104 (2025) 104726

Contents lists available at ScienceDirect

Poultry Science

journal homepage: www.elsevier.com/locate/psj

True metabolizable energy, standardized amino acid digestibility, and digestibility of phosphorus in soybean expellers produced from conventional or high-oil varieties of soybeans fed to chickens

M. Cristobal, P.L. Utterback, H.H. Stein, C.M. Parsons *

Department of Animal Sciences, University of Illinois, Urbana 6180

ARTICLE INFO

Keywords:
Amino acid
Digestibility
Energy
Phosphorus
Soybean expellers

ABSTRACT

The objective was to test the hypothesis that nitrogen-corrected true metabolizable energy (**TME_n**), standardized amino acid (**AA**) digestibility, and apparent ileal P digestibility are not different in soybean expellers produced from high-oil soybeans (**SBE-HO**) compared with expellers produced from conventional soybeans (**SBE-CV**). The two soybean expellers contained approximately 46.3 % crude protein (DM basis). In Experiments 1 and 2, 2 precision-fed rooster assays were conducted to determine TME_n and standardized AA digestibility in SBE-CV and SBE-HO using conventional and cecectomized roosters, respectively. For each experiment, 6 replicate White Leghorn roosters per treatment were fasted for 26 h prior to crop intubation with 25 g of sample and excreta were collected for 48 h post-feeding. Data were analyzed as a one-way ANOVA for a completely randomized design. The TME_n of SBE-HO (3.261 kcal/g DM) was greater than SBE-CV (3.162 kcal/g DM). Standardized digestibility of most AA was approximately 90 %, and there were no differences between the two soybean expellers, but SBE-HO had greater ($P < 0.05$) concentration of some digestible AA compared with SBE-CV. In Experiment 3, an *ad-libitum*-fed broiler chicken assay was conducted to determine apparent ileal digestibility of P in SBE-HO and SBE-CV. Eighty commercial Ross 308 male chicks were fed a standard corn-SBM diet from 0 to 16 d of age, and experimental diets from d 17 to 21. The 2 experimental diets had a total Ca:total P ratio of 1.4:1 and TiO_2 was used as a digesta marker. There were 5 chicks per pen and 8 replicate pens per treatment and the pen was the experimental unit. On d 21, chicks were euthanized and ileal digesta were collected. Data were analyzed as in Experiments 1 and 2. Apparent ileal P digestibility for SBE-CV (46.8 %) was not different compared with SBE-HO (40.6 %). Overall, data indicated that SBE-HO had greater TME_n, similar digestibility of AA and P, but greater digestible concentrations of some AA compared with SBE-CV for broiler chickens.

Introduction

Soybean meal (**SBM**) is an important ingredient in pig and poultry production in the U. S. because of the superior protein quality relative to other protein sources (Ruiz et al., 2020). Global soybean production has been increasing as pig and poultry production has increased, but in recent years, elevated biodiesel production is also increasing the demand for soybeans due to increased demand for soybean oil (Fousekis, 2023). The most common methods to extract oil from soybeans are by using solvent extraction or extrusion-expelling. Whereas the solvent extraction method results in a more complete oil extraction, use of extrusion-expelling has become an alternative because of its low capital and operational costs (Pacheco et al., 2014). The soybean expellers **(SBE)** that are the co-product of extrusion-expelling of soybeans contain more metabolizable energy compared with solvent extracted SBM (NRC, 2012) because of the larger concentration of residual oil.

To improve soybean production efficiency, new varieties of soybeans have been developed (Liu et al., 2020), and taking advantages of new breeding techniques, improved management practices, and atmospheric carbon dioxide, it has been possible to increase the yield of soybean seeds (Koester, 2014). However, the improvement of soybean seeds, mainly through genetic modification, has often resulted in a decrease in oil and protein concentration (Tamagno et al., 2022). By modifying genes involved in biosynthesis and storage of lipids, it was possible to increase the accumulation of lipid droplets and increase carbon capture in ryegrass (Beechey-Gradwell et al., 2019). This new genetic

* Corresponding author at: Department of Animal Sciences, 284 ASL, 1207 West Gregory Dr. Urbana, IL 61801.
E-mail address: poultry@Illinois.edu (C.M. Parsons).

https://doi.org/10.1016/j.psj.2024.104726
Received 11 September 2024; Accepted 21 December 2024
Available online 23 December 2024

technology has been applied to soybeans by Zeakal Inc. (San Diego, CA, USA) to develop a new variety of soybeans that contain higher oil, without negatively affecting crude protein (**CP**) concentration, compared with conventional soybeans. There are, however, no data for the nutritional value of SBM or SBE produced from the new high-oil variety of soybeans. Therefore, the objective of this work was to compare nitrogen-corrected true metabolizable energy (**TME_n**), standardized amino acid (**AA**) digestibility, and apparent ileal **P** digestibility of SBE produced from the high-oil soybeans (**SBE-HO**) with expellers produced from conventional soybeans (**SBE-CV**) when fed to broiler chickens.

Materials and methods

The protocols for 3 experiments were reviewed and approved by the institutional Animal Care and Use Committee at the University of Illinois (protocol number 20131).

Ingredients and analyses

Two samples of conventional and high-oil soybeans (patented as PHOTOSEED) were procured from Zeakal Inc. (San Diego, CA, USA). The beans were then extruded and expelled at Insta Pro (Grimes, IA, USA) to produce SBE from the conventional and high-oil varieties of soybeans. Samples of whole conventional and whole high-oil soybeans and SBE-HO and SBE-CV were analyzed for dry matter (**DM**; method 930.15; AOAC Int., 2019), and N (method 990.03; AOAC Int., 2019) was determined on a FP628 protein analyzer (Leco Corporation, St. Joseph, MI). Crude protein was calculated as N × 6.25. The SBE-CV and SBE-HO were analyzed for amino acids on a Hitachi Amino Acid Analyzer (Model No. L8800; Hitachi High Technologies America, Inc., Pleasanton, CA) 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 cysteine were determined as methionine sulfone and cysteic acid after cold performic acid oxidation overnight before acid 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].

Samples were also analyzed for gross energy (**GE**) using bomb calorimetry (Model 6400; Parr Instruments, Moline, IL). Acid-hydrolyzed ether extract (**AEE**) was analyzed by crude fat extraction using petroleum ether (AnkomXT15, Ankom Technology, Macedon, NY, USA) following hydrolysis using 3 *N* HCl (AnkomHCl, Ankom Technology, Macedon, NY, USA). Soluble dietary fiber **(SDF)** and insoluble dietary fiber **(IDF)** were also analyzed in the 2 sources of SBE on an Ankom Total Dietary Fiber Analyzer (Ankom Technology, Macedon, NY, USA) using method 991.43 (AOAC Int., 2019). Total dietary fiber **(TDF)** was calculated as the sum of SDF and IDF. Trypsin inhibitor units (method Ba 12-75; AOCS, 2006) were determined in the 2 sources of soybean expellers and sugars including glucose, fructose, maltose, sucrose, stachyose, and raffinose were analyzed using high-performance liquid chromatography (Dionex App Notes 21 and 92). Ash was analyzed using method 942.05 (AOAC Int., 2019), and Ca and P (method 985.01 A, B and C; AOAC Int., 2019) were determined 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 acid (method 3050 B; Edgell, 2002). Phytate was analyzed as described by Ellis et al. (1977). Concentration of phytate-bound P in the 2 sources of SBE was calculated as 28.2 % of analyzed phytate (Tran and Sauvant, 2004).

Analyses for AA, sugars and oligosaccharides, Ca, P, and Ti were conducted at the Agricultural Experiment Station Chemical Laboratory (University of Missouri, Columbia, MO). Analyses for phytate and trypsin inhibitors were conducted at Eurofins Scientific, Inc. (Des Moines, IA), and all other analysis were conducted at the University of Illinois Urbana-Champaign.

Experiments 1 and 2: TME_n and standardized AA digestibility

Two experiments were conducted with Single Comb White Leghorn roosters using the precision-fed rooster assay (Sibbald, 1976; Parsons et al.,1982; Parsons, 1985). The TME_n was determined in conventional roosters in one assay and AA digestibility was determined in cecectomized roosters in a second assay. The 2 assays were conducted within 2 weeks of each other and the age and body weight of the roosters were similar in both assays. Cecectomies were performed as described by Parsons (1985). Roosters were fasted for 26 h prior to being crop intubated with 25 g of sample. Each source of SBE was fed to 6 individually caged roosters per treatment. All roosters were allowed free access to water throughout the experiment. Excreta (feces + urine) were quantitatively collected for 48 h post-feeding on trays placed underneath each cage, after which excreta were stored in a freezer prior to lyophilization. After lyophilization, dried excreta were weighed and ground. Excreta from conventional roosters were analyzed for GE and N, whereas excreta from cecectomized roosters were analyzed for AA as described for ingredients. Subsequently, TME_n and standardized digestibility of AA were calculated (Sibbald, 1976; Parsons et al., 1982). The 48 h precision-fed rooster assay was chosen for ME and AA digestibility evaluation because of the limited amount of SBE samples available, because this assay has been used extensively to evaluate feed ingredients in papers published in Poultry Science, and because it is a more rapid and less expensive assay than the broiler chicken AME and ileal AA digestibility assays which require much more ingredient sample to conduct.

Experiment 3: Apparent ileal P digestibility

This experiment was conducted using commercial broiler chickens (Ross 308 males) to determine apparent ileal P digestibility in SBE-HO and SBE-CV. Chickens were placed in heated Petersime starter batteries with raised wire floors in an environmentally controlled room, and fed a standard, nutritionally complete corn-SBM pretest diet for 17 d. Chickens had free access to water and feed, but on day 17, chicks were fasted overnight. On d 18, chicks were weighed, wingbanded, and allotted to 1 of 2 dietary treatments, ensuring consistency in average body weight between treatments in a completely randomized design. Average initial body weight at the start of the experimental period was 514 g and there were 8 replicate pens of 5 chickens for each dietary treatment, resulting in a total of 80 chicks in the experiment. Experimental diets were provided on an ad libitum basis from d 18 to 21. Based on analyzed Ca and P levels in SBE-CV and SBE-HO, diets containing SBE-CV or SBE-HO were formulated to contain 0.44 and 0.48 % Ca, and 0.32 and 0.35 % total P with test ingredients serving as the sole source of P in each diet. Limestone was added to provide a 1.4:1 total Ca to total P ratio (Table 1) as recommended by Rodehutscord (2013). Titanium dioxide was added at 0.5 % to each diet as an indigestible marker. Chickens were euthanized on the last day of the experimental period (d 21) via asphyxiation with carbon dioxide gas. Ileal digesta (from Meckel's diverticulum to 1.5 cm from ileal-cecal junction) were collected. Diets and ileal digesta were analyzed for Ca, P, and Ti as described for ingredients. Calculation of apparent ileal P digestibility followed the procedure by Mutucumarana et al. (2014).

Statistical analysis

Data from all 3 experiments were analyzed by ANOVA using the GLM procedure in SAS (SAS Institute. INC., 2010). Differences between treatments were considered to be significant at $P < 0.05$. For Exp. 1 and 2, the individual rooster was the experimental unit, whereas in Exp. 3, each pen containing 5 chickens was the experimental unit. Outliers were

Table 1
Ingredient composition of experimental diets in Experiment 3 for determination of apparent ileal P digestibility in soybean expellers produced from conventional soybeans (SBE-CV) or from high-oil soybeans (SBE-HO)

Dietary treatments		
Ingredient, %	SBE-CV	SBE-HO
Dextrose	33.92	33.81
SBE-CV	45.00	-
SBE-HO	-	45.00
Soybean oil	4.00	4.00
Cornstarch	10.00	10.00
Limestone	0.73	0.84
Solka floc[1]	5.00	5.00
Salt	0.40	0.40
Vitamin mix[2]	0.20	0.20
Mineral mix[3]	0.15	0.15
Titanium dioxide	0.50	0.50
Choline Cl 60 %	0.10	0.10
Analyzed, %:		
Ca	0.54	0.59
P	0.32	0.29

[1] Powdered cellulose; Fiber Sales and Development Corp., Urbana, OH.
[2] Provided per kilogram of diet: retinyl acetate, 4,400 IU; cholecalciferol, 25 μg; DL-α-tocopheryl acetate, 11 IU; vitamin B12, 0.01 mg; riboflavin 4.41 mg; D-pantothenic acid, 10 mg; niacin, 22 mg; and menadione sodium bisulfite complex, 2.33 mg.
[3] Provided per kilogram of diet: manganese, 75 mg from $MnSO_4 \cdot H_2O$; iron, 75 mg from $FeSO_4 \cdot H_2O$; zinc, 75 mg from ZnO; copper, 5 mg from $CuSO_4 \cdot 5H_2O$; iodine, 75 mg from ethylene diamine dihydroiodide; selenium, 0.1 mg from Na_2SeO_3.

identified as values that deviated from the 1st and 3rd quartile by more than 3 times the interquartile range within treatment. However, no outliers were found.

Results and discussion

Chemical analysis

On a DM basis, the whole conventional soybeans were analyzed to contain 23.1 % fat and 36.5 % CP, and the whole high-oil soybeans were analyzed to contain 25.7 % fat and 37.7 % CP. Nutrient compositions of SBE-CV and SBE-HO were generally similar (Table 2). The CP in both sources were approximately 44 %, which is in agreement with previous values (NRC, 2012; Espinosa et al., 2021). The CP content of SBE-HO was slightly higher than SBE-CV. The AEE in SBE-CV and SBE-HO also agree with previous values for SBE (Zhang et al., 1993; Karr-Lilienthal et al., 2006; Powell et al., 2011; Pacheco et al., 2014), and the SBE-HO contained slightly more AEE than SBE-CV. The SBE-HO contained slightly more P, non-phytate P, and less TDF compared with SBE-CV. Values for total Ca and total P in SBE-CV and SBE-HO agree with reported values for SBE (Karr-Lilienthal et al., 2006; Pacheco et al., 2014). Gross energy was greater in SBE-HO compared with SBE-CV, which is likely due to the greater AEE in SBE-HO. Concentrations of most indispensable AA were slightly greater in SBE-HO compared with SBE-CV (Table 4), which is likely because of greater CP in SBE-HO. Concentrations of indispensable AA in general for both SBE ingredients were close to published values for SBE (NRC, 2012; Espinosa et al., 2021).

TME_n

The TME_n for SBE-HO (3,261 kcal/kg DM) was greater ($P < 0.05$) than for SBE-CV (3,162 kcal/kg DM), and TME_n in both SBE-CV and SBE-HO are in agreement with the TMEn (3,239 kcal/kg DM) reported for SBE by Zhang et al. (1993). However, values from SBE-CV and SBE-HO were greater than the value of 2,761 kcal/kg DM for dehulled solvent extracted SBM (NRC, 1994). This is likely primarily due to greater AEE in both SBE sources compared with solvent extracted SBM. The fact that SBE-HO had greater TME_n than SBE-CV is also likely partially due to the greater content of CP and slightly higher AEE. The lower TDF in SBE-HO compared with SBE-CV likely also contributed to TME_n differences as greater TDF can reduce TME_n (Parsons et al., 2023) or AME_n in ingredients (Sacranie et al., 2012). The higher AEE and CP of the SBE-HO may be due to the higher levels of AEE and CP in the original soybeans or due to variation in processing of the two SBE or a combination of the two. Both types of soybeans were processed in the same equipment using the same processing conditions in attempt to minimize any differences due to processing method. The observation that the difference in CP between the 2 SBE was almost identical to the difference in CP between the 2 original soybeans suggests that extrusion and expelling of the high oil soybeans and may yield SBE that is higher in fat, CP and TMEn than SBE produced from conventional soybeans.

Table 2
Analyzed composition and nitrogen-corrected true metabolizable energy (TME_n) of soybean expellers produced from conventional soybeans (SBE-CV) or from high-oil soybeans (SBE-HO), as-fed basis

	SBE-CV	SBE-HO
Dry matter	94.56	94.63
Acid-hydrolyzed ether extract	6.57	7.60
Crude protein	43.15	44.56
Lys:CP	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
P	0.70	0.77
Phytate	1.60	1.71
Phytate-P[1]	0.45	0.48
Nonphytate-P[2]	0.25	0.28
Nonphytate-P, % of total P	35.71	36.36
Trypsin inhibitor (unit/mg)	5.30	6.00
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
Gross energy (kcal/kg)	4,760	4,820
TME_n[3] (kcal/kg DM)	3,162	3,261
SEM of TME_n	28	31

[1] Phytate-P was calculated by multiplying the analyzed phytate by 0.282 (Tran and Sauvant, 2004).
[2] Nonphytate-P was calculated as the difference between total P and phytate-P.
[3] TME_n values were significantly different ($P < 0.05$). TME_n values are means from 6 individually-caged conventional roosters (Experiment 1).

Standardized AA digestibility

Values for standardized digestibility of AA were not different ($P > 0.05$) between SBE-HO and SBE-CV (Table 3). Standardized digestibility of AA obtained for both SBE-CV and SBE-HO were in close agreement with values for SBE obtained using cecectomized roosters (Zhang et al., 1993; Powell et al., 2011). Trypsin inhibitor content is one of the main factors that negatively affects digestibility of CP and AA in SBM (Han et al., 1991). Another factor that can impact digestibility of CP is TDF (Gutierrez et al., 2013). Even though SBE-HO had numerically greater content of trypsin inhibitors compared with SBE-CV, this difference was too small to cause a difference in standardized digestibility of AA. When comparing concentrations of digestible AA between SBE-HO and SBE-CV (Table 4), concentrations in SBE-HO were greater ($P < 0.05$) for Asp, Glu, Pro, Val, Phe, Lys, Arg, and Trp due to higher concentration of these AA in the SBE-HO.

Table 3
Standardized amino acid digestibility values of soybean expellers produced from conventional soybeans (SBE-CV) or from high-oil soybeans (SBE-HO), Experiment 2[1]

Amino acid	SBE-CV	SBE-HO	Pooled SEM
Asp	89.3	89.6	0.69
Thr	86.5	85.4	1.30
Ser	88.9	87.3	1.02
Glu	92.3	92.0	0.90
Pro	88.1	87.4	1.05
Gly	65.3	66.4	8.18
Ala	85.8	85.4	1.18
Cys	80.4	80.4	1.69
Val	87.7	87.6	0.82
Met	93.2	92.2	1.33
Ile	91.2	90.7	0.59
Leu	90.6	89.7	0.78
Tyr	88.7	86.0	1.03
Phe	91.6	91.0	0.66
Lys	86.2	86.1	0.91
His	91.1	88.6	1.46
Arg	90.3	88.8	0.87
Trp	95.5	95.3	1.04

[1]Values are means of 6 individually-caged cecectomized roosters. There were no significant differences ($P > 0.05$) between the 2 soybean expellers for digestibility of any amino acids.

Table 4
Total and digestible concentrations of amino acids in soybean expellers produced from conventional soybeans (SBE-CV) or from high-oil soybeans (SBE-HO), as-fed basis, Experiment 2[1]

	Total amino acid concentration		Concentrations of digestible amino acids[2]		
Amino acid	SBE-CV	SBE-HO	SBE-CV	SBE-HO	Pooled SEM[3]
Asp	4.83	5.10	4.31	4.57	0.03
Thr	1.71	1.78	1.48	1.52	0.02
Ser	1.92	2.00	1.71	1.75	0.02
Glu	7.65	8.12	7.06	7.47	0.07
Pro	2.05	2.16	1.81	1.89	0.02
Gly	1.87	2.00	1.22	1.33	0.15
Ala	1.87	1.96	1.60	1.67	0.02
Cys	0.70	0.71	0.56	0.57	0.01
Val	1.97	2.06	1.73	1.80	0.02
Met	0.62	0.65	0.58	0.60	0.01
Ile	1.93	1.97	1.76	1.79	0.01
Leu	3.22	3.31	2.92	2.97	0.03
Tyr	1.58	1.67	1.40	1.44	0.02
Phe	2.12	2.19	1.94	2.00	0.01
Lys	2.70	2.86	2.33	2.46	0.03
His	1.09	1.15	0.99	1.02	0.02
Arg	2.94	3.22	2.66	2.86	0.03
Trp	0.57	0.61	0.54	0.58	0.01

[1]Values are means of 6 individually-caged cecectomized roosters. Digestible concentrations of Asp, Glu, Pro, Val, Phe, Lys, Arg, and Trp were greater ($P < 0.05$) in SBE-HO compared with SBE-CV.
[2] Digestible concentration = (total amino acid concentration × standardized digestibility)/100.
[3] SEM for digestible concentrations.

Apparent ileal P digestibility

Feed intake of chicks fed the SBE-HO diet was less ($P < 0.05$) than that of chicks fed the SBE-CV diet (Table 5). Apparent ileal P digestibility for SBE-HO was 46.8 %, which was not different ($P > 0.05$) from 40.6 % for SBE-CV (Table 5). Apparent ileal P digestibility values for both SBE-CV and SBE-HO were generally below many values previously reported for P digestibliity for SBM and corn-SBM diets. For example, studies by Nwokolo et al. (1976), Dilger and Adeloa (2006), and Mutucumarana et al. (2014; 2015) reported values of 70 % or greater for ileal P digestibility or P retention for SBM. In addition, Munoz et al. (2020), using precision-fed chickens, obtained a value 64 % for P digestibility or retention for SBM. Reducing total Ca to total P ratio from 0.80 to 0.56 increased apparent P retention from 33 to 54 % in cornstarch-SBM diets fed to 15-d old broiler chicks, indicating that greater total Ca to total P reduces P digestibility or retention (Dilger and Adeola, 2006). Additional studies with poultry have shown that increased dietary Ca level and Ca:P ratio decrease P digestibility and/or retention (Qian et al., 1996; Liu et al., 2013; Parsons and Rochell, 2024). In growing pigs, an increased Ca:P ratio also reduced the digestibility of P (Stein et al., 2011). Thus, a large part of the reason for variation in P digestibility and retention among studies may be associated with variation in dietary Ca levels and dietary Ca:P ratio..

Table 5
Apparent ileal P digestibility of soybean expellers produced from conventional soybeans (SBE-CV) or high-oil soybeans (SBE-HO) and fed to broiler chicks, Experiment 3[1]

Soybean expellers type	Weight gain (g/chicken)	Feed intake (g/chicken)	Gain:feed (g/kg)	Ileal P digestibility (%)
SBE-CV	187	247	755	46.8
SBE-HO	177	236	750	40.6
Pooled SEM	3.1	2.6	8.4	3.01
P-value	0.053	0.012	0.657	0.169

[1]Values are means of 8 pens of 5 chickens from 18 to 21 days of age for weight gain, feed intake, and gain: feed ratio. Ileal P digestibility values are at 21 days of age.

In conclusion, SBE-HO contained more total AA and TME_n, but less TDF compared with SBE-CV. There were no differences in AA digestibility between SBE-HO and SBE-CV, but because SBE-HO contains higher total AA concentration, the concentration of digestible AA was greater in SBE-HO. Apparent ileal digestibility of P was not different between SBE-HO and SBE-CV.

Disclosures

The authors declare no conflicts of interest.

Declaration of interests

There is no conflict of interest on manuscript

Acknowledgements

This work was supported by ZeaKal Inc., San Diego, CA and the United Soybean Board (St. Louis, MO).

References

AOCS, 2006. Official Methods and recommended practices, 5th ed. AOCS, Urbana, IL. 21st century.
AOAC Int, 2019. Official methods of analysis of AOAC Int, 21st ed. AOAC Int, Rockville, MD, USA.
Beechey-Gradwell, Z., Cooney, L., Winichayakul, S., Andrews, M., Hea, S.Y., Crowther, T., Roberts, N., 2019. Storing carbon in leaf lipid sinks enhances perennial ryegrass carbon capture especially under high N and elevated CO_2. J. Exp. Bot. 71, 2351–2361.
Dilger, R.N., Adeola, O., 2006. Estimation of true phosphorus digestibility and endogenous phosphorus loss in growing chicks fed conventional and low-phytate soybean meals. Poult. Sci. 85, 661–668.
Edgell, K., 2002. USEPA method study 37-sw-846 method 3050, acid digestion of sediments, sludges and soils by aa-direct aspiration. U.S. Environmental Protection Agency, Washington, D.C.
Ellis, R., Morris, E.R., Philpot, C., 1977. Quantitative determination of phytate in the presence of high inorganic phosphate. Anal. Biochem. 77, 536–539.
Espinosa, C.D., Oliveira, M.S.F., Limbach, J.R., Fanelli, N.S., Wiltafsky-Martin, M.K., Stein, H.H., 2021. Long-term steam conditioning is needed to maximize the nutritional value of expander-processed soybean expellers. Can. J. Anim. Sci. 101, 704–714.
Fousekis, P., 2023. Future prices linkages in the US soybean complex. Appl. Finance lett. 12, 119–130.

Gutierrez, N.A., Kerr, B.J., Patience, J.F., 2013. Effect of insoluble-low fermentable fiber from corn-ethanol distillation origin on energy, fiber, and amino acid digestibility, hindgut degradability of fiber, and growth performance of pigs. J. Anim. Sci. 91, 5314–5325.
Han, Y., Parsons, C.M., Hymowitz, T., 1991. Nutritional evaluation of soybeans varying in trypsin inhibitor content. Poult. Sci. 70, 896–906.
Karr-Lilienthal, L.K., Bauer, L.L., Utterback, P.L., Zinn, K.E., Frazier, R.L., Parsons, C.M., Fahey, G.C., 2006. Chemical composition and nutritional quality of soybean meals prepared by extruder/expellers processing for use in poultry diets. J. Agric. Food Chem. 54, 8108–8114.
Koester, R.P., 2014. Physiological mechanisms of yield improvement in historical U.S. soybean germplasm. Ph.D. Diss. Univ. Illinois, Urbana, IL.
Liu, J.B., Chen, D.W., Adeola, O., 2013. Phosphorus digestibility response of broiler chickens to dietary calcium –to-phosphorus ratios. Poult. Sci. 92, 1572–1578.
Liu, S., Zhang, M., Feng, F., Tian, Z., 2020. Toward a "Green revolution" for soybean. Mol. Plant. 13, 688–697.
Munoz, J.A., Utterback, P.L., Parsons, C.M., 2020. Phosphorus digestibility and bioavailability in soybean meal, spray-dried plasma protein, and meat and bone meal determined using different methods. Poult. Sci. 99, 4998–5006.
Mutucumarana, R.K., Ravindran, V., Ravindran, G., Cowieson, A.J., 2014. Measurement of true ileal digestibility of phosphorus in some feed ingredients for broiler chickens. J. Anim. Sci. 92, 5520–5529.
Mutucumarana, K., Ravindran, V., Ravindran, G., Cowieson, A.J., 2015. Measurement of true ileal phosphorus digestibility in maize and soybean meal for broiler chickens: comparison of two methodologies. Anim. Feed Sci. Technol. 206, 76–86.
NRC, 1994. Nutrient Requirements of Poultry. 9th rev. Natl. Acad. Press, Washington, DC.
NRC, 2012. Nutrient Requirements of Swine. 11th rev. Natl. Acad. Press, Washington, DC.
Nwokolo, E.N., Bragg, D.B., Kitts, W.D., 1976. A method for estimating the mineral availability in feedstuffs. Poult. Sci. 55, 2217–2221.
Pacheco, W.J., Stark, C.R., Ferket, P.R., Brake, J., 2014. Effects of trypsin inhibitor and particle size of expellers-extracted soybean meal on broiler live performance and weight of gizzard and pancreas. Poult. Sci. 93, 2245–2252.
Parsons, B.W., Rochell, S.J., 2024. Determination of phytic acid disappearance, ileal P digestibility at different Ca levels, and relative P bioavailability in soybean meal, canola meal, distillers dried grains with solubles, corn fermented protein, and wheat middlings. Poult. Sci. 103, 104037.
Parsons, C.M., 1985. Influence of caecectomy on digestibility of amino acids by roosters fed distillers' dried grains with solubles. J. Agric. Sci. 104, 469–472.
Parsons, C.M., Potter, L.M., Bliss, B.A., 1982. True metabolizable energy corrected to nitrogen equilibrium. Poult. Sci. 61, 2241–2246.
Parsons, B.W., Utterback, P.L., Parsons, C.M., Emmert, J.L., 2023. Standardized amino acid digestibility and true metabolizable energy for several increased protein ethanol co-products produced using back-end fractionation systems. Poult. Sci. 102, 102329.
Powell, S., Naranjo, V.D., Lauzon, D., Bidner, T.D., Southern, L.L., Parsons, C.M., 2011. Evaluation of an expellers-extruded soybean meal for broilers. J. Appl. Poult. Res. 20, 353–360.
Qian, H., Kornegay, E.T., Denbow, D.M., 1996. Utilization of phytate phosphorus and calcium as influenced by microbial phytase, cholecalciferol, and the calcium: total phosphorus ratio in broiler diets. Poult. Sci. 76, 37–46.
Rodehutscord, M., 2013. Determination of phosphorus availability in poultry. Working group No. 2 of the European Federation of Branches of WPSA. World's Poult. Sci. J. 69, 687. –69.
Ruiz, N., Parsons, C.M., Stein, H.H., Coon, C.N., Van Eys, J.E., Miles, R.D., 2020. A review: 100 years of soybean meal, a historical look at the soybean and its use for animal feed. Feedstuffs online. January 24, 2020. Accessed Nov. 2023. https://nutrition.ansci.illinois.edu/node/1566.
Sacranie, A., Svihus, B., Denstadli, V., Moen, B., Iji, P.A., Choct, M., 2012. The effect of insoluble fiber and intermittent feeding on gizzard development, gut motility, and performance of broiler chickens. Poult. Sci. 91, 693–700.
Stein, H.H., Adeola, O., Cromwell, G.L., Kim, S.W., Mahan, D.C., Miller, P.S., 2011. Concentration of dietary calcium supplied by calcium carbonate does not affect the apparent total tract digestibility of calcium, but decreases digestibility of phosphorus by growing pigs. J. Anim. Sci. 89, 2139–2144.
Sibbald, I.R., 1976. A bioassay for true metabolizable energy in feedingstuffs. Poult. Sci. 55, 303–308.
Tamagno, S., Sadras, V.O., Aznar-Moreno, J.A., Durrett, T.P., Ciampitti, I.A., 2022. Selection for yield shifted the proportion of oil and protein in favor of low-energy seed fractions in soybean. F. Crop Res. 279, 108446.
Sauvant, D., Tran, G., 2004. Chemical data and nutritional value. In: Tran, G., Sauvant, D., Perez, J.-M. (Eds.), Tables of composition and nutritional value of feed materials: pigs, poultry, cattle, sheep, goats, rabbits, horses and fish. Wageningen Academic Publishers, Wageningen, the Netherlands, pp. 17–24.
Zhang, Y., Parsons, C.M., Weingartner, K.E., Wijeratne, W.B., 1993. Effects of extrusion and expelling on the nutritional quality of conventional and Kunitz trypsin inhibitor-free soybeans. Poult. Sci. 72, 2299–2308.