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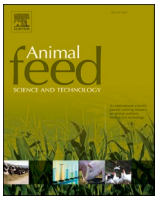

The growing area within the United States has only minor impact on digestible and metabolizable energy, and standardized total tract digestibility of phosphorus in full-fat soybeans fed to growing pigs

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A R T I C L E I N F O

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A B S T R A C T

Two experiments were conducted to test the hypothesis that there is no difference in the digestible energy (DE), the metabolizable energy (ME), or the standardized total tract digestibility (STTD) of P among five sources of full-fat soybeans (FFSB) fed to growing pigs. The five sources of FFSB (source 01, 02, 03, 04, and 05) were collected from five different states in the United States and fed to growing pigs. In experiment 1, forty-eight pigs (initial body weight: 30.86 ± 1.64 kg) were placed in metabolism crates and allotted to six diets using a randomized complete block design with eight replicate pigs per diet. A basal diet based on corn as the only source of energy and five diets containing corn and each source of FFSB were formulated. Pigs were fed experimental diets for 13 days and feces and urine were collected for four days after seven days of adaptation. Results demonstrated that ME in corn was 15.73 MJ per kg dry matter (DM), and ME in the five sources of FFSB was 20.74, 19.85, 20.59, 20.19, and 21.22 MJ ME per kg DM, respectively. In experiment 2, eighty pigs (initial body weight: 16.73 ± 3.16 kg) were housed individually in metabolism crates and allotted to a randomized complete block design with 10 diets and 8 replicate pigs per diet. Five diets contained each source of FFSB as the only source of P and five additional diets were formulated by adding 1000 phytase units (FTU)/kg of microbial phytase to the original five diets. Thus, the experiment was a 5 × 2 factorial with the five sources of FFSB and two levels of microbial phytase (i.e., 0 or 1000 FTU per kg diet). Feces were collected from pigs for four days following five days of adaptation. Results demonstrated that there were no interactions between phytase and source of FFSB, and no effects of phytase or source of FFSB were observed for feed intake, weight of feces excreted, or daily basal endogenous P loss. The STTD of P in the diet with FFSB source 05 was greater ($P < 0.05$) than the STTD of P in the other sources of FFSB if no phytase was used, but when phytase was added to the diets, no differences among the five sources of FFSB were observed (interaction, $P < 0.05$). However, the STTD of P was greater ($P < 0.05$) if phytase was used than if no phytase was used. In conclusion, results demonstrated

Abbreviations: ATTD, Apparent total tract digestibility; DE, Digestible energy; EPL, Endogenous phosphorus loss; FFSB, Full-fat soybean; FTU, Phytase units; GE, Gross energy; ME, Metabolizable energy; SEM, Standard error of the mean; STTD, Standardized total tract digestibility.

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that there were only minor differences among sources of FFSB in ME and STTD of P in FFSB was not different among the five sources if microbial phytase was used.

1. Introduction

Whole soybeans, from which the oil is not extracted, are referred to as full-fat soybeans (FFSB) and may be used in diets for poultry and pigs because of its high concentrations of protein, oil, linoleic acid, vitamin E, and lecithin (Ravindran et al., 2014). Full-fat soybeans contain 180–200 g/kg oil (Marty et al., 1994; NRC, 2012). Unprocessed raw soybeans, however, contain trypsin inhibitors that make them unsuitable for inclusion in diets for pigs and poultry, because trypsin inhibitors reduce feed efficiency due to reduced amino acid digestibility (Waldroup, 1982; Grant, 1989; Goebel and Stein, 2011). To inactivate trypsin inhibitors, soybeans need to be heated, which may be accomplished using an extruder.

Energy is one of the most expensive components in diets for pigs and it is important to estimate the energy contribution from ingredients to formulate diets that meet requirements (Noblet, 2007). There is, however, a lack of information about the amount of digestible energy (DE) and metabolizable energy (ME) that pigs can obtain from FFSB, and it is also not known if growing location of FFSB affects DE and ME.

As is the case for most plant ingredients, the majority of P in FFSB is bound to phytate, which is mostly indigestible by pigs (Zhai et al., 2022), but in most feed ingredients, it is possible to increase the digestibility of P by including microbial phytase in the diet (Pallauf et al., 1994; Almeida et al., 2013; Lautrou et al., 2021). However, there is limited data demonstrating if microbial phytase also increases the digestibility of P in FFSB and it is uncertain if the standardized total tract digestibility (STTD) of P is constant among sources of FFSB grown in different locations. Therefore, two experiments were conducted to test the null hypothesis that DE and ME and STTD of P in FFSB are not influenced by growing area and that STTD of P in FFSB is increased if microbial phytase is used.

2. Materials and methods

The protocols for two experiments were submitted to and approved by the Institutional Animal Care and Use Committee at the University of Illinois before initiation of the animal part of the experiments. Castrated male pigs that were the offspring of Line 800 boars mated to Camborough females (Pig Improvement Company, Hendersonville, TN, USA) were used in both experiments.

Five sources of FFSB were collected from five states in the soybean growing area of the U.S. (i.e., Illinois, Iowa, North Dakota, Ohio, and Pennsylvania). Samples were managed and processed under identical conditions at the same facility with high-shear dry extruders using two paired extruders (Model 2000, Insta-Pro® International, Grimes, IA, USA). The two extruders each had a capacity of 1000 kg per hour and processing parameters were adjusted to maintain a minimum processing temperature of 160 °C. The extruded materials 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 and 2). The five sources of FFSB were randomly assigned the numbers 01, 02, 03, 04, or 05.

2.1. Diets and feeding

In experiment 1, a basal diet based on corn as the only energy source was formulated and five additional diets were formulated by

Table 1
Analyzed nutrient composition and energy in corn and five sources of full-fat soybean (FFSB), as-is basis.

Item	Corn	FFSB source						
		01	02	03	04	05	Average	SD
Dry matter, g/kg	880.6	937.1	934.7	920.4	941.8	936.1	934	7.2
GE, MJ/kg	15.8	23	22.4	22.2	22.5	22.9	22.6	0.3
Crude protein, g/kg	58.1	360.4	362.8	345.0	360.0	365.8	358.8	7.2
Total dietary fiber, g/kg	127.8	184	224	208	211	199	205.2	13.3
Soluble dietary fiber, g/kg	12	5	27	13	31	14	18	9.6
Insoluble dietary fiber, g/kg	115.8	179	197	195	180	185	187.2	7.5
Acid hydrolyzed ether extract, g/kg	34.7	189	181.4	176.5	179.3	186	182.4	4.5
Ash, g/kg	13.5	58.1	59	56.2	58.4	56.9	57.7	1
Sugar profile, g/kg								
Glucose	4.7	ND[a]	ND	ND	ND	ND	ND	ND
Maltose	1.2	ND	ND	ND	ND	ND	ND	ND
Fructose	7.8	ND	ND	ND	ND	ND	ND	ND
Sucrose	10.4	45.2	50.3	42.3	45.4	54.1	47.5	4.2
Stachyose	0.3	38.9	48.1	31.9	34.9	45.9	39.9	6.2
Raffinose	1.4	7.4	7.5	7.4	6.2	5.9	6.9	0.7
Verbascose	ND	2.6	4.7	3	2.5	3.5	3.3	0.8
Starch, g/kg	645	8.5	6.7	17.2	16.1	6.1	10.9	4.8
Trypsin inhibitor, units per mg	ND	6.27	6.55	6.93	8.27	6.08	6.82	0.76

[a] ND: No detected.

mixing corn and each source of FFSB (Table 3). Thus, a total of six diets were used. Vitamins and minerals were included in all diets to meet or exceed the estimated nutrient requirements for growing pigs (NRC, 2012).

In experiment 2, five diets containing each source of FFSB, and sucrose and cornstarch were formulated and, in each diet, the source of FFSB was the only source of P. Five additional diets were formulated by adding 1000 phytase units (FTU) per kg (Quantum Blue, AB Vista, Marlborough, UK) to each of the original five diets (Table 4). Thus, the experimental design was a 5 × 2 factorial with five sources of FFSB and two levels of phytase (i.e., 0 or 1000 FTU per kg diet). Vitamins and minerals other than P and Ca were included in all diets to meet or exceed the estimated nutrient requirements for growing pigs (NRC, 2012).

In both experiments, all diets were fed in meal form and pigs were limit-fed at 3.2 times the energy requirement for maintenance (i.e., 197 kcal/kg × body weight$^{0.60}$; NRC, 2012). Daily feed allowances were provided in two equal meals at 0800 and 1700 h. Pigs had free access to water throughout the experiment.

2.2. Animal and housing

In experiment 1, forty-eight growing pigs (initial body weight: 30.86 ± 1.64 kg) were allotted to the six diets using a randomized complete block design with two blocks of 24 pigs and four pigs per diet in each block for a total of eight replicate pigs per diet. Body weight was the blocking factor. Pigs were housed individually in metabolism crates (0.81 × 2.59 m) that were equipped with a self-feeder, a bowl with a nipple waterer, and a slatted floor. A screen and a urine pan were placed under the slatted floor, which allowed for the total, but separate, collection of urine and fecal samples.

In experiment 2, eighty growing barrows (initial body weight: 16.73 ± 3.16 kg) were allotted to a randomized complete block design with 10 diets. There were two blocks of 40 pigs and four replicate pigs per diet in each block for a total of eight replicate pigs per diet. Pigs were placed in individual metabolism crates (0.69 × 0.86 m) that were equipped with a self-feeder, a nipple waterer, a slatted floor, and a screen placed under the slatted floor to allow for total collection of feces.

2.3. Sample collection

In experiment 1, feed consumption was recorded daily, and pigs were fed experimental diets for 13 days. The initial seven days were considered the adaptation period to the diet. Fecal samples were collected for four days according to the marker-to-marker approach (Adeola, 2001). Chromic oxide was the start marker that was included in the morning meal on day 8 and ferric oxide was the stop marker that was included in the morning meal on day 12. Collection of feces started when the start marker appeared in the feces and ceased when the stop marker appeared. Urine was collected in urine buckets over a preservative of 50 mL of 3 *N* HCl. Urine collection started at 0900 h on day 8 and ceased on day 12 at 0900 h. Fecal samples and 20 % of the collected urine were stored at − 20 ºC immediately after collection.

In experiment 2, feed consumption was recorded daily, and diets were fed for 12 days. The initial five days were considered the adaptation period to the diet, whereas fecal materials were collected from the feed provided during the following four days using the marker-to-marker approach as explained for experiment 1 with the exception that the start marker was indigo blue. Fecal samples were stored at - 20 °C immediately after collection.

2.4. Chemical analysis

At the conclusion of both experiments, fecal samples were dried in a 50°C forced-air drying oven, ground, mixed, and subsampled

Table 2
Analyzed mineral composition of five sources of full-fat soybeans (FFSB), as-is basis.

Item, g/kg	FFSB source					Average	SD
	01	02	03	04	05		
Phytic acid	12.5	13.9	12.3	15.4	13.5	13.5	1.1
P	4.5	5.1	4.4	5.2	4.4	4.7	0.3
Phytate-P[a]	3.5	3.9	3.5	4.3	3.8	3.8	0.3
Phytate-P, g/kg total P	779.9	768.6	783	832	861.3	804.9	35.6
Nonphytate-P[b]	1.0	1.2	1.0	0.9	0.6	0.9	0.2
Ca	2.3	2.4	3.3	2.4	2.0	2.5	0.4
Mg	2.1	2.2	2.2	2.4	2.1	2.2	0.1
K	14.6	15.3	14.2	15.1	13.4	14.5	0.7
Na	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	0.0
S	3.1	3.5	3.1	4.1	3.5	3.5	0.4
Microminerals, mg/kg							
Cu	< 23	< 23	< 23	< 23	< 23	< 23	0.0
Fe	90	97	133	215	171	141.3	46.7
Mn	29	42	35	46	33	36.7	6.3
Zn	42	52	48	58	44	48.8	5.9

[a] Phytate-P was calculated by multiplying the analyzed phytic acid by 0.282 (Tran and Sauvant, 2004).
[b] Nonphytate-P was calculated as the difference between total P and phytate-P.

Table 3
Ingredient composition and analyzed nutrient composition of experimental diets, as-is basis (experiment 1).

		Full-fat soybeans sources				
Item	Corn	01	02	03	04	05
Ingredient, g/kg						
Ground corn	968.5	573.5	573.5	573.5	573.5	573.5
Full fat soybeans	-	400.0	400.0	400.0	400.0	400.0
Dicalcium phosphate	15.0	10.0	10.0	10.0	10.0	10.0
Ground limestone	7.5	7.5	7.5	7.5	7.5	7.5
Sodium chloride	4.0	4.0	4.0	4.0	4.0	4.0
Vitamin-mineral premix[a]	5.0	5.0	5.0	5.0	5.0	5.0
Analyzed nutrient composition						
Dry matter, g/kg	885.2	913.4	915.7	908.1	914.5	911.3
Gross energy, MJ/kg	15.4	18.3	18.2	18.1	18.1	18.3
Ash, g/kg	32.9	43.3	44.8	42.7	45.1	43.6
Crude protein, g/kg	58.7	171.7	175.4	174.5	173.5	174.2
Acid hydrolyzed ether extract, g/kg	20.4	81.8	74.5	79.2	85.2	91.8

[a] 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 4
Ingredient composition and analyzed nutrient composition of experimental diets, containing full-fat soybeans (FFSB) without or with microbial phytase, as-is basis (experiment 2).

	Without phytase					With phytase				
Ingredient, g/kg	FFSB 01	FFSB 02	FFSB 03	FFSB 04	FFSB 05	FFSB 01	FFSB 02	FFSB 03	FFSB 04	FFSB 05
Corn starch	438.0	438.0	438.0	438.0	438.0	437.8	437.8	437.8	437.8	437.8
Full-fat soybeans	450.0	450.0	450.0	450.0	450.0	450.0	450.0	450.0	450.0	450.0
Sucrose	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Ground limestone	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Sodium chloride	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Vitamin-micromineral premix[a]	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Phytase premix[b]	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.2	0.2	0.2
Analyzed values										
Dry matter, g/kg	946.1	948.1	939.9	944.8	947.9	947.1	947.6	936.8	943.6	941.7
Ash, g/kg	30.7	32.1	31.1	28.3	31.8	30.4	31.4	30.9	29.6	29.7
Ca, g/kg	1.9	1.9	2.0	2.1	1.8	2.2	2.2	2.8	2.0	1.8
P, g/kg	2.2	2.3	2.0	2.4	2.2	2.2	2.3	2.1	2.4	2.2
Phytase, FTU[c]/kg	< 70	< 70	< 70	< 70	< 70	1000	920	1100	1200	1100

[a] 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.
[b] The phytase premix (Quantum Blue 5000; AB Vista, Marlborough, UK) contained 5000 phytase units per gram. At 0.2 g per kg inclusion, the premix provided 1000 units of phytase per kg of complete diet.
[c] FTU = phytase units.

prior to analysis. Urine samples from experiment 1 were thawed and mixed within animal and diet, and a sub-sample was dripped onto cotton balls that were placed in a plastic bag and lyophilized before analysis (Kim et al., 2009).

Ingredient, diet, and fecal samples were analyzed for dry matter in both experiments (method 930.15; AOAC Int.., 2019). Diet, fecal, and urine from experiment 1 and ingredient samples were analyzed for gross energy (GE) using bomb calorimetry (Model 6400; Parr Instruments, Moline, IL, USA). Ingredients and diets from both experiments were also analyzed for ash (method 942.05; AOAC Int.., 2019) and ingredients and diets from experiment 1 were analyzed for acid-hydrolyzed ether extract by acid hydrolysis 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). Crude protein in ingredients and diets from experiment 1 were 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). Ingredient samples were analyzed for insoluble dietary fiber and soluble dietary fiber according to method 991.43 (AOAC Int.., 2019) using the Ankom Total Dietary Fiber Analyzer (Ankom Technology, Macedon,

NY, USA). Total dietary fiber was calculated as the sum of insoluble and soluble dietary fiber (method 991.43; AOAC Int.., 2019). Ingredients were also analyzed for sugars including glucose, fructose, maltose, sucrose, stachyose, raffinose, and verbascose using high-performance liquid chromatography (Dionex App Notes 21 and 92). Total starch was analyzed in the five sources of FFSB and in corn by the amyloglucosidase-alpha-amylase procedure corresponding to the enzymatically hydrolyzed starch converted to glucose, and analysis of glucose by spectrophotometry (method 996.11; AOAC Int.., 2019). Trypsin inhibitor concentrations were analyzed in the five sources of FFSB and expressed as trypsin inhibitor units per mg. Concentrations of macro minerals and micro minerals in the five sources of FFSB, the concentration of P and Ca in diets from experiment 2, and the concentration of P in fecal samples from experiment 2 were analyzed by an inductively coupled plasma spectroscopy method (method 985.01 A, B, and C; AOAC, 2019) after wet ash sample preparation (method 975.03 B(b); AOAC Int.., 2019). Phytic acid was also analyzed in FFSB samples (Ellis et al., 1977). Phytate-P was calculated by multiplying the analyzed phytate by 0.282 (Tran and Sauvant, 2004). Diets from experiment 2 were analyzed for phytase activity (method 2000.12; AOAC Int.., 2019).

2.5. Calculations

In experiment 1, the apparent total tract digestibility (ATTD) of GE and dry matter was calculated for each diet, and 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 in the corn diet by the inclusion rate of corn in that diet (i.e., 968 g per kg) and the contribution of corn to the DE and ME in the corn-FFSB diets was calculated by multiplying the DE and ME in corn by the inclusion rate of corn in the corn-FFSB diets. This value was then subtracted from the DE and ME in the corn-FFSB diets to calculate the contribution of DE and ME from FFSB to the diets, and by dividing these values by the inclusion rate of FFSB in the diets, values for DE and ME in each source of FFSB were calculated by difference (Adeola, 2001).

In experiment 2, the ATTD of P in each source of FFSB was calculated (NRC, 2012). By correcting this value for the basal endogenous loss of P (EPL; 190 mg per kg of dry matter intake; NRC, 2012), the STTD of P in each source of FFSB was calculated both without and with microbial phytase.

2.6. Statistical analyses

Homogeneity of the variances and normality were confirmed, and data were analyzed using the PROC MIXED in SAS (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). 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. The pig was the experimental unit and results were considered significant at $P \leq 0.05$ and $0.05 \leq P < 0.10$ was considered a tendency. In experiment 1, diet was the fixed effect and block and replicate within block were random effects. In experiment 2, fixed effects included source of FFSB, phytase, and the interaction between FFSB and phytase, and block and replicate within block were random effects.

3. Results

Pigs remained healthy during both experiments, no feed refusals were observed, and all pigs completed their assigned treatment. In experiment 1, one pig fed the corn diet was identified as an outlier during data analysis and this pig was removed from analysis. In experiment 2, two pigs fed diets containing FFSB sources 01 and 02 and no phytase and two pigs fed diets containing FFSB source 05

Table 5
Apparent total tract digestibility (ATTD) of dry matter and gross energy (GE) and values for digestible energy and metabolizable energy in experimental diets[1] (experiment 1).

Item	Corn	Full-fat soybean sources					SEM	*P*-value	Average	SD
		01	02	03	04	05				
Intake										
Diet, kg/day	1.31	1.33	1.36	1.37	1.36	1.36	0.04	0.815	1.36	0.01
GE, MJ/day	20.07^{b}	24.34^{a}	24.69^{a}	24.79^{a}	24.72^{a}	25.01^{a}	0.59	< 0.001	24.71	0.21
Fecal excretion										
Dry feces output, kg/day	0.12	0.14	0.15	0.14	0.14	0.13	0.01	0.126	0.14	0.01
GE, MJ/day	2.32	2.70	2.91	2.75	2.67	2.57	0.14	0.103	2.73	0.11
Urine excretion										
Urine output, kg/day	2.36	4.56	5.71	4.42	6.12	4.64	1.11	0.223	5.09	0.69
GE, MJ/day	0.35^{b}	0.61^{ab}	0.68^{ab}	0.62^{ab}	0.72^{a}	0.69^{ab}	0.08	0.033	0.67	0.05
ATTD of dry matter	0.901	0.895	0.889	0.894	0.898	0.903	0.004	0.122	0.896	0.005
ATTD of GE	0.885	0.888	0.882	0.888	0.891	0.897	0.005	0.277	889.8	0.005
Energy in diets, MJ/kg (as-is)										
Digestible energy	13.62^{c}	16.27^{ab}	16.03^{b}	16.12^{b}	16.17^{ab}	16.46^{a}	0.08	< 0.001	16.21	0.15
Metabolizable energy	13.34^{c}	15.82^{ab}	15.53^{b}	15.67^{ab}	15.63^{ab}	15.95^{a}	0.09	< 0.001	15.72	0.15

[a-c] Within a row, means without a common superscript letter differ ($P < 0.05$).
[1] Each least squares mean is the mean of 8 observations, except for the diet containing corn ($n = 7$).

and no phytase were detected as outliers and removed from analysis. All other data were included in the final analysis.

3.1. Experiment 1, DE and ME in FFSB

Results indicated that feed intake was not different among diets, but GE intake of pigs fed the diets containing FFSB was greater ($P < 0.05$) compared with that of pigs fed the corn diet (Table 5). The weight of dry feces, fecal GE excretion, and urine weight were not different among treatments, but urine GE excretion was greater ($P < 0.05$) from pigs fed the diet containing FFSB source 04 than from pigs fed the corn diet. The ATTD of dry matter and GE were not different among diets. The concentration of DE was greater ($P < 0.05$) in the diet containing FFSB source 05 than in diets containing FFSB source 02, and ME was greater ($P < 0.05$) in the diet containing FFSB source 05 than in the diet containing source 03. However, all diets containing FFSB had DE and ME that were greater than the corn diet.

The DE and ME in all sources of FFSB were greater ($P < 0.05$) than in corn on an as-is and on a dry matter basis (Table 6). On a dry matter basis, DE in FFSB source 05 was greater ($P < 0.05$) than in FFSB source 02, and ME in FFSB source 05 was greater ($P < 0.05$) than in FFSB sources 02 and 04.

3.2. Experiment 2, STTD of P in FFSB

There were no interactions between use of phytase and FFSB for feed intake, daily basal endogenous P loss, or weight of feces (Table 7). No effect of use of phytase was observed for weight of feces, but there was a tendency ($P < 0.10$) for differences among sources of FFSB in weight of feces. There also was a tendency for a greater ($P < 0.10$) feed intake and EPL when phytase was used. There was no interaction between phytase and source of FFSB for P intake, ATTD of dry matter, or absorption of P, but P intake, ATTD of dry matter, and absorption of P were greater ($P < 0.05$) in pigs fed diets with phytase compared with pigs fed diets without phytase. Concentration of P in feces was greater ($P < 0.05$) from pigs fed the diet containing FFSB source 04 without microbial phytase compared with pigs fed diets containing one of the other sources of FFSB, but the concentration of P in feces was not different among the five diets containing phytase with the exception that P in feces from pigs fed the diet containing FFSB source 04 was greater ($P < 0.05$) than in feces from pigs fed the diet with FFSB source 03 (interaction; $P < 0.05$). Fecal P output was less ($P < 0.05$) from pigs fed the diet containing FFSB sources 03 or 05 without phytase compared with the other diets without phytase, but no difference was observed among sources if phytase was used (interaction; $P < 0.05$). The ATTD of P and STTD of P in the diet containing FFSB source 05 were greater ($P < 0.05$) compared with diets containing the other sources of FFSB without phytase, but there were no differences in the ATTD and STTD of P among sources of FFSB if phytase was used (interaction; $P < 0.05$). Concentration of P in feces and P output were greater ($P < 0.05$) from pigs fed diets without phytase than from pigs fed diets with phytase, but the ATTD of P and STTD of P were greater ($P < 0.05$) if phytase was used than if phytase was not used.

4. Discussion

Full-fat soybeans is a high-energy ingredient if included in diets for pigs and if FFSB is heat-treated to inactivate trypsin inhibitors, FFSB contribute approximately 16.48 MJ of ME per kg (NRC, 2012), which is due to the high concentration of fat and protein (Kil et al., 2011; Kiarie et al., 2020; Wang et al., 2023a). The dry matter in the FFSB used in the present experiments were in agreement with previous values (Cervantes-Pahm and Stein, 2008; Baker et al., 2010; Wang et al., 2023a). Gross energy, total dietary fiber, fat, and ash in the FFSB were also within the range of values observed in previous experiments, whereas crude protein was less than previously reported (NRC, 2012; Yoon and Stein, 2013; Wang et al., 2023b). As expected, FFSB contained sucrose, stachyose, and raffinose. Oligosaccharides in FFSB may reduce the digestibility of energy and reduce growth rate of weanling pigs, whereas pigs older than 6–7 weeks are expected to be able to ferment the oligosaccharides (Baker et al., 2011; Yoon and Stein, 2013), which may increase

Table 6
Digestible energy (DE) and metabolizable energy (ME) in corn and five sources of full-fat soybeans (FFSB) [1, 2] (experiment 1).

	Corn	FFSB source					SEM	P-value	FFSB	
Item		01	02	03	04	05			SD	Average
As-is basis, MJ/kg										
DE	14.07[c]	20.52[ab]	19.90[b]	20.14[b]	20.25[b]	21.00[a]	0.17	< 0.001	0.37	20.36
ME	13.78[c]	19.87[ab]	19.07[b]	19.42[ab]	19.33[ab]	20.13[a]	0.21	< 0.001	0.37	19.54
Dry matter basis, MJ/kg										
DE	16.05[c]	21.53[ab]	20.74[b]	21.36[ab]	21.18[ab]	22.15[a]	0.19	< 0.001	0.46	21.39
ME	15.73[c]	20.74[ab]	19.85[b]	20.59[ab]	20.19[b]	21.22[a]	0.23	< 0.001	0.47	20.51
Digestibility and metabolizability										
DE:GE	0.887	0.893	0.884	0.909	0.899	0.915	0.08	0.052	0.011	0.900
ME:DE	0.980	0.964	0.958	0.964	0.954	0.959	0.007	0.183	0.004	0.960
ME:GE	0.869	0.861	0.847	0.876	0.858	0.877	0.009	0.206	0.011	0.864

[a-c] Within a row means without a common superscript letter differ ($P < 0.05$).
[1] Each least squares mean is the mean of 8 observations, except for the diet containing corn ($n = 7$).
[2] GE = gross energy.

Table 7
Effects of microbial phytase on apparent total tract digestibility (ATTD) and standardized total tract digestibility (STTD) of dry matter (DM) and P in five sources of full-fat soybeans (FFSB)[1], (experiment 2).

Items	No phytase					1000 units of phytase per kg diet[2]						*P*-value		
	FFSB 01	FFSB 02	FFSB 03	FFSB 04	FFSB 05	FFSB 01	FFSB 02	FFSB 03	FFSB 04	FFSB 05	SEM	Phytase	FFSB	FFSB × Phytase
Feed intake, g/d	794	819	834	806	825	876	871	840	850	875	43.29	0.051	0.979	0.899
Fecal output, g/d	48	48	50	42	39	42	45	47	40	43	3.03	0.266	0.058	0.538
ATTD of DM, g/kg	0.939	0.943	0.940	0.948	0.954	0.952	0.949	0.944	0.953	0.951	0.003	0.011	0.008	0.212
P intake, g/d	1.71	1.88	1.69	1.96	1.80	1.88	2.00	1.70	2.06	1.91	0.10	0.049	0.002	0.904
P in feces, g/kg	19.0^{bc}	20.2^{b}	17.5^{c}	23.5^{a}	18.2^{bc}	9.4^{de}	9.9^{de}	8.7^{e}	11.4^{d}	9.7^{de}	0.90	< 0.001	< 0.001	0.020
P output, g/d	0.92^{a}	0.95^{a}	0.87^{ab}	0.98^{a}	0.72^{b}	0.39^{c}	0.44^{c}	0.40^{c}	0.45^{c}	0.42^{c}	0.06	< 0.001	0.005	0.033
P absorption, g/d	0.79	0.93	0.82	0.97	1.08	1.49	1.56	1.30	1.61	1.49	0.08	< 0.001	0.014	0.341
ATTD of P, g/kg	0.459^{c}	0.493^{c}	0.483^{c}	0.497^{c}	0.600^{b}	0.787^{a}	0.778^{a}	0.764^{a}	0.777^{a}	0.784^{a}	0.026	< 0.001	0.014	0.027
Basal EPL[3], mg/d	142.81	147.59	148.87	144.64	148.52	157.60	156.77	149.55	152.31	156.60	7.76	0.060	0.965	0.882
STTD of P[4], g/kg	542.5^{c}	572.0^{c}	571.5^{c}	570.6^{c}	682.9^{b}	870.5^{a}	856.4^{a}	851.7^{a}	850.9^{a}	865.7^{a}	26.3	< 0.001	0.014	0.026

[a-e] Within a row, means without a common superscript differ (P < 0.05).
[1] Each least squares mean is the mean of 8 observations, except for diets containing FFSB source 01 without phytase (n = 7) and FFSB source 05 without phytase (n = 6).
[2] Phytase: Quantum Blue 5000 (ABvista, Marlborough, UK).
[3] EPL = endogenous P loss, this value was estimated to be 190 mg per kg of DM intake (NRC, 2012). The daily basal EPL (mg/d) for each diet was calculated by multiplying the EPL (mg per kg of the DM intake) by the daily DM intake of each diet.
[4] Values for STTD were calculated by correcting values for ATTD for basal endogenous losses (NRC, 2012).

digestibility of energy and nutrients in FFSB if fed to older pigs instead of newly weaned pigs.

Concentrations of Ca and P in FFSB were less than expected (Cheng and Hardy, 2003; NRC, 2012; Ravindran et al., 2014; Wang et al., 2023b), but variation in the concentration of minerals in crops reflects variety and the geographic region of cultivation due to differences in soil mineral concentration (Ohlrogge, 1960). Variability in mineral concentration among different sources of FFSB has previously been observed (Wang et al., 2023b). High temperature during extrusion, may reduce the concentration of phytic acid (Alonso et al., 2000; Milani et al., 2022), but the greater concentration of phytate-bound P that was observed in this experiment compared with previous experiments indicates that the extrusion conditions used to process the FFSB in the present work was not effective in reducing the amount of phytate-bound P in the FFSB. It is likely that extrusion temperature needs to be higher to interrupt the ester bonds between P and inositol in phytase. Nevertheless, the concentration of the majority of minerals analyzed in the FFSB used in the current experiments was within the range of values previously reported (Cheng and Hardy, 2003; NRC, 2012; Kiarie et al., 2016; Wang et al., 2023b).

Differences among sources of FFSB in phytate-bound P were small, which indicates that growing condition does not impact the percentage of total P that is bound to phytate. Likewise, differences among sources of FFSB in other macro minerals were small and the concentration of all macro minerals was close to expected values. However, greater variations among sources in concentrations of micro minerals were observed, specifically for Fe, indicating that microminerals in FFSB may be influenced by concentrations of microminerals in the soil. This observation is in agreement with data demonstrating large variations among different geographical areas in the United States in the concentration of Se in corn and soybean meal (Mahan et al., 2014). It therefore appears that geographical areas have more impact on concentrations of micro minerals than macro minerals.

The greater DE and ME in FFSB than in corn, is primarily a result of the high concentration of fat in FFSB and indicates that incorporation of FFSB in diets for pigs will increase diet ME because fat in FFSB has a high digestibility (Kil et al., 2011; Kim et al., 2013). The observation that the ratio between ME and DE was not different among the five sources of FFSB indicates that absorbed nutrients from all five sources were metabolized with the same efficiency and with the same efficiency as in corn. Therefore, FFSB may be used in diets for weanling pigs and growing pigs where increased dietary energy usually results in increased growth performance (Li et at., 1990; Yang et at., 2023). Likewise, feeding high-fat diets to lactating sows results in greater weaning weights of pigs due to greater fat and energy in milk (Tilton et al., 1999). In contrast, FFSB in diets for finishing pigs may need to be restricted to reduce the risk of producing pigs with soft bellies, which results in inadequate bacon cutting yield and may result in enhanced rancidity (Leszczynski et al., 1992; Gatlin et al., 2002).

Total dietary fiber in the corn used in this experiment was greater and crude protein was less than previously determined (NRC, 2012), and therefore, the GE was less than reported, which resulted in reduced DE and ME in the corn used in this experiment compared with reported values (NRC, 2012). The reduced acid-hydrolyzed ether extract in the corn used in this experiment compared with most other values likely also contributed to the reduced DE and ME. The majority of GE in urine is N (Noblet et al., 1993), which is likely the reason for the increased GE in urine from pigs fed FFSB compared with pigs fed corn because crude protein in FFSB is greater than in corn.

Values for ATTD and STTD of P in FFSB calculated in this experiment were slightly greater than reported by NRC (2012) and also greater than in soybean meal (NRC, 2012). The reason for this observation may be that the high concentration of fat in FFSB reduces passage rate in the gastrointestinal tract, which provides more time for P digestion and absorption (Mateos et al., 1982; Paternostre et al., 2021). A greater STTD of P in FFSB compared with other ingredients has been reported previously (Liu et al., 2018).

Phosphorus is an essential nutrient that is required for bone development and other functions in the body (Palacios, 2006; Zhai et al., 2022). In plant feed ingredients such as FFSB, most P is bound to phytate, which is mostly indigestible by pigs because they do not synthesize adequate amounts of endogenous phytase to liberate P from phytate; therefore, P digestibility by pigs in plant ingredients is low (Liao et al., 2005). However, use of microbial phytase improves digestibility of P because phytase hydrolyzes the ester bond between P and the inositol ring in phytate within the gastrointestinal tract of pigs (Pallauf et al., 1994; Lautrou et al., 2021; Zhai et al., 2022). In agreement with this, phytase in this experiment increased P digestibility as has been reported for other ingredients (Arredondo et al., 2019; Hong and Kim, 2021; Lee et al., 2021; Luciano et al., 2022). This was also in agreement with previous data with FFSB (Kiarie et al., 2020) and with soybean meal (Rojas and Stein, 2012; Sotak-Peper et al., 2016). In accordance with expectations, supplementation of phytase to the diets resulted in improvements in STTD and retention of P regardless of the source of FFSB, and the hypothesis that phytase increases P digestibility was, therefore, confirmed. As a consequence, excretion of P in feces was reduced by 50–60 % when phytase was added to the diets. Therefore, inclusion of phytase in diets containing FFSB will result in reduced output of P, and the increased STTD of P will result in a reduced need for feed phosphates in the diets.

The observation that if no phytase was used, source 05 had greater STTD of P than the other sources indicates that differences in STTD of P exist among sources of FFSB as has been also reported for other ingredients (Maison et al., 2015; Sotak-Peper et al., 2016). However, when phytase was used, all sources of FFSB had STTD values that were not different demonstrating that phytase had greater effect on the sources of FFSB that had reduced digestibility compared with FFSB with greater digestibility, which has also been demonstrated when comparing soybean meal and fermented soybean meal (Rojas and Stein, 2012). Thus, usage of microbial phytase removes the variability in STTD of P among feed ingredients. The observation that there was no impact of microbial phytase on the digestibility of dry matter is in agreement with previous data (Nelson et al., 2022) and indicates that there likely was no impact of phytase on energy digestibility.

The limitations of the present research include that the effect of source of FFSB on protein composition or protein digestibility was not determined, but this information has been published in a separate manuscript in which the standardized ileal digestibility of amino acids in the same 5 sources of FFSB was reported (Ruiz-Arias et al., 2025). Likewise, the impact of microbial phytase on energy digestibility was not determined, but based on the observation that microbial phytase did not impact the ATTD of dry matter, it is

speculated that ATTD of GE was not impacted either. Due to the relatively low number of samples used, correlations between nutrient composition of FFSB and energy or P digestibility were not calculated.

5. Conclusion

Results demonstrated that phytate, minerals, and some macro nutrients varied slightly among the five sources of full-fat soybeans used, but only minor differences in metabolizable energy among the five sources of full-fat soybeans were observed. However, regardless of source, standardized total tract digestibility of P was greater if microbial phytase was added to the diet, and excretion of P in feces was reduced by 50–60 % when microbial phytase was added to diets containing full-fat soybeans.

Author statement

HHS conceptualized the experiment. NCRA conducted the animal part of the experiment and completed laboratory analyses. NCRA and SAL summarized and analyzed the data. NCRA wrote the first draft of the manuscript. HHS and SAL edited the final version of the manuscript. HHS supervised the project.

CRediT authorship contribution statement

Stein H.H.: Writing – review & editing, Funding acquisition, Conceptualization. **Lee S.A:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Ruiz-Arias N.C.:** Writing – original draft, Methodology.

Declaration of Competing Interest

The authors have no conflicts of interest

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