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Digestibility of energy and nutrients in soybean expellers produced from conventional or high-oil varieties of soybeans and fed to growing pigs

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Abstract

The objective was to test the hypothesis that standardized ileal digestibility (**SID**) of amino acids (**AA**), metabolizable energy (**ME**), and standardized total tract digestibility (**STTD**) of P in soybean expellers produced from a new variety of high-oil soybeans (**SBE-HO**) are not different when compared with expellers produced from conventional soybeans (**SBE-CV**). In experiment 1, 9 barrows (30.0 ± 1.5 kg) that had a T-cannula installed in the distal ileum were allotted to a triplicated 3 × 3 Latin Square design with 3 diets and 3 periods in each square. An N-free diet and 2 diets containing SBE-CV or SBE-HO were used. Pigs were housed individually in fully slatted pens and ileal digesta were collected on days 6 and 7 of each period. Ileal digesta and diets were analyzed for AA, and SID of AA was calculated. Results indicated that the SID of Arg, Ile, and Lys was not different between the 2 sources of soybean expellers, but the SID of other indispensable AA was greater ($P < 0.05$) in SBE-CV compared with SBE-HO. However, because of greater AA concentration, SBE-HO had greater concentrations of digestible Arg, Lys, Met, and Trp compared with SBE-CV. In experiment 2, 30 pigs (18.3 ± 1.3 kg) were randomly allotted to 3 diets containing corn, corn and SBE-CV, or corn and SBE-HO as energy sources. Pigs were housed in metabolism crates and feces and urine were separately collected for 4 d after 5 d of adaptation. Feces, urine, and diets were analyzed for gross energy and ME was calculated. Results indicated that ME in SBE-HO was not different from ME in SBE-CV. In experiment 3, 48 barrows (12.0 ± 1.6 kg) were allotted to 6 diets. The SBE-CV and SBE-HO were included in diets with 3 levels of microbial phytase (i.e., 0, 500, or 1,000 units/kg). Pigs were housed in metabolism crates and feces were collected quantitatively for 4 d after 5 d of adaptation. Feces and diets were analyzed for P and the STTD of P was calculated. Results indicated that the inclusion of phytase in the diets linearly ($P < 0.001$) increased the STTD of P regardless of the source of soybean expellers, but STTD of P was not different between SBE-HO and SBE-CV. It is concluded that if SBE-HO is included in diets for pigs instead of SBE-CV, slightly less soybean expellers are needed to meet AA requirements due to greater concentration of limiting AA, but ME and STTD of P will not be changed.

Lay Summary

Recently, a new variety of high-oil soybean patented as PHOTOSEED has been developed, but there are no data for the nutritional value of the de-oiled co-product from this variety. The hypothesis of this experiment was that the digestibility of energy and nutrients in soybean expellers produced from the new variety of high-oil soybeans (**SBE-HO**) is not different from that of soybean expellers produced from conventional soybeans (**SBE-CV**). Results indicated that SBE-HO had reduced digestibility of some amino acids compared with SBE-CV, but because of the greater concentration of amino acids in SBE-HO, the concentration of digestible amino acids was greater. Concentrations of digestible energy tended to be greater in SBE-HO than in SBE-CV, but the digestibility of phosphorus was not different between the 2 sources of soybean expellers and P digestibility was increased by phytase regardless of the origin of the expellers. It is concluded that if SBE-HO is included in diets for pigs instead of SBE-CV, the inclusion can be reduced due to the greater concentration of digestible amino acids, but energy concentration and P digestibility will not be changed.

Key words: amino acids, digestibility, metabolizable energy, phosphorus, pig, soybean expellers

Abbreviations: AA, amino acids; AID, apparent ileal digestibility; ATTD, apparent total tract digestibility; CP, crude protein; DE, digestible energy; DM, dry matter; GE, gross energy; ME, metabolizable energy; SBE-CV, soybean expellers from conventional soybeans; SBE-HO, soybean expellers from high-oil soybeans; SID, standardized ileal digestibility; STTD, standardized total tract digestibility

Introduction

Soybean oil demand has increased in recent years due to increased use in food and biofuel applications (Santeramo and Searle, 2019). As soybean oil production increases, production of the co-product from this industry, which is soybean meal or soybean expellers, also increases. Soybean meal or soybean expellers are the principal amino acid (**AA**) sources in diets for pigs, and the AA profile and digestibility of soybean meal is superior to that of other oilseed meals (Stein et al., 2008; Ruiz et al., 2020). In the last 20 yr, new varieties of soybeans have been developed to increase oil yield, but a reduced protein concentration is often the trade-off when oil is increased

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using traditional genetic selection for greater oil concentration (Tamagno et al., 2022). Recently a new variety of high-oil soybeans based on a genetic technology patented as PHOTOSEED has been developed. This technology creates more oil bodies in the green tissue by preventing the degradation of the oleosin shell from leaf proteases (Beechey-Gradwell et al., 2019). The continuous and increased capture and storage of carbon as lipids also increases carbon fixing cycles (Wu et al., 2019). The increased carbon storage creates a high demand for photosynthate, which sustains and elevates photosynthesis (Beechey-Gradwell et al., 2019). Enhanced photosynthesis may also promote higher nitrogen fixation by rhizobia and thereby increase protein concentration in the seed (Unkovich and Pate, 2000). There is, however, no information about the nutritional value of soybean meal or soybean expellers produced from the new high-oil variety of soybeans when fed to pigs. Therefore, the objective of this research was to test the hypothesis that standardized ileal digestibility (**SID**) of crude protein (**CP**) and AA, concentrations of digestible energy (**DE**) and metabolizable energy (**ME**), apparent total tract digestibility (**ATTD**) of gross energy (**GE**), and the standardized total tract digestibility (**STTD**) of P are not different in soybean expellers produced from the new high-oil soybeans compared with soybean expellers produced from conventional soybeans when fed to growing pigs.

Materials and Methods

Three experiments were conducted, and the Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocols for each experiment before animal work was initiated. Pigs were the offspring of Line 800 boars and Camborough females (Pig Improvement Company, Hendersonville, TN, USA). Conventional and high-oil soybeans (PHOTOSEED) were procured from Zeakal Inc. (San Diego, CA, USA), and beans were extruded and expelled at Insta Pro (Grimes, IA, USA) to produce soybean expellers from conventional soybeans (**SBE-CV**) and soybean expellers from high-oil soybeans (**SBE-HO**). Extrusion and oil expelling procedures were identical for both sources of soybeans and mimicked those described by Rodriguez et al. (2020). In short, soybeans were cleaned and ground and then conveyed into a single screw high-shear extruder (Model 2000 Extruder; Insta Pro, Grimes, IA, USA). During extrusion, soybeans were exposed to a maximum temperature of 160 °C for 15 to 20 s. Oil was then mechanically expelled using a Model 5005 Oil Press (Insta Pro, Grimes, IA, USA), and the press cake was cooled using a horizontal counter-flow cooler (Model 900; Insta Pro, Grimes, IA, USA). The cooled expellers were subsequently ground to the desired particle size using a hammer mill.

Experiment 1: Digestibility of AA

Nine barrows (average initial body weight: 30.0 ± 1.5 kg) that had a T-cannula installed at the distal ileum were used. Pigs were housed individually in 1.2 × 1.5 m pens equipped with a self-feeder, a nipple waterer, and fully slatted tri-bar floors. Pigs were allotted to a triplicated 3 × 3 Latin square design with 3 diets and 3 periods of 7 d in each square. There were 3 pigs per diet in each period and 9 observations per treatment. Two diets were formulated using 40.00% SBE-CV or 40.00% SBE-HO as the only AA-contributing ingredients, and a N-free diet that was used to determine the basal endogenous losses of AA, was formulated as well (Table 1). Vitamins and minerals were included in all diets to meet or exceed the estimated nutrient requirements for growing pigs

Table 1. Ingredient and analyzed nutrient compositions of experimental diets containing soybean expellers from conventional soybeans (SBE-CV) or soybean expellers produced from a variety of high-oil soybeans (SBE-HO), as-fed basis (experiment 1)

Item	SBE-CV	SBE-HO	N-free
Ingredient, %			
SBE-CV	40.00	—	—
SBE-HO	—	40.00	—
Soybean oil	3.00	3.00	4.00
Ground limestone	1.00	1.00	0.37
Dicalcium phosphate	0.75	0.75	2.10
Sucrose	15.00	15.00	20.00
Cornstarch	38.95	38.95	67.73
Solka floc[1]	—	—	4.00
Magnesium oxide	—	—	0.10
Potassium carbonate	—	—	0.40
Sodium chloride	0.40	0.40	0.40
Chromic oxide	0.40	0.40	0.40
Vitamin–mineral premix[2]	0.50	0.50	0.50
Analyzed composition, %			
Dry matter	95.65	95.66	94.16
Crude protein	16.40	18.09	0.25
Indispensable amino acids			
Arg	1.18	1.19	0.01
His	0.45	0.44	0.00
Ile	0.79	0.76	0.01
Leu	1.33	1.29	0.03
Lys	1.11	1.10	0.02
Met	0.26	0.25	0.01
Phe	0.87	0.84	0.02
Thr	0.70	0.68	0.01
Trp	0.27	0.23	0.02
Val	0.81	0.79	0.01
Dispensable amino acids			
Ala	0.78	0.76	0.01
Asp	2.00	1.97	0.02
Cys	0.28	0.27	0.01
Glu	3.25	3.21	0.04
Gly	0.77	0.77	0.01
Pro	0.84	0.84	0.01
Ser	0.81	0.78	0.01
Tyr	0.58	0.54	0.01

[1]Fiber Sales and Development Corp., Urbana, OH, USA.
[2]The vitamin–micromineral premix provided the following quantities of vitamins and micro minerals per kg of complete diet: vitamin A as retinyl acetate, 10,622 IU; vitamin D_3 as cholecalciferol, 1,660 IU; vitamin E as DL-alpha-tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.40 mg; thiamin as thiamin mononitrate, 1.08 mg; riboflavin, 6.49 mg; pyridoxine as pyridoxine hydrochloride, 0.98 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.2 mg; niacin, 43.4 mg; folic acid, 1.56 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 123 mg as iron sulfate; I, 1.24 mg as ethylenediamine dihydriodide; Mn, 59.4 mg as manganese hydroxychloride; Se, 0.27 mg as sodium selenite and selenium yeast; and Zn, 124.7 mg as zinc hydroxychloride.

(NRC, 2012). All diets contained 0.40% chromic oxide as an indigestible marker. A sample of each diet was collected at the time of diet mixing.

Pigs were fed their respective diets at 3.0 times the maintenance requirement for ME (i.e., 197 kcal ME per kg weight$^{0.60}$; 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 experimental period lasted 7 d with the initial 5 d being considered the adaptation period, whereas ileal digesta were collected on days 6 and 7 for 9 h using standard procedures (Stein et al., 1998). Pigs were fed experimental diets each day at 0700 hours and ileal digesta samples were collected from 0700 to 1600 hours. Cannulas were opened at the beginning of collection and a 225-mL plastic bag was attached to the cannula barrel using a cable tie. 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. At the conclusion of the experiment, ileal digesta samples were thawed, and mixed within animal and diet, and a subsample was lyophilized and finely ground (Lagos and Stein, 2019).

Samples of the SBE-CV and SBE-HO, ileal digesta, and diets, were analyzed for dry matter (**DM**; method 930.15; AOAC Int., 2019) and N was also analyzed in these samples (method 990.03; AOAC Int., 2019) using a FP628 protein analyzer (Leco Corporation, St. Joseph, MI, USA). Crude protein was calculated as N × 6.25. Amino acids in the 2 sources of soybean expellers, diets, and ileal digesta samples were analyzed on a Hitachi Amino Acid Analyzer (Model No. L8800; Hitachi High Technologies America, Inc., Pleasanton, CA, USA) using ninhydrin for postcolumn derivatization and norleucine as the internal standard. Prior to analysis, samples were hydrolyzed with 6 *N* HCl for 24 h at 110 °C [method 982.30 E(a); AOAC Int., 2019]. Methionine and Cys were determined as Met sulfone and cysteic acid after cold performic acid oxidation overnight before hydrolysis [method 982.30 E(b); AOAC Int., 2019]. Tryptophan was determined after NaOH hydrolysis for 22 h at 110 °C [method 982.30 E(c); AOAC Int., 2019]. Chromium in diets and ileal digesta samples was analyzed using the Inductive Coupled Plasma Atomic Emission Spectrometric method (method 990.08; AOAC Int., 2019).

The apparent ileal digestibility (**AID**) and SID of CP and AA were calculated using the analyzed CP, AA, and Cr concentrations in the diet and ileal digesta samples (Stein et al., 2007). Basal endogenous losses of CP and AA were calculated from pigs fed the N-free diet as previously described (Stein et al., 2007). Values for AID and SID of CP and AA calculated for each diet also represented the AID and SID of CP and AA in SBE-CV and SBE-HO, respectively, because these ingredients were the only AA-containing ingredients in the diets. Values for concentrations of standardized ileal digestible AA were calculated by multiplying the analyzed CP and AA in each source of soybean expellers by the digestibility value for CP and each AA.

Data were analyzed using the PROC MIXED procedure (SAS Inst. Inc., Cary, NC, USA). The model included diet as the fixed effect and square, period, and animal as the random effects. The homogeneity of the variances among treatments was confirmed using the UNIVARIATE procedure, and outliers were identified as values that deviated from the 1st and 3rd quartile by more than 3 times the interquartile range within the treatment. However, no outliers were identified. Mean values were calculated using the LSMEANS statement. The pig was the experimental unit for all analyses. Statistical significance and tendency were considered at $P < 0.05$ and $0.05 \le P < 0.10$, respectively.

Experiment 2: Concentrations of DE and ME

Thirty barrows and gilts (average initial body weight: 18.3 ± 1.3 kg) were allotted to a completely randomized design with 3 diets and 10 replicate pigs per diet. Pigs were housed individually in metabolism crates (0.71 × 0.84 m) equipped with a self-feeder, a nipple waterer, and a fully slatted floor. A screen and a urine pan were placed under the slatted floor to allow for the total, but separate, collection of urine and fecal samples.

A basal diet containing corn as the sole source of energy and 2 diets containing corn and 40.00% SBE-CV or corn and 40.00% SBE-HO were formulated; thus, a total of 3 diets were used (Table 2). Vitamins and minerals were included in all diets to meet or exceed current requirement estimates (NRC, 2012). A sample of each diet was collected at the time of diet mixing. Pigs were limit-fed at 3.2 times the ME requirement for maintenance and daily provisions of feed were provided each day in 2 equal meals at 0800 and 1600 hours. The ME in the diets was calculated based on the ME in corn and soybean expellers that were reported previously (NRC, 2012). Water was available at all times. The initial 5 d were considered the adaptation period to the diets. Color markers were included in the morning meals on day 6 (chromic oxide) and day 10 (ferric oxide). Fecal collections were initiated when chromic oxide appeared in the feces and ceased when ferric oxide appeared according to standard procedures using the marker-to-marker approach (Adeola, 2001). Feces were collected twice daily and stored at –20 °C immediately after collection. Urine collections were initiated on day 6 at 0900 hours and ceased on day 10 at 0900 hours. Urine was collected in buckets placed under the crates. The collected urine was weighed daily, and a 10% subsample was stored at –20 °C. Urine buckets were emptied every morning, and a preservative of 50 mL of 3 *N* HCl was added to the urine buckets before the beginning of urine collection each day.

At the conclusion of the experiment, urine samples were thawed, and a subsample was lyophilized before analysis (Kim et al., 2009). For this procedure, 10 mL of urine was dripped on a cotton ball that was placed in a plastic bag, the bag with the urine and cotton ball was lyophilized, and GE was analyzed using bomb calorimetry (Model 6400; Parr Instruments, Moline, IL, USA). Fecal samples were dried in a 55 °C forced air drying oven for 7 d to reach less than 10% moisture and samples were ground using a swing-type grain mill (model: RRH-500, Zhejiang Winki Plastic Industry Co., Ltd., Zhejiang, China) prior to analysis. Diet and fecal samples were analyzed for DM as described in experiment 1. Fecal, diet, and ingredient samples were also analyzed for GE.

The 2 sources of soybean expellers were also analyzed for acid-hydrolyzed ether extract by crude fat extraction using petroleum ether (Ankom^{XT15}, Ankom Technology, Macedon, NY, USA) following hydrolysis with 3*N* HCl (Ankom^{HCl}, Ankom Technology, Macedon, NY, USA). Insoluble dietary fiber and soluble dietary fiber were also analyzed in the 2 sources of soybean expellers on an Ankom Total Dietary Fiber Analyzer (Ankom Technology, Macedon, NY, USA) using method 991.43 (AOAC Int., 2019). Total dietary fiber was calculated as the sum of insoluble and soluble dietary

Table 2. Ingredient and analyzed nutrient compositions of experimental diets containing soybean expellers from conventional soybeans (SBE-CV) or soybean expellers produced from a variety of high-oil soybeans (SBE-HO), as-fed basis (experiment 2)

Item	Corn	SBE-CV	SBE-HO
Ingredient composition, %			
Ground corn	97.05	57.45	57.45
SBE-CV	—	40.00	—
SBE-HO	—	—	40.00
Dicalcium phosphate	1.35	0.95	0.85
Ground limestone	0.70	0.70	0.80
Sodium cloride	0.40	0.40	0.40
Vitamin–micromineral premix[1]	0.50	0.50	0.50
Total	100.00	100.00	100.00
Analyzed composition			
Dry matter, %	87.36	91.28	91.02
Gross energy, kcal/kg	3,722	4,178	4,186

[1]The vitamin–micromineral premix provided the following quantities of vitamins and micro minerals per kg of complete diet: vitamin A as retinyl acetate, 10,622 IU; vitamin D_3 as cholecalciferol, 1,660 IU; vitamin E as $_{DL}$-alpha-tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.40 mg; thiamin as thiamin mononitrate, 1.08 mg; riboflavin, 6.49 mg; pyridoxine as pyridoxine hydrochloride, 0.98 mg; vitamin B_{12}, 0.03 mg; $_D$-pantothenic acid as $_D$-calcium pantothenate, 23.2 mg; niacin, 43.4 mg; folic acid, 1.56 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 123 mg as iron sulfate; I, 1.24 mg as ethylenediamine dihydriodide; Mn, 59.4 mg as manganese hydroxychloride; Se, 0.27 mg as sodium selenite and selenium yeast; and Zn, 124.7 mg as zinc hydroxychloride.

fiber. Trypsin inhibitor units were also analyzed (method Ba 12-75; AOCS, 2006) and both sources of soybean expellers were analyzed for glucose, fructose, maltose, sucrose, stachyose, and raffinose using high-performance liquid chromatography (method 977.2, AOAC Int., 2007).

The ATTD of GE and DM was calculated for each diet, and the DE and ME in each diet were calculated as well (NRC, 2012). The DE and ME in corn were calculated by dividing the DE and ME of the basal diet by the inclusion rate of corn in that diet. The contribution of DE and ME from corn to the DE and ME in the diets containing corn and SBE-CV or corn and SBE-HO were subtracted from the DE and ME of each diet, and the DE and ME in SBE-CV and SBE-HO were calculated by difference (Adeola, 2001).

Data were analyzed using the PROC MIXED in SAS. The homogeneity of the variances among treatments was confirmed using the UNIVARIATE procedure. Outliers were identified as values that deviated from the 1st and 3rd quartile by more than 3 times the interquartile range within the treatment. However, no outliers were identified. Diet was the fixed effect, and replicate was the random effect. Least squares means were calculated and separated using the PDIFF statement with Tukey's adjustment if the model was significant. The pig was the experimental unit for all analyses. Statistical significance and tendency were considered at $P < 0.05$ and $0.05 \le P < 0.10$, respectively.

Experiment 3: Digestibility of P

Forty-eight barrows (average initial weight: 12.0 ± 1.6 kg) were allotted to 6 diets and 2 blocks using a randomized complete block design with weaning group being the block. There were 4 replicate pigs per diet in each block for a total of 8 replicate pigs per diet in the 2 blocks. Pigs were housed individually in the same metabolism crates as used in experiment 2. Six diets were arranged in a 2 × 3 factorial with 2 sources of soybean expellers, (SBE-CV and SBE-HO) and 3 levels of microbial phytase (0, 500, or 1,000 phytase units per kg; Quantum Blue, AB Vista, Marlborough, UK). Cornstarch and sucrose were also included in the diets, and 40.00% SBE-CV or 40.00% SBE-HO were the only sources of P in the diets (Table 3). Limestone was added to the diets to satisfy a Ca to P ratio of 1.3:1. Vitamins and minerals other than Ca and P were included in all diets to meet or exceed the estimated nutrient requirements for weanling pigs (NRC, 2012). Feed and water were provided as in experiment 2. Indigo blue was used as the fecal color marker and was provided in the morning meals on days 6 and 10. The fecal collection started when the initial marker appeared in the feces after day 6 and ceased when the second marker appeared after day 10 (Adeola, 2001). A sample of each diet was collected at the time of diet mixing.

Fecal samples were thawed at the conclusion of the experiment and mixed within pig and diet and dried and ground as described in experiment 2. Ash in ingredient and diet samples was analyzed (method 942.05; AOAC Int., 2019) and Ca and P in ingredient, diet, and fecal samples were analyzed as well (method 985.01 A, B and C; AOAC Int., 2019) using inductively coupled plasma-optical emission spectrometry (ICP-OES; Avio 200, PerkinElmer, Waltham, MA, USA). Sample preparation included dry ashing at 600 °C for 4 h (method 942.05; AOAC Int., 2019) and wet digestion with nitric acids (method 3050 B; U.S. Environmental Protection Agency, 2000). Phytase activity in diet samples was analyzed (method 2000.12; AOAC Int., 2019), and DM in diets and fecal samples was analyzed as described for experiment 1. Ingredients were analyzed for phytate (Ellis et al., 1977) and the concentration of phytate-bound P in the 2 sources of soybean expellers was calculated as 28.2% of analyzed phytate (Tran and Sauvant, 2004; Lee et al., 2023).

The ATTD of P and Ca in each diet was calculated (NRC, 2012). By correcting values for ATTD of P for the basal endogenous loss of P (i.e., 190 mg per kg DM intake; NRC, 2012), the STTD of P in each ingredient without and with phytase was calculated. Because each source of soybean expellers was the only source of P in the diets, the ATTD of P and STTD of P also represented the ATTD of P and STTD of P in each sources of soybean expellers.

Data were analyzed using the PROC MIXED in SAS. The homogeneity of the variances among treatments was confirmed using the UNIVARIATE procedure, and outliers were identified as values that deviated from the 1st and 3rd quartile by more than 3 times the interquartile range within the treatment. One outlier was identified for the diet containing SBE-HO and 500 phytase unit/kg, and another outlier was identified in the diet containing SBE-HO and 1,000 phytase unit/kg. Two outliers were identified in the diet containing SBE-CV and 500 phytase unit/kg. The statistical model included diet as the fixed effect and block and replicate within the block as the random effects. Least squares means were calculated using the LSMEANS statement in SAS, and outliers were not included in the means. Contrasts were used to analyze the effects of the source of soybean expellers, linear effect of increasing phytase, and the interaction between the source of soybean expellers and phytase. The pig was the experimental

Table 3. Ingredient and analyzed nutrient compositions of experimental diets containing soybean expellers produced from conventional soybeans (SBE-CV) or expellers produced from a variety of high-oil soybeans (SBE-HO) as-fed basis (experiment 3)[1,2]

Item	SBE-CV	SBE-HO
Ingredient composition, %		
SBE-CV	40.00	—
SBE-HO	—	40.00
Soybean oil	3.00	3.00
Sucrose	10.00	10.00
Cornstarch	45.40	45.40
Ground limestone	0.70	0.70
Sodium chloride	0.40	0.40
Vitamin–micromineral premix[3]	0.50	0.50
Total	100.00	100.00
Analyzed composition, %		
Dry matter	95.33	95.18
Ash	4.18	4.54
Ca	0.37	0.46
P	0.30	0.32

[1]Four additional diets were formulated by adding 500 or 1,000 units of phytase per kg of diet to each of diets (Quantum Blue, AB Vista, Marlborough, UK). Thus a total of 6 diets were prepared.
[2]Analyzed phytase activity in diets formulated to contain 0, 500, or 1,000 phytase units/kg and SBE-CV was 70, 440, and 1,100 phytase units/kg, respectively; and SBE-HO diets analyzed 70, 600, and 760 phytase units/kg, respectively.
[3]The vitamin–micromineral premix provided the following quantities of vitamins and micro minerals per kg of complete diet: vitamin A as retinyl acetate, 10,622 IU; vitamin D_3 as cholecalciferol, 1,660 IU; vitamin E as $_{DL}$-alpha-tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.40 mg; thiamin as thiamin mononitrate, 1.08 mg; riboflavin, 6.49 mg; pyridoxine as pyridoxine hydrochloride, 0.98 mg; vitamin B_{12}, 0.03 mg; $_{D}$-pantothenic acid as $_{D}$-calcium pantothenate, 23.2 mg; niacin, 43.4 mg; folic acid, 1.56 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 123 mg as iron sulfate; I, 1.24 mg as ethylenediamine dihydriodide; Mn, 59.4 mg as manganese hydroxychloride; Se, 0.27 mg as sodium selenite and selenium yeast; and Zn, 124.7 mg as zinc hydroxychloride.

unit for all analyses. Statistical significance and tendency were considered at $P < 0.05$ and $0.05 \leq P < 0.10$, respectively.

Results

Concentrations of GE, CP, acid-hydrolyzed ether extract, P, and Ca were greater, and the concentration of total dietary fiber was less in SBE-HO than in SBE-CV (Table 4). Concentrations of phytate and trypsin inhibitors were greater in SBE-HO compared with SBE-CV. Even though the concentration of phytate was greater, the non-phytate P as a percentage of total P was greater in SBE-HO due to the greater total P compared with SBE-CV. Concentrations of the most indispensable AA were greater in SBE-HO than in SBE-CV. Pigs remained healthy during each of the 3 experiments and very little feed refusals were observed.

Experiment 1: Digestibility of AA

The AID and SID of CP and Lys were not different between SBE-CV and SBE-HO, but the AID and SID of all other indispensable AA were greater ($P < 0.05$) or tended to be greater ($P < 0.10$) in SBE-CV compared with SBE-HO (Table 5). The AID and SID of all dispensable AA except Cys and Pro were greater ($P < 0.05$) or tended to be greater ($P < 0.10$) in SBE-CV compared with SBE-HO. However, the concentration of standardized ileal digestible AA was not different between SBE-CV and SBE-HO with the exception that SBE-HO had

Table 4. Analyzed composition of soybean expellers produced from conventional soybeans (SBE-CV) or expellers produced from a a variety of high-oil soybeans (SBE-HO), as-fed basis

Item, %	SBE-CV	SBE-HO
Dry matter	94.56	94.63
Gross energy, kcal/kg	4,760	4,820
Acid-hydrolyzed ether extract	6.57	7.60
Crude protein	43.15	44.56
Lys:crude protein	6.26	6.42
Total dietary fiber	24.10	22.90
Soluble dietary fiber	5.00	3.00
Insoluble dietary fiber	19.10	19.90
Ash	6.62	6.90
Ca	0.37	0.36
Total P	0.70	0.77
Phytate	1.60	1.71
Phytate P[1]	0.45	0.48
Non-phytate P[2]	0.25	0.28
Non-phytate P, % of total P	35.77	37.10
Indispensable amino acids		
Arg	2.94	3.22
His	1.09	1.15
Ile	1.93	1.97
Leu	3.22	3.31
Lys	2.70	2.86
Met	0.62	0.65
Phe	2.12	2.19
Thr	1.71	1.78
Trp	0.57	0.61
Val	1.97	2.06
Total	18.87	19.80
Dispensable amino acids		
Ala	1.87	1.96
Asp	4.83	5.10
Cys	0.70	0.71
Glu	7.65	8.12
Gly	1.87	2.00
Pro	2.05	2.16
Ser	1.92	2.00
Tyr	1.58	1.67
Total	22.47	23.72
Total amino acids	41.69	43.89
Trypsin inhibitor, unit/mg	5.30	6.00
Sugars and oligosaccharides		
Glucose	0.05	0.05
Sucrose	5.73	5.08
Maltose	0.28	0.27
Fructose	0.05	0.05
Stachyose	5.68	5.05
Raffinose	1.62	1.34

[1]Phytate P was calculated by multiplying the analyzed phytate by 0.282 (Tran and Sauvant, 2004; Lee *et al.*, 2023).
[2]Nonphytate P was calculated as the difference between total P and phytate P.

Table 5. Apparent ileal digestibility (AID) and standardized ileal digestibility (SID) of crude protein (CP) and amino acids (AA) in soybean expellers produced from conventional soybeans (SBE-CV) or expellers produced from a variety of high-oil soybeans (SBE-HO), fed to growing pigs (experiment 1)[1,2]

Item, %	AID				SID			
	SBE-CV	SBE-HO	SEM	*P*-value	SBE-CV	SBE-HO	SEM	*P*-value
Crude protein	79.1	78.0	1.18	0.467	91.8	89.5	1.18	0.146
Indispensable AA								
Arg	92.2	90.6	0.60	0.086	98.6	96.9	0.60	0.078
His	87.5	84.5	1.05	0.032	92.9	90.1	1.05	0.038
Ile	87.1	84.9	0.74	0.046	91.9	89.8	0.74	0.064
Leu	86.6	83.8	1.04	0.028	91.4	88.7	1.04	0.036
Lys	85.8	84.6	1.08	0.333	91.7	90.6	1.08	0.355
Met	89.2	86.8	0.91	0.018	94.2	91.9	0.91	0.028
Phe	87.4	84.5	0.95	0.020	92.3	89.6	0.95	0.028
Thr	78.0	74.1	1.24	0.026	87.4	83.8	1.24	0.037
Trp	88.0	84.0	0.83	0.003	94.5	91.6	0.83	0.017
Val	82.9	79.4	1.15	0.014	90.0	86.7	1.15	0.019
Total	86.5	84.0	0.88	0.029	93.5	91.2	0.88	0.040
Dispensable AA								
Ala	80.6	77.1	1.21	0.039	90.6	87.3	1.21	0.054
Asp	84.0	81.8	0.81	0.076	88.6	86.5	0.81	0.085
Cys	73.8	70.5	1.57	0.153	85.1	82.2	1.57	0.203
Glu	87.9	85.8	1.24	0.030	92.1	90.0	1.24	0.033
Gly	69.7	61.3	2.39	0.002	103.9	95.5	2.39	0.002
Pro	59.5	50.2	8.99	0.175	155.9	146.5	8.99	0.175
Ser	83.9	80.3	0.80	0.006	92.0	88.8	0.80	0.010
Tyr	84.9	80.8	0.91	0.004	97.6	94.3	0.91	0.019
Total	81.4	77.6	1.31	0.016	98.2	94.7	1.31	0.024
Total AA	83.4	80.1	0.98	0.026	94.0	91.0	0.98	0.036

[1]Each least squares mean represents 9 observations.
[2]Values for SID were calculated by correcting the values for AID for the basal ileal endogenous losses. The basal ileal endogenous losses were determined (g/kg DM intake) as CP, 23.04; Arg, 0.83; His, 0.27; Ile, 0.42; Leu, 0.71; Lys, 0.73; Met, 0.14; Phe, 0.47; Thr, 0.73; Trp, 0.19; Val, 0.64; Ala, 0.87; Asp, 1.02; Cys, 0.35; Glu, 1.50; Gly, 2.93; Pro, 8.99; Ser, 0.73; and Tyr, 0.81.

greater ($P < 0.05$) concentrations of standardized ileal digestible Arg, Lys, Met, Trp, Asp, and Glu compared with SBE-CV (Table 6).

Experiment 2: Concentrations of DE and ME

Feed intake and GE intake were not different between pigs fed the diets containing SBE-CV and SBE-HO, but feed intake and GE intake of pigs fed the corn diet were less ($P < 0.05$) compared with the 2 diets containing soybean expellers (Table 7). The weight of dried feces and fecal excretion of GE were less ($P < 0.05$) from pigs fed the corn diet compared with pigs fed the diets containing SBE-CV or SBE-HO. The weight of urine and urine excretion of GE from pigs fed the corn diet were also less ($P < 0.05$) than from pigs fed diets containing SBE-CV or SBE-HO, but the ATTD of GE was not different among the 3 diets. Concentrations of DE and ME were greater ($P < 0.05$) in the 2 diets containing SBE-CV or SBE-HO than in the corn diet, but DE and ME were not different between the 2 diets containing soybean expellers. On an as-fed basis, concentrations of DE and ME were not different between SBE-CV or SBE-HO. However, on a DM basis, the concentration of DE tended to be greater ($P = 0.076$) in SBE-HO compared with SBE-CV, but no difference in ME between the 2 sources of soybean expellers was observed.

Experiment 3: Digestibility of P

As phytase increased in diets, P intake of pigs linearly increased in both SBE-CV and SBE-HO diets, but the increase was greater in the diets containing SBE-HO than SBE-CV (interaction; $P = 0.041$; Table 8). There were no interactions between source of soybean expellers and phytase for fecal excretion of P and Ca, the ATTD of P and Ca, the STTD of P, or for Ca intake. Regardless of phytase level, fecal P excretion from pigs was not different between the 2 sources of soybean expellers. The ATTD of P was greater ($P < 0.05$) and the STTD of P tended to be greater ($P = 0.055$) in SBE-HO than in SBE-CV. Calcium intake was greater ($P = 0.001$) in pigs fed SBE-CV compared with SBE-HO, but fecal Ca excretion and the ATTD of Ca were not different between the 2 sources of soybean expellers. Fecal P excretion was reduced (linear, $P < 0.001$) by phytase, which resulted in increases (linear, $P < 0.001$) in ATTD and STTD of P. Increasing phytase in diets did not affect Ca intake, but fecal Ca excretion was reduced (linear, $P < 0.001$) by increasing phytase, and ATTD of Ca was increased (linear, $P < 0.001$) with increasing phytase.

Table 6. Concentrations of standardized ileal digestible crude protein (CP) and amino acids (AA) in soybean expellers produced from conventional soybeans (SBE-CV) or expellers produced from a variety of high-oil soybeans (SBE-HO) fed to growing pigs, as-fed basis (experiment 1)[1,2]

Item, g/kg	SBE-CV	SBE-HO	SEM	*P*-value
CP	396.1	398.8	5.17	0.682
Indispensable AA				
Arg	29.0	31.2	0.19	<0.001
His	10.1	10.4	0.12	0.114
Ile	17.7	17.7	0.14	0.858
Leu	29.4	29.4	0.34	0.880
Lys	24.8	25.9	0.30	0.008
Met	5.8	6.0	0.06	0.037
Phe	19.6	19.6	0.20	0.836
Thr	14.9	14.9	0.21	0.901
Trp	5.4	5.6	0.05	0.007
Val	17.7	17.9	0.23	0.612
Total	176.5	180.5	1.69	0.059
Dispensable AA				
Ala	16.9	17.1	0.23	0.562
Asp	42.8	44.1	0.40	0.033
Cys	6.0	5.8	0.11	0.429
Glu	70.5	73.1	0.99	0.005
Gly	19.4	19.1	0.47	0.339
Pro	31.9	31.7	1.91	0.832
Ser	17.7	17.8	0.16	0.667
Tyr	15.4	15.8	0.15	0.110
Total	220.6	224.6	3.02	0.200
Total AA	392.1	399.2	4.17	0.207

[1]Each least squares mean represents 9 observations.
[2]Values for standardized ileal digestible AA were calculated by multiplying analyzed CP and AA in each source of soybean expellers by the corresponding digestibility value.

Discussion

Results of this research provide data for the digestibility of AA, energy, P and Ca in a new source of SBE-HO that potentially can become an important crop in the future. Previously, data for the same variety of soybeans fed to poultry were published (Cristobal et al., 2025). These data will allow feed formulators to include SBE-HO in diets for pigs, which can then be used to determine growth performance and carcass composition of pigs fed diets containing SBE-HO. The data in this manuscript, therefore, represents a first step in introducing this ingredient to the swine industry.

The SBE-HO contained more trypsin inhibitors than SBE-CV. It is possible that the high-oil soybeans originally contained more trypsin inhibitors compared with the conventional soybeans, but the level of trypsin inhibitor in soybean meal or soybean expellers depends on the heat treatment applied to soybeans during processing (Vagadia et al., 2017). Even though both sources of soybean expellers were processed at the same facility, it is possible that different heat treatments were applied to the 2 sources of soybeans, and because trypsin inhibitors are heat labile (Palacios et al., 2004), it is possible that SBE-CV was exposed to higher temperatures or for longer time, which may be the reason for the difference in analyzed trypsin inhibitors.

The SID of indispensable AA in the 2 sources of soybean expellers agreed with previous values (NRC, 2012; Kiarie et al., 2020; Rodriguez et al., 2020). The SID of AA is reduced by increasing levels of trypsin inhibitors in diets fed to pigs (Batterham et al., 1993; Li et al., 1998; Chen et al., 2020). Indeed, increasing trypsin inhibitor units by 1 percentage unit reduced SID of most indispensable AA by 2 to 4 percentage units (Goebel and Stein, 2011). Therefore, the observation that SBE-CV had a greater SID of most indispensable AA compared with SBE-HO may be a result of the reduction in trypsin inhibitors. Nevertheless, because SBE-HO had a greater concentration of total AA compared with SBE-CV, concentrations of standardized ileal digestible Arg, Lys, Met, and Trp were greater in SBE-HO compared with SBE-CV.

Addition of oil to diets results in increased AID of AA (Li and Sauer, 1994; Cervantes-Pahm and Stein, 2008; Kil and Stein, 2011). Therefore, it was expected that the SID of AA in SBE-HO was greater than in SBE-CV, but that was not the case. However, the difference in the concentration of fat between the 2 sources of soybean expellers was approximately 1 percentage units and because the inclusion of soybean expellers was 40% in the diets, the difference in fat between the 2 diets was minimal, which is likely the reason for the lack of impact on measured values for SID of AA.

The Lys:CP ratio for a high-quality soybean meal is between 6.2 to 6.6% and a ratio below 6.0% indicates heat damage in the soybean meal (Stein et al., 2008). When subjected to excessive heating, both the concentration and digestibility of Lys are reduced due to the Maillard reaction (Hurrell and Carpenter, 1981). The Lys:CP ratio in both SBE-CV and SBE-HO was in agreement with previous values for high-quality soybean expellers (Webster et al., 2003; Rodriguez et al., 2020; Espinosa et al., 2021), which indicates that the 2 sources were not heat-damaged.

Pigs used to determine SID of AA had an initial body weight of 30 kg. There is no change in the digestibility of AA in pigs that are between 20 and 100 kg (Pedersen et al., 2016) and it is, therefore, likely that the results of this experiment can be extrapolated to all pigs in the growing-finishing phases of production.

Values for the ATTD of GE and concentrations of DE and ME in corn were in agreement with previous values (NRC, 2012). However, DE and ME in SBE-CV and SBE-HO were slightly greater than previous values (Rodriguez et al., 2020), which is likely due to the greater concentration of acid-hydrolyzed ether extract in the soybean expellers used in this experiment compared with the soybean expellers used in previous experiments. The DE and ME in SBE-CV used in this experiment were close to values obtained for dry extruded-expelled soybean expellers that had lower concentrations of ether extract but contained more CP (Woodworth et al., 2001). It was expected that SBE-HO generates more energy than SBE-CV because SBE-HO contained more fat and CP, and less total dietary fiber. However, the lack of differences in DE and ME between SBE-CV and SBE-HO indicates that the differences in nutrient concentrations between the 2 ingredients were too small to result in a difference in DE and ME. A lack of differences in DE and ME despite small differences in nutritional composition was previously reported when comparing dry extruded-expelled soybean expellers without and with hulls (Woodworth et al., 2001).

Whereas sows usually have a greater digestibility of energy than growing pigs (Shi and Noblet, 1993; Le Goff and Noblet,

Table 7. Digestible energy (DE) and metabolizable energy (ME) and apparent total tract digestibility (ATTD) of gross energy (GE) in experimental diets and in soybean expellers produced from conventional soybeans (SBE-CV) or expellers produced from a variety of high-oil soybeans (SBE-HO), as-fed basis (experiment 2)[1]

Item	Corn	SBE-CV	SBE-HO	SEM	*P*-value
Intake					
Feed, g/d	733b	974a	950a	36.08	<0.001
GE, kcal/d	2,728b	4,069a	3,976a	155	<0.001
Fecal excretion					
Dry feces output, g/d	61b	98a	87a	5	<0.001
GE, kcal/d	280b	434a	388a	21	<0.001
Urine excretion					
Urine output, g/d	2,599b	5,389a	4,435a	571	0.004
GE, kcal/d	75b	154a	170a	18	0.002
ATTD of GE, %	89.1	89.3	90.3	0.8	0.500
Energy in diets, kcal/kg					
DE	3,314b	3,732[a]	3,779a	29	<0.001
ME	3,205b	3,574[a]	3,624a	39	<0.001
Energy in ingredients[2], kcal/kg					
As-fed basis					
DE	—	4,366	4,483	56	0.141
ME	—	4,176	4,301	64	0.168
Dry matter basis					
DE	—	4,497	4,647	57	0.076
ME	—	4,301	4,458	70	0.101

[1]Each least squares mean represents 9 observations.
[2]Concentrations of DE and ME in corn on an as-fed basis were 3,420 and 3,308 kcal/kg, respectively.
[a,b]Means within a row that do not have a common superscript are different ($P < 0.05$).

Table 8. Effects of increasing phytase levels on apparent total tract digestibility (ATTD) and standardized total tract digestibility (STTD) of P in soybean expellers produced from conventional soybeans (SBE-CV) or expellers produced from a variety of high-oil soybeans (SBE-HO) and ATTD of Ca in diets fed to growing pigs, as-fed basis (experiment 3)[1,2]

Item	Source	SBE-CV			SBE-HO				Contrast *P*-value		
	Microbial phytase, unit/kg	0	500	1,000	0	500	1,000	SEM	Source	Linear[3]	Interaction
P digestibility											
P intake, g/d		2.19	2.22	2.43	2.41	2.29	2.41	0.07	0.032	0.020	0.041
P in feces, %		2.11	1.26	1.43	2.23	1.12	1.21	0.07	0.221	<0.001	0.513
P excretion in feces, g/d		0.98	0.65	0.53	1.08	0.45	0.51	0.06	0.373	<0.001	0.467
ATTD of P, %		55.21	70.65	78.31	55.43	80.27	78.89	2.08	0.044	<0.001	0.840
STTD[4] of P, %		61.34	76.77	83.76	61.09	86.12	84.56	2.08	0.055	<0.001	0.891
Ca digestibility											
Ca intake, g/d		2.76	3.17	3.71	3.49	2.78	2.75	0.10	0.001	0.101	0.085
Ca in feces, %		2.29	1.72	1.98	2.63	1.90	1.83	0.16	0.361	0.002	0.558
Ca excretion in feces, g/d		1.07	0.86	0.75	1.28	0.77	0.75	0.09	0.566	<0.001	0.197
ATTD of Ca, %		61.27	72.71	80.09	63.76	72.46	72.45	2.47	0.385	<0.001	0.296

[1]Each least squares mean represents 8 observations except for the 2 diets containing SBE-HO with 500 and 1,000 phytase unit/kg ($n = 7$) and the diet containing SBE-CV with 500 phytase unit/kg ($n = 6$).
[2]Analyzed phytase activity in diets formulated to contain 0, 500, or 1,000 phytase units/kg and SBE-CV was 70, 440, and 1,100 phytase units/kg, respectively. The SBE-HO diets analyzed values were 70, 600, and 760 phytase units/kg, respectively.
[3]Linear effects of increasing phytase in diets.
[4]Values for STTD of P were calculated by correcting values for the ATTD of P with the basal endogenous loss (i.e., 190 mg/kg DM intake, NRC, 2012).

2001; Lowel et al., 2015), there is a lack of data comparing energy digestibility in young growing pigs to older growing pigs. It is, therefore, not known if the data obtained from this experiment, where pigs were 18.30 kg at the start of the experiment, are representative of older pigs. However, the observation that the DE in the corn used in this experiment (3,415 kcal/kg) was close to the NRC value (3,451 kcal/kg; NRC, 2012) indicates that there likely is not much difference between DE and ME values obtained in 18-kg pigs and older growing-finishing pigs.

Values for the ATTD and STTD of P in SBE-HO were slightly greater than values reported for soybean meal (NRC, 2012). The observation that addition of microbial phytase to both sources of soybean expellers increased the STTD of P, is in agreement with results from previous experiments in which soybean meal was used (Almeida and Stein, 2010; Rojas and Stein, 2012; Almaguer et al., 2014; Sotak-Peper et al., 2016). The tendency for greater STTD of P in SBE-HO compared with SBM-CV is likely a result of the slightly greater concentration of non-phytate P in SBE-HO than in SBE-CV. In general, however, the STTD of P in soybean expellers was in agreement with STTD of P in soybean meal.

The majority of Ca in all diets was from limestone, and the ATTD of Ca in the diets, therefore, represents the ATTD of Ca in the mixture of limestone and soybean expellers. The ATTD of Ca that was determined was within the range of values for ATTD of Ca that has been reported for limestone (González-Vega et al., 2015; Lee et al., 2019). To our knowledge, the ATTD of Ca in soybean expellers has not been reported previously, but the current data indicate that the ATTD of Ca in soybean expellers is not different from the ATTD of Ca in limestone.

The observation that the use of microbial phytase in diets increased the STTD of P in the 2 sources of soybean expellers indicates that both SBE-CV and SBE-HO have sufficient substrate (i.e., phytate) for microbial phytase to be able to release P from phytate. In previous experiments, quadratic increases in STTD of P were observed as phytase levels increased in the diets (Kerr et al., 2010; Almeida et al., 2013; She, et al., 2018), but due to the limited number of phytase levels used in this experiment, only linearity was tested. It is likely that greater levels of phytase are needed to obtain a quadratic response to phytase (Arredondo et al., 2019).

The observation that the ATTD of Ca in diets was increased by phytase agrees with the results of previous experiments (González-Vega et al., 2015; She et al., 2018; Lee et al., 2019). Phytate forms a Ca-phytate complex, which reduces Ca digestibility (Walk, 2016), but addition of microbial phytase to the diet results in release of Ca from the complex, which leads to an increase in the digestibility of Ca (Almeida and Stein, 2012; González-Vega et al., 2015; Lee et al., 2019).

Growing-finishing pigs have a gradually reduced digestibility of P and Ca as they increase in body weight (Lagos et al., 2022), and sows have much lower STTD of Ca and P than growing pigs (Lee et al., 2021). It is therefore likely that the values for STTD of Ca and P obtained in this experiment are greater than what will be obtained in finishing pigs or sows.

Conclusions

The SBE-HO contained more nutrients and less fiber compared with SBE-CV. Concentrations (g/kg) of standardized ileal digestible AA were not different between SBE-HO and SBE-CV for most AA, but concentrations of digestible Arg, Lys, Met, and Trp were greater in SBE-HO compared with SBE-CV. It will, therefore, be possible to reduce inclusion of soybean expellers in diets based on SBE-HO compared with SBE-CV. The SBE-HO also tended to contain more DE and to have greater STTD of P than SBE-CV. It is concluded that if SBE-HO is included in diets for pigs instead of SBE-CV, the nutritional value of the diet will not be compromised.

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Author contributions

Minoy A. Cristobal (Methodology, Writing—original draft), Su A. Lee (Formal analysis, Resources, Writing—review & editing), Leidy Torres-Mendoza (Investigation, Methodology), Andrea P. Mallea (Methodology), C. M. Parsons (Writing—review & editing), and Hans H. Stein (Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing—review & editing)

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