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There are only minor differences among soybeans grown in different areas of the United States in nutrient composition and digestibility of amino acids by growing pigs

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ABSTRACT

An experiment was conducted to determine the chemical composition of full-fat soybeans (FFSB) from different regions of the United States (source 01, 02, 03, 04, and 05) and to test the hypothesis that there is no difference in the standardized ileal digestibility (SID) by growing pigs of crude protein (CP) and amino acids (AA) among FFSB sources regardless of where in the United States they were grown. The ground soybeans were extruded and analyzed for dry matter, gross energy, nitrogen, AA, acid-hydrolyzed ether extract, ash, minerals, starch, insoluble dietary fiber, soluble dietary fiber, sugars, and trypsin inhibitors. In the SID experiment, each source of FFSB was included in one diet as the only source of AA and a N-free diet was formulated to determine basal endogenous losses of AA; thus, a total of six diets were prepared. Six growing barrows (initial body weight: 85.50 ± 3.34 kg) that had a T-cannula installed in the distal ileum were allotted to a 6 × 6 Latin square design with six diets and six 7-day periods. Ileal digesta were collected from the cannulas on days 6 and 7 of each period and SID of CP and AA was calculated. Results indicated that the main nutrients in FFSB were CP, acid-hydrolyzed ether extract, and insoluble dietary fiber with an average of 338.0, 171.9, and 176.4 g per kg, respectively. The FFSB also contained an average of 10.3 g per kg starch, 112.5 g per kg sugars, 54.4 g per kg ash, and 21.3 MJ per kg gross energy. The unanalyzed rest fraction in FFSB was 20.6 g per kg on average. Results from the SID experiment demonstrated that there were no differences among the five sources of FFSB for the SID of CP and AA, except that the SID of Glu in FFSB source 02 was greater ($P < 0.05$) than in FFSB source 01. There was also a tendency ($P < 0.10$) for the SID of Arg, Gly, and Tyr to be greater in FFSB source 02 compared with FFSB source 01 and the SID of Tyr in FFSB source 02 also tended ($P < 0.10$) to be greater than in FFSB sources 04 and 05. In conclusion, only minor differences in chemical composition among five sources of FFSB grown in different regions of the United States were observed and the SID of CP and the majority of indispensable AA were not different among the five sources indicating that growing region does not affect digestibility of AA in FFSB.

Abbreviations: AA, amino acids; AID, apparent ileal digestibility; CP, crude protein; DM, dry matter; FFSB, full-fat soybean; SID, standardized ileal digestibility; SBM, soybean meal; SEM, standard error of means; TI, trypsin inhibitors.

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1. Introduction

Soybean protein is used in diets for pigs and poultry to compensate for the low concentration of amino acids (AA) in cereal grains (Basuchaudhuri, 2020), and the high nutritional value of soybeans is determined largely by the AA composition of the protein (Liener, 1981). Full-fat soybeans (FFSB) contain approximately 370 g per kg crude protein (CP) and 180–200 g oil (Marty et al., 1994; NRC, 2012). Soybean oil contains linoleic acid, vitamin E, and lecithin (Ravindran et al., 2014), which are valuable nutrients in swine diets. However, raw soybeans also contain several antinutritional factors including trypsin inhibitors (TI), which depress growth rate and decrease efficiency of feed utilization (Grant, 1989), because the protein digesting enzymes are impaired by the TI, which reduces AA digestibility (Waldroup, 1982; Goebel and Stein, 2011). Therefore, all soybean products need to be heat-treated to inactivate the TI before they can be fed to pigs. In the traditional crushing of soybeans, oil is extracted using a solvent and this process is followed by toasting to remove residual solvent. However, the toasting process also inactivates TI, and the resulting ingredient is called solvent-extracted soybean meal (SBM). It is also possible to use FFSB directly in diets for pigs and poultry without extraction of oil, but to inactivate the TI, it is necessary to heat the soybeans before usage (Goebel and Stein, 2011; Ravindran et al., 2014), which can be accomplished by extrusion. However, to successfully incorporate FFSB in diets for pigs, the nutritional value of extruded FFSB needs to be determined. The chemical composition of soybeans has been reported (Grieshop et al., 2003; Baker et al., 2010; Kiarie et al., 2020), and it was demonstrated that the nutritional composition is influenced by genotype, geographical growing region, and environmental conditions (Qin et al., 1998). There is, however, a lack of data for the composition of FFSB collected from different growing areas in the United States, and it is not known if the nutritional value of FFSB is constant among different growing regions within the United States. There is also limited information about the digestibility of AA in FFSB when fed to pigs, and the impact of growing region of FFSB on the digestibility of AA has not been reported. Therefore, the objective of this work was to test the hypothesis that growing region of soybeans does not influence chemical composition or the standardized ileal digestibility (SID) of CP and AA when fed to growing pigs.

2. Materials and methods

The protocol for the SID experiment was submitted to and approved by the Institutional Animal Care and Use Committee at the University of Illinois prior to initiation of the animal work. Pigs that were the offspring of Line 800 boars mated to Camborough females (Pig Improvement Company, Hendersonville, TN, USA) were used.

Soybeans were collected from Illinois, Iowa, North Dakota, Ohio, and Pensylvania to represent the entire growing area of the United States. Samples were collected and arbitrarily labeled source 01, 02, 03, 04, and 05, respectively. The raw soybeans were coarsely ground using a 9.5 mm screen in a MixMill™ (A.T. Ferrell Company Inc., Hereford, TX, USA). The grinder was flushed and cleaned between each source of FFSB to prevent cross contamination. The ground soybeans were then processed with high-shear dry extruders using two paired extruders (Model 2000, Insta-Pro® International, Grimes, IA, USA) that each had a capacity of 1000 kg per hour. The two extruders used identical process parameters and were adjusted to maintain a minimum processing temperature of 160 °C. The extruded FFSB were cooled with ambient air using a rotary drum cooler (Model 900, Insta-Pro® International, Grimes, IA, USA) to produce the final product of FFSB (Tables 1–4).

2.1. Analysis of soybeans

Samples of the extruded FFSB were finely ground through a 0.5 mm screen, using a grain mill (500 G Swing Type Grain Mill, RRH,

Table 1
Analyzed nutrient composition of five sources of full-fat soybeans (FFSB)[1,2].

Item, g/kg	FFSB 01	FFSB 02	FFSB 03	FFSB 04	FFSB 05	Average	SD
Dry matter, g/kg	937.1	934.7	920.4	941.8	936.1	934.0	7.20
Gross energy, MJ/kg	21.6	21.1	21.2	21.0	21.6	21.3	0.24
Crude protein, g/kg	338.4	341.6	329.9	336.4	343.9	338.0	4.83
Total dietary fiber, g/kg	171.8	209.9	198.9	197.2	187.1	193.0	12.82
Soluble dietary fiber, g/kg	4.7	25.4	12.4	29.0	13.2	16.9	8.96
Insoluble dietary fiber, g/kg	168.1	185.5	186.4	168.2	173.9	176.4	8.07
Acid-hydrolyzed ether extract, g/kg	177.5	170.8	168.8	167.5	174.9	171.9	3.74
Ash, g/kg	54.6	55.5	53.7	54.6	53.5	54.4	0.73
Starch, g/kg	8.0	6.3	16.4	15.0	5.7	10.3	4.53
Trypsin inhibitors, units per mg	5.9	6.2	6.6	7.7	5.7	6.4	0.72
Sucrose, g/kg	42.4	47.4	40.4	42.4	50.9	44.7	3.83
Raffinose, g/kg	6.9	7.1	7.1	5.8	5.5	6.5	0.67
Stachyose, g/kg	36.5	45.3	30.5	32.6	43.1	37.6	5.77
Verbascose, g/kg	2.4	4.4	2.9	2.3	3.3	3.1	0.76
Rest fraction[c], g/kg	41.3	−8.3	31.5	26.2	12.1	20.6	17.23

[1]All data except dry matter were calculated on the basis of 880 g per kg dry matter.

[2]Glucose, fructose, and maltose in the five sources of FFSB were analyzed but not detected.

[c] Rest fraction = calculated using equation: [dry matter − (crude protein + acid-hydrolyzed ether extract + ash + total dietary fiber + sucrose + stachyose, + raffinose + verbascose + starch)] (Fanelli et al., 2023).

Zhejiang, China) before analysis. Dry matter (DM) was analyzed using a drying oven for 2 h at 135 °C (method 930.15; AOAC Int.., 2019) and ash was analyzed by drying at 600 °C (method 942.05; AOAC Int.., 2019). Gross energy was analyzed using bomb calorimetry (Model 6400; Parr Instruments, Moline, IL, USA) and the internal standard was benzoic acid. Crude protein was calculated as nitrogen × 6.25 and nitrogen was measured using the combustion procedure (method 990.03; AOAC Int.., 2019) on a LECO FP628 (LECO Corp., Saint Joseph, MI, USA). Amino acids 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]. Trypsin inhibitor concentrations were analyzed (method Ba 12–75; AOCS, 2006) and phytic acid was analyzed as well (Ellis et al., 1977). Acid-hydrolyzed ether extract was analyzed using 3 *N* HCl (Ankom HCl Hydrolysis System, Ankom Technology, Macedon, NY, USA) followed by fat extraction (Ankom XT-15 Extractor, Ankom Technology, Macedon, NY, USA; method 2003.06; AOAC Int.., 2019). Ingredients were analyzed for insoluble dietary fiber and soluble dietary fiber according to method 991.43 (AOAC Int.., 2019) using the Ankom Dietary Fiber Analyzer (Ankom Technology, Macedon, NY, USA). Total dietary fiber was calculated as the sum of insoluble and soluble dietary fiber. Sugars including glucose, fructose, maltose, sucrose, stachyose, raffinose, and verbascose were analyzed using high-performance liquid chromatography (Dionex App Notes 21 and 92). Macro minerals and micro minerals were analyzed (i.e., Ca, P, Mg, K, Na, S, Cu, Fe, Mn, Zn) by an inductively coupled plasma spectroscopy method (method 985.01 A, B, and C; AOAC Int.., 2019) after wet ash sample preparation (method 975.03 B(b); AOAC Int.., 2019). Total starch was analyzed in the five sources of FFSB by the amyloglucosidase-alpha-amylase procedure corresponding to the enzymatically hydrolyzed starch converted to glucose, and subsequent analysis of glucose by spectroscopy (method 996.11; AOAC Int.., 2019).

2.2. Digestibility of CP and AA

Each source of FFSB was included in one diet as the only source of AA and a nitrogen-free diet was formulated to determine basal endogenous losses of AA; thus, a total of six diets were prepared (Tables 5 and 6). Vitamins and minerals were included in all diets to meet current nutrient requirements for growing pigs (NRC, 2012). Diets were provided at a level of 3.2 times the maintenance energy requirement for growing pigs (i.e., 197 kcal metabolizable energy per kg body weight$^{0.60}$; NRC, 2012). The daily allotment of feed was provided each day at 0800 h and water was available at all times. All diets contained 4 g per kg chromic oxide as an indigestible marker.

Six growing barrows (initial body weight: 85.50 ± 3.34 kg) that had a T-cannula installed in the distal ileum were allotted to a 6 × 6 Latin square design with 6 diets and six periods (Kim and Stein, 2009). Therefore, there were 6 replicate pigs per diet. Cannulas were installed in the pigs when they had a body weight of approximately 25 kg and pigs had been used in a previous experiment before being fed a commercial grower diet for two weeks and then allotted to the six diets used in current experiment. Pigs were individually housed in pens (1.2 × 1.5 m) in an environmentally controlled room and each pen was equipped with a feeder, a drinking nipple, and fully-slatted tribar floors. Pig weights were recorded at the beginning of each period and at the conclusion of the experiment.

Each experimental period lasted 7 days where the initial 5 days were the adaptation period to the diets and ileal digesta were collected on days 6 and 7 for 9 h per day using standard procedures (Stein et al., 1998). 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

Table 2
Amino acid (AA) composition of five sources of full-fat soybeans (FFSB)[a].

Item, g/kg	FFSB 01	FFSB 02	FFSB 03	FFSB 04	FFSB 05	Average	SD
Indispensable AA							
Arg	26.7	26.9	25.6	27.1	27.1	26.7	0.55
His	10.0	10.3	9.6	10.1	10.2	10.0	0.24
Ile	19.3	19.5	18.5	19.0	19.0	19.0	0.35
Leu	29.4	29.6	28.0	29.2	29.2	29.1	0.55
Lys	24.8	25.0	23.8	25.1	25.5	24.9	0.57
Met	5.0	5.2	4.9	5.4	5.5	5.2	0.23
Phe	19.7	19.8	18.7	19.2	19.6	19.4	0.38
Thr	14.1	14.9	14.2	14.8	14.9	14.6	0.33
Trp	5.0	4.8	4.6	3.4	5.2	4.6	0.64
Val	19.7	19.8	18.5	19.4	19.7	19.4	0.50
Dispensable AA							
Ala	16.3	16.6	15.7	16.4	16.5	16.3	0.32
Asp	42.2	42.7	41.0	43.1	43.1	42.4	0.77
Cys	5.2	5.7	5.4	6.3	6.1	5.7	0.41
Glu	65.9	69.7	63.7	67.7	66.7	66.8	1.98
Gly	16.2	16.7	15.6	16.4	16.5	16.3	0.37
Pro	18.4	19.6	17.8	19.0	18.9	18.7	0.60
Ser	14.7	15.4	15.3	15.7	15.4	15.3	0.32
Tyr	13.0	12.6	12.1	13.1	13.1	12.8	0.36

[a] All data were calculated on the basis of 880 g per kg dry matter.

Table 3
Concentration of amino acids (AA) in full-fat soybeans (FFSB) expressed as g per kg crude protein.

Item, g/kg	FFSB 01	FFSB 02	FFSB 03	FFSB 04	FFSB 05	Average	SD
Indispensable AA							
Arg	78.8	78.8	77.7	80.6	78.7	78.9	0.92
His	29.7	30.0	29.0	30.0	29.5	29.6	0.38
Ile	56.9	57.1	55.9	56.4	55.2	56.3	0.66
Leu	86.8	86.5	84.9	86.9	85.0	86.1	0.90
Lys	73.3	73.3	72.2	74.7	74.1	73.5	0.86
Met	14.7	15.2	14.8	16.1	15.9	15.3	0.57
Phe	58.3	57.9	56.8	57.2	56.9	57.4	0.58
Thr	41.6	43.6	43.2	43.9	43.2	43.1	0.78
Trp	14.7	14.1	13.9	10.0	15.0	13.5	1.82
Val	58.3	57.9	55.9	57.8	57.4	57.5	0.81
Dispensable AA							
Ala	45.2	45.5	44.6	45.6	45.1	45.2	0.35
Asp	116.8	117.2	116.5	120.0	117.3	117.6	1.25
Cys	14.4	15.7	15.4	17.5	16.7	15.9	1.07
Glu	182.6	191.0	180.9	188.6	181.8	185.0	4.04
Gly	44.7	45.8	44.4	45.8	44.8	45.1	0.59
Pro	51.1	53.8	50.4	52.8	51.4	51.9	1.23
Ser	40.8	42.5	43.5	43.6	42.1	42.5	1.03
Tyr	35.8	34.7	34.5	36.4	35.5	35.4	0.70

Table 4
Analyzed mineral composition of five sources of full-fat soybeans (FFSB)[a].

Item, g/kg	FFSB 01	FFSB 02	FFSB 03	FFSB 04	FFSB 05	Average	SD
Phytic acid	10.30	11.50	10.30	12.70	11.20	11.20	0.89
Total P	3.70	4.20	3.70	4.30	3.60	3.90	0.29
Phytate-P[b]	2.90	3.20	2.90	3.50	3.10	3.12	0.22
Phytate-P, g/kg total P	644.50	636.80	658.80	684.10	712.50	667.34	27.74
Non-phytate-P[c]	0.80	1.00	0.80	0.70	0.50	0.76	0.16
Ca	1.90	2.00	2.80	2.00	1.70	2.08	0.38
Mg	1.70	1.80	1.90	2.00	1.70	1.82	0.12
K	12.10	12.70	11.90	12.40	11.10	12.04	0.54
Na	< 2.60	< 2.60	< 2.60	< 2.60	< 2.60	< 2.60	0
S	2.60	2.90	2.60	3.40	2.90	2.88	0.29
Microminerals, mg/kg							
Fe	743.70	803.60	1119.00	1767.80	1414.60	1169.74	383.61
Mn	239.60	348.00	294.50	378.20	273.00	306.66	50.21
Zn	347.10	430.80	403.90	476.90	364.00	404.54	46.62

[a] All data were calculated on the basis of 880 g per kg dry matter.
[b] Phytate-P was calculated by multiplying the analyzed phytate by 0.282 (Tran and Sauvant, 2004).
[c] Non-phytate-P was calculated as the difference between total P and phytate-P.

and bags were replaced whenever they were full or at least once every 30 min. All samples were stored at −20 ºC after collection to prevent bacterial degradation of AA (Lee et al., 2021). On the completion of one experimental period, animals were deprived of feed overnight and the following morning, a new experimental diet was offered.

At the conclusion of the experiment, ileal digesta samples were thawed and mixed within animal and diet, and a sub-sample was lyophilized and finely ground prior to chemical analysis. Diets and ileal digesta samples were analyzed for DM, CP, and AA using the methods explained for the FFSB sources. Chromium was analyzed in experimental diets and ileal digesta using the Inductively Coupled Plasma Atomic Emission Spectrometric method (method 990.08; AOAC Int.., 2019). Samples were prepared for analysis using nitric acid-perchloric acid [method 968.08D(b); AOAC Int.., 2019].

2.3. Calculations and statistical analyses

For each analysis of each source of FFSB, all analyzed components were added and subtracted from the concentration of DM in each ingredient to calculate the rest fraction using the following equation (Fanelli et al., 2023):

$$\text{Rest fraction} = [DM - (CP + \textit{acid hydrolyzed ether extract} + ash + \textit{total dietary fiber} + sucrose + stachyose + raffinose + verbascose + starch)]$$

Phytate-P was calculated by multiplying the analyzed phytate by 0.282 (Tran and Sauvant, 2004), and non-phytate P was calculated as the difference between total P and phytate P. the average of each analysis for the 5 sources of FFSB was calculated and the standard deviation was calculated for each average value. The concentration of AA expressed relative to CP was calculated using the

Table 5
Ingredient composition of experimental diets, as-fed basis[a].

Ingredient, g/kg	FFSB 01	FFSB 02	FFSB 03	FFSB 04	FFSB 05	N-free
FFSB	400	400	400	400	400	-
Cornstarch	473	473	473	473	473	682.5
Sucrose	100	100	100	100	100	200
Soybean oil	-	-	-	-	-	40
Solka floc[b]	-	-	-	-	-	40
Dicalcium phosphate	9	9	9	9	9	15.5
Ground limestone	5	5	5	5	5	4
Magnesium oxide	-	-	-	-	-	1
Potassium carbonate	-	-	-	-	-	4
Sodium chloride	4	4	4	4	4	4
Vitamin-mineral premix[c]	5	5	5	5	5	5
Chromic oxide	4	4	4	4	4	4

[a] FFSB = full-fat soybeans.
[b] Fiber Sales and Development Corp., Urbana, OH, USA.
[c] 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, 1660 IU; vitamin E as $_{DL}$-alpha-tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.40 mg; thiamin as thiamine 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.

Table 6
Nutrient composition of experimental diets containing five sources of full-fat soybeans (FFSB), as-fed basis.

Ingredient, g/kg	FFSB 01	FFSB 02	FFSB 03	FFSB 04	FFSB 05	N-free
Dry matter	911.6	917.7	900.7	908.5	908.5	901.1
Crude protein	138.6	140.1	135.9	136.5	140.5	2.2
Indispensable amino acids						
Arg	10.6	11.7	9.7	9.2	9.7	0.1
His	4	4.5	3.7	3.6	3.8	0
Ile	7.4	8.3	7.2	6.9	7.2	0.3
Leu	11.9	13	11.2	10.7	11.1	0.3
Lys	10	11.1	9.3	9.1	9.5	0.1
Met	2	2.3	1.8	1.8	1.9	0
Phe	7.8	8.6	7.4	7	7.3	0.1
Thr	6	6.6	5.3	5.2	5.4	0
Trp	1.8	2.1	1.7	2.1	1.9	0.1
Val	7.5	8.5	7.4	7.1	7.4	0.1
Dispensable amino acids						
Ala	6.7	7.4	6.3	6.1	6.3	0.2
Asp	17.5	19.4	16.2	15.8	16.4	0.1
Cys	2.1	2.6	2.1	2.3	2.2	0
Glu	27.6	31	26	25.7	26.4	0.3
Gly	6.6	7.3	6.2	6.1	6.2	0.1
Pro	7.7	8.8	7.1	7	7.2	0.3
Ser	6.7	7.1	5.6	5.5	5.7	0.1
Tyr	4.9	5.1	4.1	3.4	3.9	0.1

analyzed concentration of each AA divided by the analyzed concentration of CP in each source of FFSB and multiplied by one thousand and expressed as g per kg of protein. The standard deviation and average of all samples from each FFSB source within each group of analysis were calculated.

In the SID experiment, basal endogenous losses of CP and AA were calculated from pigs fed the nitrogen-free diet (Stein et al., 2007). Apparent ileal digestibility (AID) of CP and all AA was calculated using the analyzed CP, AA, and Cr concentrations in the diets and ileal digesta samples. The SID values were calculated by correcting AID values for the basal endogenous losses of CP and AA (Stein et al., 2007). Concentrations of standardized ileal digestible AA in each source of FFSB were calculated by multiplying the concentration of each AA by the calculated SID of that AA.

The homogeneity of the variances and normality of data were confirmed by the UNIVARIATE procedure and data were analyzed using the PROC MIXED procedure (SAS Institute Inc., 2018). Outliers were identified as values that deviated from the predicted mean by more than two times the internally studentized residual within the treatment (Tukey, 1977). The model included diet as the fixed effect and period and animal as random effects. Mean values were calculated using the LSMeans statement and if the model was significant, means were separated using the PDIFF statement with Tukey's adjustment. Pig was the experimental unit and results were considered significant at $P \leq 0.05$ and $0.05 < P < 0.10$ was considered a tendency.

3. Results

3.1. Chemical composition of FFSB

The main nutrients in FFSB were CP, acid-hydrolyzed ether extract, and insoluble dietary fiber, which on average were present in concentration of 338.0 ± 4.83, 171.9 ± 3.74, and 176.4 ± 8.07 g per kg, respectively, and the average gross energy was 21.3 ± 0.24 MJ per kg (Table 1). The 5 sources of FFSB also contained an average of 44.7 ± 3.83 g per kg sucrose, and 37.6 ± 5.77 g per kg stachyose. Among the indispensable AA, Leu (29.1 ± 0.55 g per kg), Arg (26.7 ± 0.55 g per kg), and Lys (25.0 ± 0.57 g per kg) were present in the greatest concentrations (Table 2), as well as expressed as g per kg of CP (Table 3). Phytic acid averaged 11.20 ± 0.89 g/kg, which corresponded to 3.12 ± 0.22 g per kg phytate-bound P (Table 4). Because total P averaged 3.90 ± 0.29 g per kg, non-phytate P was calculated to be 0.76 ± 0.16 g per kg. Calcium analyzed 2.08 ± 0.38 g per kg and K had an average of 12.04 ± 0.54 g per kg. Among microminerals, Fe was present at the greatest concentration (1169.74 ± 383.61 mg per kg), followed by Zn (404.54 ± 46.62 mg per kg), and Mn (306.66 ± 50.21 mg per kg). The rest fraction in FFSB was between −8.3 and 41.3 g per kg, with an average of 20.6 ± 17.3 g per kg.

3.2. Digestibility of AA

Pigs remained healthy during the experiment, no feed refusals were observed, and all pigs completed the experiment. During statistical analysis, 1 pig fed the diet containing FFSB source 01 was detected as an outlier and data from this pig was not included in the statistical analysis. All other data were included in the analysis. The AID of CP and most AA was not different among the five sources of FFSB (Table 7). However, the AID of Arg, Cys, and Glu was greater ($P \leq 0.05$) in FFSB source 02 than in FFSB source 01. The AID of Tyr was also greater ($P \leq 0.05$) in FFSB source 02 compared with FFSB sources 04 and 05 and the AID of Gly tended ($P = 0.054$) to be greater in source 02 than in source 01.

No differences in the SID of CP and AA were observed among the five sources of FFSB except that the SID of Glu in FFSB source 02 was greater ($P = 0.05$) than in FFSB source 01 (Table 8). However, there was a tendency ($P < 0.10$) for the SID of Arg, and Gly to be greater in FFSB source 02 compared with FFSB source 01, and the SID of Tyr in FFSB source 02 also tended ($P < 0.10$) to be greater than in sources 04 and 05.

The concentration of all standardized ileal digestible AA in FFSB source 02 was greater ($P < 0.05$) than in FFSB source 03, except for the concentration of Thr, Trp, Pro, and Ser (Table 9). The concentration of digestible Arg, His, Met, Thr, Cys, Glu, Gly, and Ser in FFSB source 02 was also greater ($P < 0.05$) than in FFSB source 01. However, FFSB source 01 had a greater concentration of digestible Arg, Trp, and Tyr than FFSB source 03. Likewise, FFSB sources 04 and 05 had greater ($P < 0.05$) concentration of standardized ileal digestible Arg, His, Lys, Met, and Cys than FFSB source 03, but FFSB sources 04 and 05 had concentrations of standardized ileal digestible Ile, Phe, and Glu that were less ($P < 0.05$) than in FFSB source 02, whereas FFSB source 04 had a lower ($P < 0.05$) concentration of digestible Trp than FFSB from other origins. In contrast, the greatest concentration of digestible Trp among all sources, except source 01, was in source 05 ($P < 0.05$). The concentration of digestible His was less ($P < 0.05$) in source 04 than in source 02,

Table 7
Apparent ileal digestibility of crude protein and amino acids (AA) in five sources of full-fat soybeans (FFSB)[a].

Item	FFSB 01	FFSB 02	FFSB 03	FFSB 04	FFSB 05	SEM	P-value	Average	SD[b]
Crude protein	0.76	0.81	0.81	0.81	0.81	0.017	0.163	0.80	0.02
Indispensable AA									
Arg	0.90[b]	0.92[a]	0.91[ab]	0.90[ab]	0.90[ab]	0.006	0.042	0.91	0.01
His	0.84	0.89	0.87	0.86	0.86	0.015	0.170	0.86	0.02
Ile	0.81	0.86	0.86	0.84	0.84	0.013	0.131	0.84	0.02
Leu	0.82	0.87	0.86	0.84	0.84	0.016	0.179	0.84	0.02
Lys	0.84	0.89	0.88	0.87	0.87	0.013	0.196	0.87	0.02
Met	0.81	0.87	0.84	0.83	0.83	0.018	0.223	0.84	0.02
Phe	0.82	0.87	0.86	0.84	0.84	0.020	0.114	0.85	0.02
Thr	0.73	0.79	0.76	0.75	0.74	0.018	0.136	0.75	0.02
Trp	0.81	0.85	0.85	0.86	0.83	0.020	0.275	0.84	0.02
Val	0.77	0.83	0.82	0.81	0.80	0.017	0.141	0.81	0.02
Dispensable AA									
Ala	0.73	0.81	0.79	0.78	0.77	0.025	0.222	0.78	0.03
Asp	0.82	0.87	0.85	0.84	0.84	0.011	0.101	0.84	0.01
Cys	0.68[b]	0.78[a]	0.72[ab]	0.74[ab]	0.72[ab]	0.022	0.050	0.73	0.03
Glu	0.85[b]	0.90[a]	0.89[ab]	0.88[ab]	0.88[ab]	0.012	0.042	0.88	0.02
Gly	0.66[b]	0.76[a]	0.71[ab]	0.73[ab]	0.70[ab]	0.026	0.054	0.71	0.03
Pro	0.63	0.76	0.67	0.73	0.69	0.070	0.284	0.70	0.04
Ser	0.81	0.85	0.82	0.81	0.81	0.013	0.135	0.82	0.02
Tyr	0.81[ab]	0.85[a]	0.83[ab]	0.79[b]	0.79[b]	0.012	0.008	0.81	0.02

[a-b]Within a row, means without a common superscript differ ($P < 0.05$).
[a] Each least square mean represents 6 observations, except for FFSB source 01 (n = 5).
[b] The average and standard deviation is for the means.

Table 8
Standardized ileal digestibility (SID) of crude protein and amino acids (AA) in five different sources of full-fat soybeans (FFSB)[1,2].

Item	FFSB 01	FFSB 02	FFSB 03	FFSB 04	FFSB 05	SEM	P-value	Average	SD[c]
Crude protein	0.85	0.90	0.89	0.89	0.89	0.017	0.165	0.88	0.04
Indispensable AA									
Arg	0.94	0.96	0.96	0.95	0.95	0.006	0.089	0.95	0.02
His	0.87	0.92	0.92	0.90	0.90	0.015	0.205	0.90	0.04
Ile	0.85	0.90	0.89	0.88	0.87	0.013	0.165	0.88	0.03
Leu	0.85	0.90	0.89	0.88	0.87	0.018	0.203	0.88	0.04
Lys	0.87	0.91	0.91	0.91	0.90	0.013	0.219	0.90	0.03
Met	0.84	0.90	0.88	0.87	0.87	0.018	0.283	0.87	0.04
Phe	0.86	0.90	0.90	0.88	0.87	0.013	0.148	0.88	0.03
Thr	0.82	0.87	0.85	0.84	0.83	0.018	0.273	0.84	0.04
Trp	0.85	0.89	0.90	0.90	0.87	0.020	0.355	0.88	0.05
Val	0.82	0.88	0.87	0.86	0.85	0.017	0.182	0.85	0.04
Dispensable AA									
Ala	0.81	0.88	0.87	0.86	0.85	0.025	0.257	0.85	0.06
Asp	0.86	0.90	0.89	0.88	0.88	0.011	0.145	0.88	0.03
Cys	0.78	0.86	0.82	0.84	0.81	0.022	0.163	0.82	0.06
Glu	0.88^{b}	0.92^{a}	0.92^{ab}	0.91^{ab}	0.90^{ab}	0.012	0.050	0.91	0.03
Gly	0.85	0.93	0.90	0.93	0.89	0.026	0.094	0.90	0.07
Pro	1.12	1.18	1.19	1.26	1.21	0.070	0.237	1.19	0.17
Ser	0.87	0.90	0.89	0.88	0.88	0.013	0.314	0.89	0.03
Tyr	0.86	0.89	0.88	0.85	0.84	0.012	0.051	0.86	0.03

[a-b]Within a row, means without a common superscript letter differ ($P < 0.05$).
[1]Each least square mean represents 6 observations, except for FFSB source 01 ($n = 5$).
[2]Values for SID were calculated by correcting values for apparent ileal digestibility for basal ileal endogenous losses. The basal ileal endogenous losses were determined (g/kg dry matter intake) as CP,12.45; Arg, 0.49; His, 0.15; Ile, 0.29; Leu, 0.42; Lys, 0.31; Met, 0.06; Phe, 0.28; Thr, 0.52; Trp, 0.08; Val, 0.38; Ala, 0.50; Asp, 0.67; Cys, 0.22; Glu, 0.78; Gly, 1.27; Pro, 3.92; Ser, 0.43; Tyr, 0.21; and total AA, 10.99.
[c] The average and standard deviation is for the means.

Table 9
Concentration of standardized ileal digestible amino acids in five sources of full-fat soybeans (FFSB)[1,2].

Item, g/kg	FFSB 01	FFSB 02	FFSB 03	FFSB 04	FFSB 05	SEM	P-value	SD	Average
Crude protein	295.0	305.8	294.8	300.0	305.8	4.458	0.093	5.4	300.3
Indispensable AA									
Arg	23.7^{b}	24.3^{a}	23.0^{c}	24.2^{a}	24.1^{ab}	0.138	<0.001	0.5	23.9
His	8.5^{bc}	8.8^{a}	8.2^{c}	8.5^{b}	8.6^{ab}	0.074	<0.001	0.2	8.5
Ile	15.8^{ab}	16.4^{a}	15.5^{b}	15.7^{b}	15.5^{b}	0.175	0.008	0.4	15.8
Leu	24.2^{ab}	24.9^{a}	23.5^{b}	24.1^{ab}	23.9^{b}	0.263	0.008	0.5	24.1
Lys	20.8^{ab}	21.4^{a}	20.3^{b}	21.2^{a}	21.5^{a}	0.213	0.002	0.5	21.0
Met	4.1^{b}	4.4^{a}	4.0^{b}	4.4^{a}	4.4^{a}	0.051	<0.001	0.2	4.3
Phe	16.3^{ab}	16.7^{a}	15.8^{b}	15.9^{b}	16.0^{b}	0.173	0.004	0.4	16.1
Thr	11.2^{b}	12.1^{a}	11.4^{ab}	11.7^{ab}	11.6^{ab}	0.198	0.023	0.3	11.6
Trp	4.2^{ab}	4.0^{bc}	3.9^{c}	2.9^{d}	4.3^{a}	0.068	<0.001	0.6	3.8
Val	15.7^{ab}	16.2^{a}	15.1^{b}	15.6^{ab}	15.8^{ab}	0.219	0.013	0.4	15.7
Dispensable AA									
Ala	13.1^{ab}	13.6^{a}	12.8^{b}	13.2^{ab}	13.1^{ab}	0.218	0.016	0.3	13.1
Asp	34.4^{ab}	35.9^{a}	34.2^{b}	35.4^{ab}	35.3^{ab}	0.417	0.033	0.7	35.1
Cys	4.0^{b}	4.6^{a}	4.1^{b}	4.9^{a}	4.7^{a}	0.092	<0.001	0.4	4.5
Glu	55.3^{bc}	60.3^{a}	55.0^{c}	57.7^{b}	56.6^{bc}	0.576	<0.001	2.2	56.9
Gly	13.2^{b}	14.5^{a}	13.2^{b}	14.3^{ab}	13.8^{ab}	0.370	0.009	0.6	13.8
Pro	19.5	21.7	19.8	22.4	21.4	1.233	0.060	1.3	21.0
Ser	12.3^{b}	13.1^{a}	12.8^{ab}	12.9^{a}	12.7^{ab}	0.162	0.005	0.3	12.8
Tyr	10.6^{a}	10.5^{a}	10.0^{b}	10.4^{ab}	10.3^{ab}	0.130	0.011	0.2	10.3

[1]Each least square mean represents 6 observations, except for FFSB source 01 ($n = 5$).
[2]All data presented on the basis of 880 g per kg dry matter.
[a-d]Within a row, means without a common superscript differ ($P < 0.05$).

and the concentration of digestible Leu in source 05 was less ($P < 0.05$) than in source 02. Full-fat soybeans sources 04 and 05 had greater ($P < 0.05$) concentration of digestible Met and Cys than source 01, and FFSB source 04 also had a greater ($P < 0.05$) concentration of digestible Arg and Ser than FFSB source 01.

4. Discussion

Soybeans are one of the primary agricultural commodities globally with an annual production averaging almost 400 million metric tons (USDA, 2023) and Brazil, the United States, and Argentina are the major global producers of soybeans. In 2021, soybeans occupied 33 % of the total crop area in the United States (ASA, 2022). The predominant use of soybeans involves crushing to yield soy oil and SBM (Galkanda-Arachchige et al., 2021), but if oil is not removed, FFSB can be a source of energy and nutrients in animal diets, provided that they are heat treated to inactivate TI (Goebel and Stein, 2011). Extrusion of FFSB involves exposing soybeans to appropriate pressure and temperature, which causes inactivation of TI, denaturation of proteins, enhanced protein digestibility, and reduced concentration of TI and phytic acid (Alonso et al., 2000; Milani et al., 2022).

The sources of FFSB used in this work were from different locations in the United States, but the processing was similar for all sources and completed at the same facility (Insta-Pro® International, Grimes, IA, USA). The concentration of DM in each source of FFSB was greater than previously reported (Cervantes-Pahm and Stein, 2008; Baker et al., 2010; NRC, 2012), which likely is a consequence of the extrusion that provides heat to the beans, and therefore, reduces moisture concentration. The concentration of CP was in agreement with data reported by Cervantes-Pahm and Stein (2008), but less than reported by other authors (Baker et al., 2010; NRC, 2012). Concentrations of gross energy, total dietary fiber, and ash were greater, and fat was less than reported (NRC, 2012; Yoon and Stein, 2013; Ravindran et al., 2014), and concentrations of sucrose, stachyose and raffinose, were in agreement with previous values (Baker et al., 2011; NRC, 2012; Yoon and Stein, 2013). Trypsin inhibitors in the FFSB were reduced to between 5.7 and 7.7 TIU per mg (DM basis), which is slightly greater than reported by others (Baker et al., 2010; Kiarie et al., 2020; Wang et al., 2023). Concentrations of TI in FFSB are negatively correlated with energy utilization in pigs, as demonstrated in previous experiments (Wang et al., 2023). This relationship indicates that greater levels of TI may impair the digestive efficiency and overall energy availability from FFSB in swine diets. A high concentration of TI also results in decreased SID of AA (Goebel and Stein, 2011; Yáñez et al., 2019). In contrast high temperatures during extrusion may cause Maillard reaction (González-Vega et al., 2011; Kim et al., 2012; Oliveira et al., 2020), which will also reduce the SID of AA, specifically Lys. However, the fact that the Lys to CP ratio in the sources of FFSB used in the experiment was greater than 60 g per kg indicates that samples were not heat damaged (González-Vega et al., 2011).

The concentration of phytic acid, phytate-P, and the percentage of phytate-P of total P in FFSB was greater than reported values (NRC, 2012; Cheng and Hardy, 2003). Phytate in FFSB can reduce not only the digestibility of P, but also the digestion of Ca and micronutrients. Therefore, a large part of phytate-P is not used by pigs, but is excreted in the feces, but extrusion may reduce the levels of phytate bound P in feed ingredients (Alonso et al., 2000). The concentration of Ca in FFSB analyzed in this work was less than previous values (Kiarie et al., 2020). The mineral composition of soil has a significant impact on the nutrient mineral concentration in crops, including FFSB, which may be the reason for the lower concentration of Ca (Ohlrogge, 1960). Nevertheless, the concentration of most other minerals in the FFSB samples was consistent with previously reported values (Cheng and Hardy, 2003; NRC, 2012; Kiarie et al., 2016).

The rest fraction was calculated at 20.6 ± 17.23 g per kg for the 5 sources of FFSB. It is not clear what the composition of the rest fraction is, but it is possible that some of the analyzed components may have been underestimated due to the high concentration of fat in the samples as has been demonstrated for dietary fiber (Mertens, 2003), and other proximate components (Shurson et al., 2021). However, having a rest fraction of 10–50 g per kg is not uncommon when practical feed ingredients are analyzed (Navarro et al., 2018; Fanelli et al., 2023). Concentrations of AA were consistent among the 5 sources of FFSB. These results align with data by NRC (2012) and Kaewtapee et al. (2017), and the AA composition in FFSB used in this work was comparable to SBM (NRC, 2012). However, the total amount of AA in FFSB was 200–350 g per kg less than in SBM, which is due to the oil extraction from FFSB to produce SBM, which concentrates the AA in SBM compared with FFSB.

The observation that only minor differences in the SID of CP and AA among the 5 sources of FFSB were calculated indicates that growing region within the United States does not impact protein quality. This observation is in agreement with data indicating that the SID of AA in SBM is not impacted by growing region (Sotak-Peper et al., 2017; Lagos and Stein, 2017). The SID of CP and AA in the FFSB used in this experiment were close to previous values (Cervantes-Pahm and Stein, 2008; Baker et al., 2010; Kiarie et al., 2020). Previous data demonstrated that the SID of AA in FFSB was less than in SBM (NRC, 2012; Yáñez et al., 2019), but that may be due to either over-heating or under-heating of the FFSB. Also, the concentration of TI serves as a common indicator of soybean quality, particularly in relation to the SID of Lys, because of the strong negative correlation between TI concentrations and SID of Lys (Kaewtapee and Mosenthin, 2024). However, the SID of AA that were calculated in this experiment were close to the values reported by Goebel and Stein (2011) and Yáñez et al., 2019 for SBM. It is also possible that if the FFSB are not dehulled, the fiber in the diets may reduce the SID of AA because fiber often results in reduced digestibility of AA (Baker et al., 2010; Fouhse et al., 2016; Sanchez-Zannatta et al., 2023). In contrast, the fat in FFSB may increase SID of AA due to slower gastric and intestinal emptying, which increases the time to digest proteins by proteolytic enzymes (Cervantes-Pahm and Stein, 2008; Goebel and Stein, 2011).

Growing pigs have a constant SID of AA in the period from 20 to 130 kg (Pedersen et al., 2016). It is, therefore, most likely that the SID values obtained in this experiment where pigs had a starting body weight of 85 kg are representative for the entire growing-finishing period. The endogenous losses of AA that were determined in this experiment are in very good agreement with average values from previous experiments (Jansman et al., 2002) further indicating that the values for SID of AA obtained in this experiment are representative of pigs in the entire growing-finishing period.

The observation that the calculated concentration of standardized ileal digestible AA differed somewhat among some of the sources of FFSB may be related to the number of sunlight hours that soybeans receive during the growing season, because shading stress impacts soybean senescence, resulting in increased retention of nitrogen in soybean leaves, stems, and seeds (Deng et al., 2024). Because non-AA nitrogen is not utilized by pigs, this nitrogen does not have a nutritional value. Nevertheless, the observation that the differences in concentration of digestible AA among sources were minor, although in some instances significant, indicates that the AA value of FFSB is relatively constant regardless of the growing region in the United States.

5. Conclusion

The chemical composition of five sources of full-fat soybean was consistent regardless of where they were grown. Although there were minor differences in concentrations of crude protein and some amino acids among the full-fat soybeans, these differences were relatively small. Specifically, a reduction in crude protein and some amino acids was observed in full-fat soybean source 03 compared with the other sources. However, only minor variations in the standardized ileal digestibility of amino acids were observed, indicating that, under the conditions used in this work that included only five sources of soybeans, the origin of the soybeans did not impact amino acid digestibility. Thus, it is concluded that the chemical composition and standardized ileal digestibility of crude protein and amino acids in full-fat soybeans produced in the United States are not significantly influenced by the location where the soybeans were grown.

CRediT authorship contribution statement

Lee S.A.: Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation. **Stein Hans:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Ruiz-Arias N.C.:** Writing – original draft, Methodology, Investigation.

Declaration of Competing Interest

The authors have no conflicts of interest.

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