Grimes, IA.
[a–c]Within a row, means without a common superscript differ ($P < 0.05$).

Table 7. Concentrations of energy and ATTD of GE and TDF in soybean expellers and SBM fed to pigs[1] (experiment 2)

Item	Corn	Soybean expellers[2]	SBM	SEM	P-value
ATTD, %					
GE	87.3	86.9	83.7	1.8	0.331
TDF	58.9[b]	82.7[a]	80.2[a]	3.1	<0.001
As-fed basis, kcal/kg					
GE	3,887	4,631	4,141	—	—
DE	3,344[b]	4,023[a]	3,465[b]	80	<0.001
ME	3,248[b]	3,853[a]	3,248[b]	85	<0.001
NE[3]	2,571[a]	2,552[a]	2,028[a]	62	<0.001
DM basis, kcal/kg					
GE	4,404	4,965	4,481	—	—
DE	3,642[b]	4,306[a]	3,749[b]	86	<0.001
ME	3,538[b]	4,124[a]	3,515[b]	92	<0.001
NE	2,913[a]	2,736[a]	2,194[b]	67	<0.001
Metabolizability, %					
ME to DE	97.1[a]	95.7[ab]	93.7[b]	0.74	0.015
ME to GE	84.8	83.2	78.4	1.96	0.090
NE to ME	79.2[a]	66.2[b]	62.4[c]	0.21	<0.001

[1]Each least squares mean represents eight observations, with the exception that corn only had seven observations because one of the collected samples was an outlier.
[2]Insta-Pro International, Grimes, IA.
[3]NE in corn, soybean expellers, and SBM was predicted from ME and analyzed nutrient composition by using an equation published previously (Noblet et al., 1994).
[a–c]Within a row, means without a common superscript differ ($P < 0.05$).

that the soybean expellers were not heat damaged (González-Vega et al., 2011). Therefore, it appears that the extrusion procedures used to produce the soybean expellers did not result in over-heating and destruction of Lys. The high shear dry extrusion procedure requires a pressure of ~700 kg/cm^2, which generates the heat (Nelson et al., 1987), but because the soybean materials were exposed to this pressure and the maximum temperature of ~160 °C for <20 s, destruction of AA in the soybean expellers was avoided. The fact that the Lys to CP ratio in the SBM used in this experiment was 6.05% also indicates that the SBM was not overprocessed (González-Vega et al., 2011).

The observation that analyzed trypsin inhibitor concentrations was 3.40 and 4.60 units/mg for SBM and soybean expellers further demonstrates that these soybean products were not overheated. Inactivation of trypsin inhibitors is sufficient to not impair AA digestibility if the concentration of trypsin inhibitors has been reduced to around 4 units/mg (Goebel and Stein, 2011). It, therefore, appears that the temperature applied to both soybean products was sufficient to inactivate trypsin inhibitors sufficiently. Fiber, stachyose, raffinose, and trypsin inhibitors may negatively influence the digestibility of AA (Feng et al., 2007; Oliveira and Stein, 2016), but concentrations of these anti-nutritional factors were not different between the two sources of soybean products used in the experiment. It is, therefore, unlikely that differences in anti-nutritional factors contributed to the observed differences in the digestibility of AA between SBM and soybean expellers.

Dietary fat may increase AA digestibility by increasing the retention time of digesta in the intestinal tract, which allows more time for AA digestion and absorption (Zhao et al., 2000; Cervantes-Pahm and Stein, 2008; Kil and Stein, 2011). However, the observation that values for the SID of AA in soybean expellers are greater than in SBM is likely not a result of increased concentration of intact fat in soybean expellers because soybean oil was added to the diet containing SBM to avoid the confounding effect of different fat concentrations between diets containing SBM and soybean expellers. Therefore, the increased SID of AA in soybean expellers appears to be a result of the proteins in soybean expellers being better digested in the small intestine of pigs compared with proteins in solvent-extracted SBM. It is not clear what the reason for this increased digestibility is, but greater SID of AA in 00-rapeseed expellers compared with 00-rapeseed meal has also been reported (Maison and Stein, 2014). Differences in the temperature used in drying or heating after extraction of oil may be one of the factors that affect the SID of CP and AA. Thus, although none of the soybean products were overheated, the difference in AA digestibility between soybean expellers and SBM is likely a result of the different processing procedures used to generate the two products. However, more research is needed to confirm this hypothesis.

Concentrations of starch and fiber in the corn used in this experiment were in agreement with published values, but the GE was less than reported (NRC, 2012). Therefore, concentrations of DE, ME, and NE in the corn used in this experiment were also less than reported values (NRC, 2012). This is likely a result of lower fat concentration in the corn used in this experiment compared with corn used in previous studies.

Because there were more orts from pigs fed the corn diet than from pigs fed the diets containing the two sources of soybean products, the feed intake was less in pigs fed the diet containing corn. The DE, ME, and NE in SBM were less than some reported values (NRC, 2012), which is likely because of the greater concentration of TDF in the SBM used in this experiment. In contrast, the DE, ME, and NE in the soybean expellers were in agreement with published data (Woodworth et al., 2001; Velayudhan et al., 2015; Stein et al., 2016). The observation that the concentrations of DE, ME, and NE in soybean expellers were greater than in SBM is likely a result of greater AEE concentration in soybean expellers. Fat produces more energy and has less metabolic heat production and thus greater efficiency than starch or proteins (Just, 1982). Therefore, a greater concentration of AEE contributed to greater energy contents in soybean expellers compared with SBM. This is also reflected in the equations to predict DE, ME, and NE in which coefficients for fat are greater than for other nutrients (Noblet and Perez, 1993; Noblet et al., 1994; NRC, 2012). The greater energy concentration in soybean expellers compared with SBM may also be a result of cell wall components being ruptured by high shear and dry extrusion, but more research is needed to confirm this hypothesis.

The ATTD of TDF in diets and corn are in agreement with previous data (Abelilla and Stein, 2019; Rodriguez et al., 2020). There are very limited data for the ATTD of TDF in SBM and soybean expellers fed to pigs, but the lack of difference in the ATTD of TDF between the two soybean products is likely a result of the fact that the concentration of TDF was not different between the two sources. This observation also indicates that the difference in the concentration of fat between the two soybean sources did not influence the digestibility of TDF. The greater ATTD of TDF in soybean expellers and SBM compared with corn likely is a result of the greater concentration of soluble dietary fiber in the two soybean products compared with corn.

Conclusion

Soybean expellers contain less CP and AA, but more AEE, than SBM. Values for the AID and SID of most AA in soybean expellers were greater than in SBM. Greater concentrations of DE, ME, and NE were also observed in soybean expellers than in SBM, but the ATTD of TDF was not different between the two soybean products. Results of this research indicate that soybean expellers can be used in diets fed to pigs without negatively affecting the concentrations of ME and NE or SID of AA in the diet.

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Conflict of interest statement

The authors declare no real or perceived conflicts of interest.

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