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Original Research Article

Nutritional values of soybean meal from different sources in multiparous sows

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ABSTRACT

This study determined the available energy content, apparent total tract digestibility (ATTD) of nutrients, and ileal amino acid (AA) digestibility of soybean meal (SBM) from different sources in non-gestating, non-lactating sows. In Exp. 1, 24 multiparous Landrace × Yorkshire (LY) sows (parity 3 to 5) were allotted to a replicated 12 × 3 Youden square design consisting of 12 diets and 3 periods. The 12 diets included 11 test diets containing SBM from different sources and a corn-based diet. Each period included a 5-d adaptation and a 5-d total fecal and urine collection. In Exp. 2, 8 multiparous LY sows (parity 3 to 5) were allotted to a replicated 4 × 3 Youden square design with 4 diets and 3 periods. The 4 diets included a nitrogen-free diet and 3 SBM diets (3 representative SBM samples were selected from Exp. 1). Our results showed that the coefficient of variation of ether extract, crude fiber, neutral detergent fiber, and acid detergent fiber levels in 11 SBM samples were >20%. There were no differences in digestible energy (DE), metabolizable energy (ME), and the ATTD of gross energy, nitrogen, and neutral detergent fiber values between different SBM samples ($P > 0.05$). Additionally, no differences in AA digestibility were identified among the 3 representative SBM samples ($P > 0.05$). In conclusion, there were no differences in DE, ME, and AA digestibility between different SBM samples fed to multiparous non-gestating sows. When formulating diets for sows, it is important to consider the differences in the nutritional value of SBM at different physiological stages.

1. Introduction

Soybean meal (SBM) is an excellent source of amino acids (AA) in swine diets (Qin et al., 2016; Lopez et al., 2020). The shortage of protein ingredients and relatively high SBM prices highlight the urgent need for an accurate understanding of the nutritional value of SBM in pig diets. Soybean is the raw material for SBM and is one of the world's most productive crops, with Brazil, the USA, Argentina, and China among the top soybean producers (FAO, 2021). It is reported that the growing environment and quality of soybeans can affect the nutritional value of SBM (Grieshop et al., 2003; García-Rebollar et al., 2016). When fed to piglets and growing pigs, the standardized ileal digestibility (SID) for AA in different SBM was different (Goerke et al., 2012; Lagos and Stein, 2017). Similarly, when fed to growing pigs, digestible energy (DE) and metabolizable energy (ME) contents in different SBM were different (Lopez et al., 2020).

Sows have important roles in pig production. However, a lack of specific nutritional value parameters for SBM at different physiological sow stages limits its efficient use in diets. When formulating sow diets, formulators often refer to SBM digestibility data from growing pigs, which may be inaccurate (Lowell et al., 2015; Święch, 2017). It is reported that the SID for AA in SBM is different when fed

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to pigs of different weights (Urbaityte et al., 2009). The SID values for all AA (except Trp and Asp) in SBM for gestating sows were significantly higher than those values for growing pigs (Stein et al., 2001). The apparent total tract digestibility (ATTD) values of crude protein (CP) and gross energy (GE) in pregnant sows were higher than that of growing pigs (Lowell et al., 2015). Additionally, energy utilization in pregnant sows may be higher than that of non-pregnant sows (Zhuo et al., 2023a). Consequently, it is crucial to assess the nutritional value of SBM in sows at different physiological stages for the improved formulation of low-cost diets. Our previous studies reported that ME and SID values for some AA (Lys, Val, Ala, Asp, and Tyr) in SBM were different when fed to mid-gestating and late-gestating sows (Wang et al., 2022, 2023a). To our knowledge, the nutritional values of SBM from different origins in multiparous non-gestating sows have not been reported. Therefore, we evaluated the nutritional values of SBM from different origins in multiparous non-gestating sows. The information presented in this study will improve data reliability when formulating sow diets.

2. Materials and methods

2.1. Animal ethics statement

The Animal Care and Use Committee of Sichuan Agricultural University (SICAU20210038, Ya'an, China) approved animal experiment protocols.

2.2. Experimental design and sample collection

Before the study commencement, 11 representative solvent-extracted SBM samples from major SBM-producing regions in China were gathered (Table 1). The chemical composition of all SBM samples was analyzed (Table 2). The diets were prepared as mash, and all ingredients were ground through a 2.5-mm screen using a hammer mill. Feed ingredients and finished feeds were collected and immediately sent to the laboratory for chemical composition analysis. During feed distribution, the DM content of each diet was measured to accurately calculate the nutrient intake of the sows.

Exp. 1. Twenty-four non-pregnant, non-lactating Landrace × Yorkshire (LY) sows (225.8 ± 11.1 kg, parity 3–5) were allotted to a repeated 12 × 3 Youden square design, consisting of 12 diets and 3 periods. The 12 diets included a corn-based diet and 11 SBM diets (Table 3). The chemical composition of the diets is shown in Table 4. Each period lasted for 12 days, including 5 days for adaptation and 5 days for urine and feces collection. Each sow was fed 5 kg/d (simulated feed intake as for commercial pig farms) during the trial. Sows were individually placed in metabolic cages (length 2.1 m × height 1.2 m × width 1.0 m). Sows were fed the same amount of feed at 08:00 and 15:00 and had free access to water. The room temperature was controlled at 20 ± 2 °C.

On the morning of the 6th and 11th day of each period, 2% ferric oxide was added to diets as a color marker. Feces were collected using the marker-to-marker approach (Adeola, 2001). From 09:00 on day 6 to 09:00 on day 11, urine was collected into buckets (containing 50 mL 6 mol/L HCl) under metabolic cages. This method avoided urine and feces contamination based on previous observations (Yang et al., 2021). Daily collected urine volumes and feces weights were recorded, after which samples were immediately placed at −20 °C. Feed refusals and spillages were collected twice daily during the collection period, then dried and weighed. After the animal trial, urine and feces samples were thawed and thoroughly mixed. Finally, feces and urine subsamples were processed using a previously published method (Wang et al., 2021).

Exp. 2. The apparent ileal digestibility (AID) and SID values of AA in 3 representative SBM samples fed to multiparous sows were determined. We fitted 8 non-gestating, non-lactating LY sows (235.1 ± 8.6 kg, parity 3–5) with a T-cannula (Stein et al., 1998). Sows were then assigned to a replicated 4 × 3 Youden square design consisting of 4 diets and 3 periods. The 4 diets included 3 SBM diets (SBM 6, 8, and 11 as the sole source of AA) and an N-free diet (Table 3). The N-free diet was used to measure basal ileal endogenous AA and CP losses (Adeola et al., 2016). All diets contained 0.3% chromium (Cr) trioxide as an indigestible marker. The chemical composition of diets is shown in Table 5. The daily feed intake for each sow was 3 kg. The metabolic cages, room temperature and feeding method were the same as those in Exp. 1.

Each period consisted of 5 days of adaptation and 2 days of digesta collection. Ileal digesta samples were collected from 08:00 to 20:00. A plastic bag was attached to the open cannula using an

Table 1
The origins of soybean meals.

No.	Source of soybean	Plants[1]	Location of plants in China	Type of meal
1	Brazil	A1	Sichuan, Deyang	Hulled
2	Brazil	B	Guangxi, Fangchenggang	Hulled
3	Argentina	C1	Sichuan, Meishan	Hulled
4	Brazil	A2	Sichuan, Deyang	Dehulled
5	Brazil	D	Guangxi, Qinzhou	Hulled
6	Brazil	E1	Guangxi, Beihai	Hulled
7	Brazil	E2	Guangxi, Beihai	Dehulled
8	USA	F1	Guangxi, Fangchenggang	Dehulled
9	USA	F2	Guangxi, Fangchenggang	Hulled
10	China	G1	Heilongjiang, Harbin	Hulled
11	China	G2	Heilongjiang, Harbin	Hulled

[1] The same capital letter indicates beans were processed in the same plant, and different numbers indicate different soybean varieties.

Table 2
Chemical composition (% of dry matter, unless otherwise indicated) of the different soybean meals ($n = 11$).[1]

Item	Mean	Maximum	Minimum	CV
Dry matter	88.0	89.2	87.1	0.7
Gross energy, MJ/kg	19.5	19.6	19.3	0.5
Crude protein	51.1	53.6	49.6	3.0
Ether extract	1.1	1.6	0.9	27.0
Crude fiber	6.0	7.8	4.5	22.9
Neutral detergent fiber	12.6	16.4	9.5	20.0
Acid detergent fiber	7.3	10.3	4.8	26.5
Ash	6.6	7.1	6.0	4.6
Indispensable amino acids				
Arg	3.56	3.87	3.32	4.1
His	1.32	1.43	1.24	4.1
Ile	2.15	2.29	1.94	5.7
Leu	3.72	4.06	3.40	5.5
Lys	3.14	3.43	2.93	4.1
Met	0.83	0.93	0.76	6.5
Phe	2.49	2.71	2.23	6.3
Thr	1.98	2.19	1.80	5.5
Trp	0.64	0.71	0.52	9.4
Val	2.24	2.39	2.03	5.2
Dispensable amino acids				
Ala	2.15	2.35	1.99	5.2
Asp	5.57	6.12	5.11	5.6
Cys	1.01	1.13	0.93	6.5
Glu	9.26	9.97	8.54	5.0
Gly	2.06	2.26	1.87	5.7
Pro	2.49	2.69	2.25	6.0
Ser	2.51	2.77	2.32	5.2
Tyr	1.84	1.95	1.69	5.5

CV = coefficient of variation.
[1] The data in the table are the mean value, range and coefficient of variation of 11 SBM from different sources.

Table 3
Composition of diets used in Exps. 1 and 2 (as-fed basis, %).

Item	Exp. 1		Exp. 2		
	Basal diet	Test diet	N-free diet	SBM-hulled diet	SBM-dehulled diet
Ingredients					
Corn	96.23	70.73	–	–	–
Soybean meal	0.00	25.50	–	36.80	34.40
Corn starch	–	–	69.66	57.30	59.70
Soybean oil	–	–	2.00	–	–
Sucrose	–	–	10.00	–	–
Dextrose	–	–	10.00	–	–
Cellulose[1]	–	–	4.00	2.00	2.00
Dicalcium phosphate	1.88	1.88	2.20	1.85	1.85
Limestone	0.74	0.74	0.69	0.60	0.60
Choline chloride (50%)	0.25	0.25	0.25	0.25	0.25
NaCl	0.40	0.40	0.40	0.40	0.40
Chromic oxide	–	–	0.30	0.30	0.30
Vitamin-mineral premix[2]	0.50	0.50	0.50	0.50	0.50
Total	100.00	100.00	100.00	100.00	100.00

[1] Made by Chemical Reagents Company (Beijing, China).
[2] Premix provided per kg of complete diet: VA 6000; VD_3 2000 IU; VE 80 IU; VK 3.8 mg; VB_1 2.0 mg; riboflavin 6.0 mg; VB_6 4.0 mg; VB_{12} 0.02 mg; niacin 26.0 mg; pantothenic acid 18.0 mg; folic acid 3.2 mg; biotin 0.4 mg; Fe 100 mg; Cu 20 mg; Zn 100 mg; Mn 25 mg; I 0.4 mg; Se 0.30 mg.

Table 4
Chemical composition of experimental diets used in Exp. 1 (% of dry matter, unless otherwise indicated).

Item	Basal diet	SBM diets[1]		
		Mean	Range	CV
Dry matter	86.9	87.7	87.1–88.4	0.5
Crude protein	9.1	19.2	18.3–20.1	3.1
Ether extract	2.2	1.6	1.1–2.0	14.7
Ash	4.0	5.3	5.0–5.6	3.5
Neutral detergent fiber	10.3	10.7	9.0–12.8	11.8
Gross energy, MJ/kg	17.6	18.0	17.9–18.1	0.5

[1] The data are the mean, range and coefficient of variation (CV) for 11 different SBM diets.

Table 5
Chemical composition of experimental diets used in Exp. 2 (% of dry matter).

Item	Soybean meal diet[1]			N-free diet
	6-BR	8-USA	11-CN	
Dry matter	87.7	87.7	87.8	90.2
Crude protein	18.6	17.9	18.3	0.1
Indispensable amino acids				
Arg	1.22	1.13	1.23	0.01
His	0.47	0.46	0.44	0.00
Ile	0.81	0.75	0.73	0.03
Leu	1.37	1.28	1.26	0.03
Lys	1.08	1.02	1.06	0.02
Met	0.29	0.25	0.27	0.01
Phe	0.89	0.84	0.84	0.03
Thr	0.71	0.67	0.66	0.01
Trp	0.21	0.18	0.20	0.00
Val	0.81	0.79	0.76	0.04
Dispensable amino acids				
Ala	0.79	0.79	0.75	0.04
Asp	1.98	1.87	1.88	0.02
Cys	0.36	0.34	0.34	0.00
Glu	3.37	3.16	3.17	0.04
Gly	0.74	0.71	0.68	0.01
Pro	1.00	0.91	0.84	0.04
Ser	0.91	0.86	0.85	0.01
Tyr	0.64	0.59	0.63	0.01

[1] Soybean sources are Brazil (sample 6), USA (sample 8), and China (sample 11), respectively.

elastic band to collect ileal digesta. The plastic bag was replaced every 20 min or when the bag was half full, after which it was immediately frozen at −20 °C. After animal testing, ileal chyme from sows at each period was thawed for mixing, and subsamples were taken. Approximately 600 g digesta subsamples were freeze-dried and ground through a 1-mm screen prior to analysis.

2.3. Chemical analysis

Dry matter (DM; method 930.15), ether extract (EE; method 920.39), ash (method 942.05), and AA (method 982.30) contents in samples were analyzed (AOAC, 2007). The content of GE in all samples was analyzed using an adiabatic oxygen bomb calorimeter (Parr Instruments Co., Moline, IL, USA). Nitrogen (N) content in samples was determined using the Kjeldahl method (method 990.03; AOAC, 2007). The content of CP was determined as N × 6.25. Crude fiber (CF), neutral detergent fiber (NDF), and acid detergent fiber (ADF) levels were analyzed using a fiber analyzer (Ankom Technology, Macedon, NY, USA; Van Soest et al., 1991). The Cr (method 990.08) contents in diets and digesta were analyzed according to AOAC (2007).

2.4. Calculations

In Exp. 1, the ATTD of DM, GE, N, NDF, and available energy values were calculated according to Kong and Adeola (2014) as follows:

$$D_{ti} = D_{bd} + (D_{td} - D_{bd})/P_{ti},$$

where D_{ti}, D_{bd} and D_{td} are the digestibility coefficients (%) of nutrient in the test ingredient, basal diet, and test diet, respectively, and P_{ti} is the fraction of nutrient in the test diet provided by the test ingredient.

$$\text{DE or ME} = D_{ti} \times GE_{ti},$$

where D_{ti} is the energy digestibility or metabolizability of the test ingredient, and GE_{ti} is the GE of the test ingredient.

In Exp. 2, basal ileal endogenous losses (BEL) of CP and AA in sows and AID and SID values for CP and AA in SBM were calculated according to Stein (2007). All values were calculated on a DM basis. The calculating equations were as follows:

$$\text{AID (\%)} = [1 - (N_{\text{digesta}}/N_{\text{diet}}) \times (Cr_{\text{diet}}/Cr_{\text{digesta}})] \times 100;$$

$$\text{BEL of AA} = AA_{\text{digesta}} \times (Cr_{\text{diet}}/Cr_{\text{digesta}});$$

Table 6
The apparent total tract digestibility (ATTD) of gross energy (GE), metabolizability of GE, and nitrogen balance in experimental diets for sows in Exp. 1 (on a dry matter basis).

Item	Corn diet[1]	SBM diets (n = 11)[2]			P-value[3]	P-value[4]
		Mean	Range	RSD		
DMI, kg/d	4.0	4.2	3.9–4.3	3.35	0.609	0.447
ATTD of GE, %	91.0	90.3	89.9–91.0	0.35	0.539	0.123
Metabolizability of GE, %	89.3[a]	88.1[b]	87.7–89.0	0.41	0.394	<0.001
ME:DE, %	98.0	97.6	97.2–97.8	0.23	0.607	0.204
N balance, g/d						
N intake	59.0[b]	128.9[a]	119.5–137.3	3.58	0.566	<0.001
Feces N	7.9[b]	14.7[a]	13.2–16.1	5.98	0.246	<0.001
Urine N	24.5[b]	55.0[a]	49.8–59.3	5.70	0.915	<0.001
Retained N[5]	26.6[b]	59.2[a]	52.1–68.8	9.18	0.365	<0.001
N net utilization[6], %	44.5	45.8	42.4–50.3	6.73	0.589	0.853

DMI = dry matter intake; ME = metabolizable energy; DE = digestible energy; ME:DE = the ratio of ME to DE; N = nitrogen; SBM = soybean meal; RSD = relative standard deviation.
[a,b]Means within a row with unlike superscript letters were significantly different (P < 0.05).
[1] Corn diet indicates sows were fed a basal diet.
[2] SBM diets indicate sows fed on diets containing different soybean meal. Since there was no statistical difference between the SBM, diets, the mean values and ranges are given in this table.
[3] P-value, comparison between different SBM diets.
[4] P-value, comparison between corn diet and SBM diets.
[5] Retained N (g/d) = N intake - feces N − urine N.
[6] N net utilization (%) = retained N/N intake × 100.

$$\text{SID (\%)} = \text{AID} + (\text{BEL of AA}/AA_{\text{diet}}) \times 100,$$

where N_{digesta} and N_{diet} represent nutrient content (g/kg DM) in ileal digesta and the diet, respectively; Cr_{diet} and Cr_{digesta} represent Cr content (g/kg DM) in the diet and ileal digesta, respectively; AA_{digesta} and AA_{diet} represent AA content (g/kg DM) in ileal digesta and the diet, respectively.

The BEL of CP and SID of CP were calculated using the above equations.

2.5. Statistical analysis

The normality of residual and outliers were tested using the UNIVARIATE procedures in SAS 9.4 (SAS Inst. Inc., Cary, NC, USA). Outliers were identified as values that deviated from the treatment mean by more than 3 times the interquartile range. There was no outlier detected in the dataset. Digestibility data were analyzed using PROC MIXED, with sow as the experimental unit. The model included the fixed effect of SBM or diet and the random effects of sows and period. The statistical model was as follows:

$$Y_{ijk} = \mu + T_i + P_j + S_k + e_{ijk},$$

Table 7
Digestible energy, metabolizable energy, and the apparent total tract digestibility (ATTD) of nutrients in different soybean meals (SBM) for sows (on a dry matter basis).

Item	Corn	SBM (n = 11)[1]				P-value[3]
		Mean	Range	RSD	P-value[2]	
ATTD of GE, %	91.0[a]	88.4[b]	86.9–90.8	1.28	0.510	<0.001
ATTD of N, %	86.6[b]	89.6[a]	87.8–91.4	1.29	0.109	0.006
ATTD of NDF, %	71.9[a]	61.4[b]	55.3–67.7	6.72	0.921	<0.001
DE, MJ/kg DM	16.7[b]	17.2[a]	16.9–17.7	1.47	0.356	<0.001
ME, MJ/kg DM	16.4[b]	16.6[a]	16.2–17.1	1.56	0.337	0.019
ME:DE, %	98.0	95.9	95.0–97.0	0.74	0.606	0.052

DE = digestible energy; ME = metabolizable energy; ME:DE = the ratio of ME to DE; GE = gross energy; DM = dry matter; N = nitrogen; NDF = neutral detergent fiber; RSD = relative standard deviation.
[1] Since there was no statistical difference between the SBM samples from different sources, this table only shows the mean and range of the 11 SBMs.
[2] P-value, comparison between different SBM samples.
[3] P-value, comparison between corn and SBM samples.

where Y_{ijk} is the observation of dependent variables; μ is the general mean; T_i is the fixed effect of treatment; P_j is the period effect; S_k is the sow effect; e_{ijk} is random error. The LSMEANS statement was used to calculate treatment means. Statistical differences for major effects were tested using Tukey's multiple range tests. A significant difference was accepted at P < 0.05. The data between the corn and SBM groups were compared using the PROC T-Test procedure in SAS with sows as experimental units.

3. Results

3.1. SBM chemical composition

The coefficient of variation (CV) for EE, CF, NDF, and ADF were all >20% (Table 2). Based on DM, the average CP, EE, CF, NDF, ADF, and ash contents in SBM were 51.1%, 1.1%, 6.0%, 12.6%, 7.3%, and 6.6%, with ranges of 49.6% − 53.6%, 0.9% − 1.6%, 4.5% − 7.8%, 9.5% − 16.4%, 4.8% − 10.3%, and 6.0% − 7.1%, respectively. The average GE value in SBM was 19.5 MJ/kg, with a range of 19.3 to 19.6 MJ/kg. The overall AA content was relatively stable with a CV < 10%. Average Lys, Met, Trp, and Thr concentrations in SBM were 3.14%, 0.83%, 0.64%, and 1.98%, with ranges of 2.93% − 3.43%, 0.76% − 0.93%, 0.52% − 0.71%, and 1.80% − 2.19%, respectively.

3.2. Digestible energy, metabolizable energy and nutrients digestibility in Exp. 1

The ATTD of GE, metabolizability of GE, and N balance in experimental diets for multiparous sows are shown (Table 6). There were no significant differences in dry matter intake (DMI), N intake, feces N, urine N, and N net utilization in sows across the 11 SBM groups (P > 0.05). There were no significant differences in the ATTD of GE, metabolizability of GE, and ME:DE among different SBM diets (P > 0.05). Since there was no significant difference between different SBM treatment groups, only the mean values and ranges are given in the table for readers' convenience. Sows fed a corn-based diet had lower N intake, feces N, urine N, and retained N compared to those fed SBM diets (P < 0.001). The metabolizability of GE in the corn diet for sows was significantly higher than that in the SBM diet (P < 0.001). As shown in Table 7, based on DM, the average DE, ME, and ATTD values of GE in SBM were 17.2 MJ/kg (range: 16.9–17.7 MJ/kg), 16.6 MJ/kg (range: 16.2–17.1 MJ/kg), and 88.4% (range: 86.9% – 90.8%), respectively. Furthermore, there were no differences in DE, ME, or ATTD values of GE between SBM samples (P > 0.05). Similarly, there were no differences in the ME:DE among the 11 SBM samples, which averaged 95.9%. Additionally, there were no significant differences in ATTD values for N and NDF between SBM samples, with mean values of 89.6%, and 61.4%, respectively. The ATTD of GE and NDF in the corn sample was significantly higher than that in the SBM samples (P < 0.001). On DM basis, the DE, ME and ME:DE of the corn sample were 16.7 MJ/kg, 16.4 MJ/kg, and 98.0%, respectively. Corn's DE and ME were significantly lower than that of SBM (P < 0.05).

3.3. AA digestibility in Exp. 2

The AID and SID values of AA in 3 representative SBM samples are shown in Tables 8 and 9, respectively. There were no differences in AID and SID values in all AA across SBM samples (P > 0.05). Mean AID and SID values for CP were 80.4% (range: 79.8%–80.9%) and 86.8% (range: 86.2%–87.5%), respectively. Across all essential AA in SBM, mean AID and SID values for Arg and His were the highest, with AID values of 91.1% and 87.4%, and SID values of 93.7% and 90.3%, respectively. Mean AID and SID values for Thr and Val were the lowest, with AID values of 79.0% and 79.8%, and SID values of 85.2% and 84.8%, respectively. The BEL values for AA ranged from 0.09 g/kg DMI for Trp to 2.05 g/kg DMI for Pro (Table 9). The highest endogenous AA losses were identified for Pro, Glu, Gly, and Asp.

4. Discussion

The chemical composition of SBM samples in our study was within previously reported ranges (NRC, 2012; Ibáñez et al., 2020). The mean EE content in SBM was low (1.1%) because all SBM were solvent-extracted; the oil was extracted during processing (Adewole et al., 2016). The CV of CF, NDF, and ADF were >20%, probably because different growing environments and varieties affect the physicochemical properties of crops (Li et al., 2014; Ravindran et al., 2014). In addition, SBM 4, 7, and 8 were dehulled and the remaining SBM were hulled. Soyhull contains a high content of fiber, and removing soyhull during processing may affect AA and GE digestibility in SBM (Dilger et al., 2004). The AA content in SBM samples in our study was stable, consistent with previous reports (Li et al., 2015; García-Rebollar et al., 2016). Based on DM, it was reported that Lys (3.28% vs. 3.16%), Thr (2.08% vs. 2.04%), and Trp (0.73% vs. 0.71%) content in SBM produced from USA beans were higher than that of SBM produced from Argentinian soybeans (García-Rebollar et al., 2016). This observation was consistent with our results, where Lys, Thr, and Trp contents in SBM 7 and 8 were higher than that of SBM 3.

Table 8
Apparent ileal digestibility of amino acids (%) in soybean meal fed to non-pregnant sows (Exp. 2).[1]

Item	Soybean meal[2]			Mean	RSD	P-value
	6-BR	8-USA	11-CN			
CP	80.4	80.9	79.8	80.4	3.05	0.788
Indispensable AA						
Arg	91.9	91.1	90.1	91.1	1.79	0.198
His	87.0	88.3	86.9	87.5	2.61	0.543
Ile	84.1	84.6	83.1	84.0	1.55	0.238
Leu	83.7	84.4	82.9	83.7	1.52	0.225
Lys	83.9	85.0	84.2	84.4	1.73	0.481
Met	85.5	86.0	83.8	85.2	1.83	0.083
Phe	85.2	85.9	83.2	84.9	2.81	0.154
Thr	79.5	79.5	78.2	79.0	3.73	0.757
Trp	84.9	84.1	82.7	84.0	2.53	0.247
Val	79.7	81.6	78.0	79.8	3.12	0.065
Dispensable AA						
Ala	77.2	79.0	76.5	77.7	2.95	0.240
Asp	84.2	83.8	83.5	83.8	2.71	0.914
Cys	75.1	75.0	76.2	75.4	3.37	0.747
Glu	85.9	87.0	85.4	86.1	1.99	0.295
Gly	74.4	76.7	74.6	75.3	6.14	0.664
Pro	84.0	83.0	82.5	83.3	3.04	0.645
Ser	82.9	83.1	81.0	82.3	3.12	0.396
Tyr	83.1	83.9	82.2	83.1	2.32	0.409

CP = crude protein; RSD = relative standard deviation; AA = amino acid.
[1] Values are the mean of six observations/sample.
[2] Soybean sources are Brazil (sample 6), USA (sample 8), and China (sample 11).

Table 9
Standardized ileal digestibility of amino acids (%) in soybean meal fed to non-pregnant sows (Exp. 2).[1,2]

Item	Soybean meal[3]			Mean	RSD	P-value
	6-BR	8-USA	11-CN			
CP	86.7	87.5	86.2	86.8	2.84	0.730
Indispensable AA						
Arg	94.4	93.9	92.6	93.7	1.75	0.182
His	89.8	91.1	89.8	90.3	2.51	0.558
Ile	87.5	88.2	86.8	87.5	1.45	0.285
Leu	86.9	87.8	86.4	87.1	1.46	0.232
Lys	87.4	88.8	87.8	88.0	1.69	0.370
Met	89.7	90.8	88.2	89.7	1.81	0.053
Phe	88.0	88.9	86.8	87.9	1.97	0.147
Thr	85.4	85.7	84.5	85.2	3.44	0.816
Trp	89.2	89.0	87.2	88.6	2.39	0.253
Val	84.6	86.6	83.2	84.8	2.89	0.081
Dispensable AA						
Ala	83.2	85.0	82.8	83.7	2.68	0.296
Asp	87.7	87.5	87.2	87.5	2.58	0.956
Cys	82.6	82.9	84.2	83.1	3.09	0.650
Glu	88.7	90.0	88.3	89.0	1.93	0.267
Gly	86.1	88.8	87.2	87.4	5.32	0.610
Pro	104.6	105.5	106.9	105.5	2.48	0.397
Ser	87.6	88.1	86.1	87.3	2.92	0.442
Tyr	86.7	87.8	85.9	86.8	2.26	0.318

CP = crude protein; RSD = relative standard deviation; AA = amino acid.
[1] Values are the mean of six observations/sample.
[2] Values for standardized ileal digestibility were calculated by correcting apparent ileal digestibility for basal endogenous losses. Basal endogenous losses were determined (g/kg dry matter intake) as CP, 11.74; Arg, 0.31; His, 0.13; Ile, 0.27; Leu, 0.44; Lys, 0.38; Met, 0.12; Phe, 0.25; Thr, 0.42; Trp, 0.09; Val, 0.39; Ala, 0.47; Asp, 0.70; Cys, 0.27; Glu, 0.95; Gly, 0.86; Pro, 2.05; Ser, 0.43; Tyr, 0.23.
[3] Soybean sources are Brazil (sample 6), USA (sample 8), and China (sample 11).

There were no significant differences in the ATTD of GE, metabolizability of GE, and ME:DE among the 11 SBM diets. Additionally, there were no differences in DE, ME, and ATTD values for GE, N, and NDF across different SBM samples. These results were consistent with previous studies in growing pigs and pregnant sows (Li et al., 2015; Wang et al., 2022). It is reported that the fiber content of ingredients is negatively correlated with the CP digestibility in pigs (Chasse et al., 2021; Fan et al., 2001). This phenomenon was not found in this study, possibly due to the relatively small difference in dietary fiber content between the treatment groups and the relatively strong fiber digestion of sows. This is consistent with previous report that the inhibitory effect of fiber on energy digestibility of growing pigs is stronger than that of adult sows (Le Goff and Noblet, 2001). The dietary fiber fraction of SBM may compromise the ability of growing pigs to obtain adequate energy but has less impact on energy retention in adult pigs (Jarrett and Ashworth, 2018). Adult sows had a greater ability to degrade fiber than growing pigs and also had a higher energy digestibility (Li et al., 2021).

In this study, the average ATTD of GE, DE, and ME values of SBM were 88.4%, 17.2 MJ/kg DM, and 16.6 MJ/kg DM, respectively. These values were higher than the corresponding mean values (84.8%, 16.7 MJ/kg DM, and 15.8 MJ/kg DM) of SBM in growing pigs as previously reported (Lopez et al., 2020). The ATTD of GE and ME values in SBM in our study were also higher than corresponding mean values (86.5% and 15.9 MJ/kg DM) in solvent-extracted SBM as reported by the NRC (2012). In this study, the ATTD of GE, DE and ME of corn were 91.0%, 16.7 MJ/kg DM and 16.4 MJ/kg DM, respectively. These values were also higher than the corresponding values (87.7%, 16.4 MJ/kg DM and 16.1 MJ/kg DM) reported for yellow dent corn by the NRC (2012). As previously reported, sows have a more developed gastrointestinal tract and greater hindgut fermentation capacity than growing gilts and can obtain more energy from difficult-to-digest ingredients (Casas and Stein, 2017). Corn was used as the basal diet in this study, and since its N and fiber contents were relatively low, it is expected the SBM supplemented diets had increased N excretion and N digestion.

As shown in Table 10, the average GE of the 11 SBM samples is consistent with previously reported values (Li et al., 2015; INRA, 2024). In this study, the DE values of all SBM samples closely approximated the corresponding recommendation in NRC (2012). Furthermore, these values exceeded the INRA (2024) recommendation for growing pigs and were slightly lower than the recommendation for adult sows by INRA (2024). The ME values of all SBM samples exceeded the recommendations of NRC (2012) and INRA (2024) but were close to the values reported by others (Li et al., 2015; Sotak-Peper et al., 2015; Lopez et al., 2020). In this study, the ME:DE for corn was similar to that reported by the NRC (2012) (approximately 98%), while the mean ME:DE for SBM was slightly higher than the value reported by the NRC (95.9% vs. 91.9%). It is worth noting that although the ME:DE value of SBM was slightly higher than that reported by the NRC (2012), it closely aligned with values reported by Li et al. (2015) (96.0%) and Lopez et al. (2020) (94.6%). Interestingly, it has been reported that the ME:DE for extruded full-fat soybean (96.3% vs. 93.9%) and cottonseed meal (92.0% vs. 90.8%) in multiparous non-pregnant sows are also higher than the values recommended by the NRC (2012) (Wang et al., 2023c; Zhuo et al., 2023a). This may be related to the different physiological stages of the study subjects. Compared to growing-finishing pigs, in this study, daily fecal and urinary energy excretion of sows were both higher than previously reported, with the difference in fecal energy excretion being higher than that in urinary energy excretion (Li et al., 2015; Lopez et al., 2020). According to the report, dietary fiber intake in sows leads to increased endogenous protein losses and a higher transfer of urinary N to fecal microbial proteins (Yang et al., 2021). In addition, we cannot ignore the fact that the calculation of metabolizable energy should include energy loss from gas production (mainly methane). When sows consume high-fiber diets, the loss of energy as gas can reach up to 3.0% of DE, whereas gas energy loss for growing-finishing pigs fed typical diets is only around 0.5% of DE (NRC, 2012). Since this loss was not considered in our calculation of ME, the ME values for sows may be slightly overestimated.

In practical production conditions, sows are provided ad libitum feed for e higher intakes during non-pregnancy stage after weaning to compensate for backfat loss during lactation. In Exp. 1, the feed intake for sows was set at 5 kg/d, which is similar to the feeding levels at commercial pig farms. It is reported that the level of feed intake by gestating sows did not affect the digestibility of GE and nutrients in the diets (Casas and Stein, 2017). In the current experimental setup, non-pregnant sows had higher feed intake (5 vs. 3 kg/d), so N retention values in sows in SBM groups were higher than values (42.8 g/d) in pregnant sows in our previous report (Wang et al., 2022). However, it is relatively close to the reported value (50 g/d) for non-pregnant sows by Zhuo et al. (2023a). It is noteworthy that sows in the SBM group had significantly higher nitrogen retention than those in the corn group, which is due to the higher CP intake in the SBM group. There were no significant differences in the net utilization rate of N between the corn group and the SBM group, and the values were close to those reported previously in mid-gestation sows (Wang et al., 2022). Additionally, average DE, ME, and the ATTD of GE, N and NDF values of SBM (17.2 MJ/kg, 16.6 MJ/kg, 88.4%, 89.6%, and 61.4%, respectively) in this study were lower than mid-gestating (17.9 MJ/kg, 16.6 MJ/kg, 91.6%, 92.4%, and 70.0%, respectively) and late-gestating sow values (17.9 MJ/kg, 17.2 MJ/kg, 91.8%, 92.0%, and 72.1%, respectively) in our previous report (Wang et al., 2022). Sows experience changes in their gut microbiome and hormone levels after pregnancy, which can affect nutrient digestibility (Niu et al., 2019). However, the specific mechanism needs further exploration (Zhuo et al., 2023a). The DE, ME, and the ATTD of GE, N and NDF values of SBM in this study were higher than non-pregnant sow values (15.5 MJ/kg, 13.8 MJ/kg, 79.0%, 88.0%, and 60.3%) in previous report (Dong et al., 2020). The possible reason is that Dong et al. (2020) used the time-based total collection method. However, the speed of digesta passage varies between pigs (Casas and Stein, 2017). Sows are more prone to constipation after eating a low-fiber diet, so the marker-to-marker total collection method is more suitable for digestibility trials.

The feed intake of sows in Exp. 2 was set at 3 kg/d due to the poor palatability of the N-free diet, and the fact that our previous study in non-pregnant sows with different feed intakes had no effects on SID values of AA (Wang et al., 2023d). The BEL of AA was considered an inevitable loss (Jansman et al., 2002). Although there were differences between the two studies in terms of diet composition and sow parity, the BEL values of most AA in sows and SID values of all AA (except Ala, Met, and Cys) in SBM in the current study were similar to corresponding SBM values in our previous report (Wang et al., 2023a). This fully demonstrated the accuracy and reliability of our data. However, the BEL values of CP and AA were lower than the values obtained using a casein-corn starch diet

Table 10
Comparison of digestible energy (DE), metabolizable energy (ME), and ratios of ME:DE in soybean meal.

Item	GE, MJ/kg DM	DE, MJ/kg DM	ME, MJ/kg DM	ME:DE, %
NRC (2012)	20.1	17.3	15.9	91.9
INRA-growing pig (2024)[1]	19.5	16.5	15.1	91.5
INRA-adult pig (2024)[1]	19.5	17.6	16.0	90.9
Lopez et al. (2020)	19.8	16.7	15.7	94.0
Li et al. (2015)	19.5	17.6	16.9	96.0
Sotak-Peper et al. (2015)	19.6	17.8	16.9	94.9
This experiment	19.5	17.2	16.6	95.9

GE = gross energy; DM = dry matter; ME:DE = the ratio of ME, to DE.
[1] The methane energy losses was considered in the INRA values.

(Velayudhan et al., 2019). This is consistent with previous reports and may be due to a lack of dietary peptides in the intestine, which reduces endogenous AA losses (Butts et al., 1993; Adeola et al., 2016). Among all essential AA in SBM, Arg had the highest AID and SID values. It was reported that Arg first appears in isolated intestinal loops after enzymatic hydrolysis and protease and peptidase specificity in the small intestine may facilitate Arg digestion (Low, 1980). The SID values for Pro in SBM were higher than 100%, which indicated that endogenous Pro secretion was high. When fed a N-free diet, sows are in a negative N balance and their muscles break down large Gln amounts, which are eventually metabolized to Pro, Cit and Glu (De Lange et al., 1989). The BEL values of CP and AA in this study were lower than the values obtained in restricted-fed gestating sows (Stein et al., 1999). This is consistent with a previous report (Zhuo et al., 2023b), possibly because pregnancy causes an increase in gut microbial diversity (Gosalbes et al., 2019; Zhuo et al., 2020).

According to a previous report, increased dietary CP levels may activate related metabolic pathways, enhance AA metabolism, and affect AA digestibility (Wang et al., 2023b). Therefore in Exp. 2, different SBM replacement rates (34.40% vs. 36.80%) were used in dehulled SBM and hulled SBM diet groups. These results showed no significant differences in AID and SID values for all AA across SBM from different sources. This observation was consistent with our previous study (Wang et al., 2023a). It was also previously reported that average SID values for CP and AA in SBM from the USA and Brazil fed to piglets were similar (Goerke et al., 2012). Conversely, when fed to growing pigs, averaged SID values for CP in Brazilian SBM differed by up to 13% from that of USA SBM (Karr-Lilienthal et al., 2004). The differences between aforementioned studies may have been due to quality management adjustments by SBM producers, such as technological advances in soybean breeding, planting, and processing (Goerke et al., 2012). Additionally, test animals in this study were multiparous sows, which have a more developed gut when compared to growing pigs (Casas and Stein, 2017). This factor may also reduce digestibility differences caused by anti-nutrient factors such as fiber and oligosaccharides between different SBM sources (Dilger et al., 2004; Baker and Stein, 2009).

Overall, average SID values for essential AA in SBM (84.8% for Val to 93.7% for Arg) in our study were higher than those of solvent-extracted SBM (83% for Thr to 92% for Arg) reported by the NRC (2012). It was also higher than corresponding SBM values (71.3% for Trp to 89.7% for Arg) fed to piglets as previously reported (Goerke et al., 2012). This is consistent with previous report that adult sows have a more developed gut and that the SID values for CP and most AA of SBM are higher in gestating sows than in growing pigs (Stein et al., 2001). The SID of CP and most AA in SBM measured in this study were also higher than that measured in growing-finishing pigs by Yan et al. (2022). Additionally, average SID values for essential AA in SBM in this study were lower than those in mid-gestating sows (88.2% for Trp to 94.1% for Arg) and late-gestating sows (86.4% for Val to 94.2% for Arg) as previously reported by us (Wang et al., 2023a). The SID values for AA of SBM in pregnant sows were higher than values in non-pregnant sows, and SID values of AA in non-pregnant sows were higher than values in growing pigs, consistent with changes in SBM available energy in Exp. 1. Similarly, the SID value for CP of SBM in non-pregnant sows in the current study was higher than previously reported value in growing pigs and lower than previously reported value in pregnant sows (Stein et al., 2001).

5. Conclusion

In conclusion, there were no significant differences in available energy and AA digestibility in SBM from different sources in multiparous non-gestating sows. The nutritional value of SBM may have varied with the physiological state of the pigs, so these differences should be considered when formulating pig diets. Our study data provide a basis for the accurate use of SBM in sow diets.

Credit Author Statement

Ke Wang: Writing – original draft, Investigation, Data curation, Conceptualization. **Long Huang:** Conceptualization. **Pu Yang:** Data curation, Conceptualization. **Yong Zhuo:** Writing – review & editing, Supervision. **Lianqiang Che:** Writing – review & editing, Supervision. **Shengyu Xu:** Writing – review & editing. **Lun Hua:** Writing – review & editing. **Jian Li:** Writing – review & editing. **Bin Feng:** Data curation. **Zhengfeng Fang:** Data curation. **Xilun Zhao:** Writing – review & editing. **Xuemei Jiang:** Writing – review & editing. **Yan Lin:** Writing – review & editing, Investigation. **De Wu:** Writing – review & editing, Supervision.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, and there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the content of this paper.

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References

Adeola O. Digestion and balance techniques in pigs. In: Lewis AJ, Southern LL, editors. Swine nutrition. 2nd. Washington, DC: CRC Press; 2001. p. 903–16.
Adeola O, Xue PC, Cowieson AJ, Ajuwon KM. Basal endogenous losses of amino acids in protein nutrition research for swine and poultry. Anim Feed Sci Technol 2016;221:274–83.
Adewole DI, Rogiewicz A, Dyck B, Slominski BA. Chemical and nutritive characteristics of canola meal from Canadian processing facilities. Anim Feed Sci Technol 2016;222:17–30.
Association of Official Analytical Chemist. Official methods of analysis. 18th ed. Gaithersburg, MD, USA: AOAC; 2007.
Baker KM, Stein HH. Amino acid digestibility and concentration of digestible and metabolizable energy in soybean meal produced from conventional, high-protein, or low-oligosaccharide varieties of soybeans and fed to growing pigs1. J Anim Sci 2009;87:2282–90.
Butts CA, Moughan PJ, Smith WC, Carr DH. Endogenous lysine and other amino acid flows at the terminal ileum of the growing pig (20 kg bodyweight): the effect of protein-free, synthetic amino acid, peptide and protein alimentation. J Sci Food Agric 1993;61.
Casas GA, Stein HH. Gestating sows have greater digestibility of energy in full fat rice bran and defatted rice bran than growing gilts regardless of level of feed intake. J Anim Sci 2017;95.
Chassé É, Guay F, Knudsen KEB, Zijlstra R, Létourneau-Montminy M. Toward precise nutrient value of feed in growing pigs: effect of meal size, frequency and dietary fibre on nutrient utilisation. Animals-Basel 2021;11.
de Lange CF, Sauer WC, Souffrant W. The effect of protein status of the pig on the recovery and amino acid composition of endogenous protein in digesta collected from the distal ileum. J Anim Sci 1989;67:755–62.
Dilger RN, Sands JS, Ragland D, Adeola O. Digestibility of nitrogen and amino acids in soybean meal with added soyhulls. J Anim Sci 2004;82:715–24.
Dong WX, Zhang G, Li ZC, Liu L, Zhang S, Li DF. Effects of different crude protein and dietary fiber levels on the comparative energy and nutrient utilization in sows and growing pigs. Animals-Basel 2020;10:495.

Fan MZ, Sauer WC, Li S. Variability of apparent ileal amino acid digestibility in high-protein wheat samples for growing-finishing pigs. J Anim Feed Sci 2001;10:103–18.
Food and Agriculture Organization of the United Nations (FAO). FAOSTAT, crop production. http://www.fao.org/faostat/zh/#data/QCL. [Accessed 24 March 2023].
García-Rebollar P, Cámara L, Lázaro RP, Dapoza C, Pérez-Maldonado R, Mateos GG. Influence of the origin of the beans on the chemical composition and nutritive value of commercial soybean meals. Anim Feed Sci Technol 2016;221:245–61.
Goerke M, Eklund M, Sauer N, Rademacher M, Piepho H-P, Mosenthin R. Standardized ileal digestibilities of crude protein, amino acids, and contents of antinutritional factors, mycotoxins, and isoflavones of European soybean meal imports fed to piglets. J Anim Sci 2012;90:4883–95.
Gosalbes MJ, Compte J, Moriano-Gutierrez S, Vallès Y, Jiménez-Hernández N, Pons X, et al. Metabolic adaptation in the human gut microbiota during pregnancy and the first year of life. EBioMedicine 2019;39:497–509.
Grieshop CM, Kadzere CT, Clapper GM, Flickinger EA, Bauer LL, Frazier RL, Jr GCF. Chemical and nutritional characteristics of United States soybeans and soybean meals. J Agric Food Chem 2003;51:7684–91.
Ibáñez MA, de Blas C, Cámara L, Mateos GG. Chemical composition, protein quality and nutritive value of commercial soybean meals produced from beans from different countries: a meta-analytical study. Anim Feed Sci Technol 2020;267:114531–46.
INRA. INRAE-CIRAD-AFZ Feed tables. Nat Inst Agri Res 2024. https://www.feedtables.com/content/soybean-meal-oil-5-46-protein-oil. [Accessed 4 May 2024].
Jansman AJM, Smink W, Leeuwen PV, Rademacher M. Evaluation through literature data of the amount and amino acid composition of basal endogenous crude protein at the terminal ileum of pigs. Anim Feed Sci Technol 2002;98:49–60.
Jarrett S, Ashworth CJ. The role of dietary fibre in pig production, with a particular emphasis on reproduction. J Anim Sci Biotechnol 2018;9:59.
Karr-Lilienthal LK, Merchen NR, Grieshop CM, Flahaven MA, Mahan DC, Fastinger ND, et al. Ileal amino acid digestibilities by pigs fed soybean meals from five major soybean-producing countries. J Anim Sci 2004;82:3198–209.
Kong C, Adeola O. Evaluation of amino acid and energy utilization in feedstuff for swine and poultry diets. Asian Austral J Anim 2014;27:917–25.
Lagos LV, Stein HH. Chemical composition and amino acid digestibility of soybean meal produced in the United States, China, Argentina, Brazil, or India. J Anim Sci 2017;95:1626–36.
Le Goff G, Noblet J. Comparative total tract digestibility of dietary energy and nutrients in growing pigs and adult sows. J Anim Sci 2001;79:2418–27.
Li H, Yin J, Tan B, Chen J, Zhang H, Li Z, et al. Physiological function and application of dietary fiber in pig nutrition: a review. Anim Nutr 2021;7:259–67.
Li QF, Shi M, Shi CX, Liu DW, Piao XS, Li DF, et al. Effect of variety and drying method on the nutritive value of corn for growing pigs. J Anim Sci Biotechnol 2014;5:18.
Li ZC, Wang XX, Guo PP, Liu L, Piao XS, Stein HH, et al. Prediction of digestible and metabolisable energy in soybean meals produced from soybeans of different origins fed to growing pigs. Arch Anim Nutr 2015;69:473–86.
Lopez DA, Lagos LV, Stein HH. Digestible and metabolizable energy in soybean meal sourced from different countries and fed to pigs. Anim Feed Sci Technol 2020;268.
Low AG. Nutrient absorption in pigs. J Sci Food Agric 1980;31:1087–130.
Lowell JE, Liu YH, Stein HH. Comparative digestibility of energy and nutrients in diets fed to sows and growing pigs. Arch Anim Nutr 2015;69:79–97.
Niu Q, Li P, Hao SS, Kim SW, Du TR, Hua JD, Huang RH. Characteristics of gut microbiota in sows and their relationship with apparent nutrient digestibility. Int J Mol Sci 2019;20:870.
NRC. Nutrient requirements of swine. 11th revised ed. Washington, DC, US: National Academy Press; 2012.
Qin J, Zhang JN, Liu D, Yin CC, Wang FM, Chen PY, et al. iTRAQ-based analysis of developmental dynamics in the soybean leaf proteome reveals pathways associated with leaf photosynthetic rate. Mol Genet Genom 2016;291:1595–605.
Ravindran V, Abdollahi MR, Bootwalla SM. Nutrient analysis, metabolizable energy, and digestible amino acids of soybean meals of different origins for broilers. Poultry Sci 2014;93:2567–77.
Sotak-Peper KM, Gonzalez-Vega JC, Stein HH. Concentrations of digestible, metabolizable, and net energy in soybean meal produced in different areas of the United States and fed to pigs. J Anim Sci 2015;93:5694–701.
Stein HH, Kim SW, Nielsen TT, Easter RA. Standardized ileal protein and amino acid digestibility by growing pigs and sows. J Anim Sci 2001;79:2113–22.
Stein HH, Sève B, Fuller MF, Moughan PJ, de Lange CFM. Invited review: amino acid bioavailability and digestibility in pig feed ingredients: terminology and application. J Anim Sci 2007;85:172–80.
Stein HH, Shipley CF, Easter RA. Technical Note: a technique for inserting a T-cannula into the distal ileum of pregnant sows. J Anim Sci 1998;76:1433–6.
Stein HH, Trottier NL, Bellaver C, Easter RA. The effect of feeding level and physiological status on total flow and amino acid composition of endogenous protein at the distal ileum in swine. J Anim Sci 1999;77:1180–7.
Święch E. Alternative prediction methods of protein and energy evaluation of pig feeds. J Anim Sci Biotechnol 2017;8:39–53.
Urbaityte R, Mosenthin R, Eklund M, Piepho H-P, Sauer N, Rademacher M. Standardised ileal crude protein and amino acid digestibilities in protein supplements for piglets. Arch Anim Nutr 2009;63:356–78.
Van Soest PJ, Robertson JB, Lewis BA. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. J Dairy Sci 1991;74:3583–97.
Velayudhan DE, Hossain MM, Stein HH, Nyachoti CM. Standardized ileal digestibility of amino acids in canola meal fed to gestating and lactating sows. J Anim Sci 2019;97:4219–26.
Wang K, Wang Y, Guo L, Zhuo Y, Hua L, Che LQ, et al. Standardized ileal digestibility of amino acids in soybean meal fed to non-pregnant and pregnant sows. J Anim Sci Biotechnol 2023a;14:123.
Wang K, Zou X, Guo L, Huang L, Wang Y, Yang P, et al. The nutritive value of soybean meal from different sources for sows during mid- and late gestation. J Anim Sci 2022;100:skac298.
Wang L, Zeng ZC, Hu QL, Wang L, Shi HW, Lai CH, et al. Determination and prediction of the available energy and amino acids digestibility of full-fat soybean fed to growing pigs. J Anim Sci 2023b;101:skac395.
Wang L, Zhou JY, Chen YF, Wang L, Pan HM, Hu QL, et al. Chemical composition, energy content, and amino acid digestibility in Cyperus esculentus co-products fed to growing pigs. J Anim Sci 2021;99:1–9.
Wang Y, Li GW, Ma XY, Xu SY, Lin Y, Hua L, et al. Chemical composition, energy content and apparent total tract digestibility of extruded full fat soybean from different sources fed to non-gestating, gestating and lactating sows. J Anim Sci 2023c;101:skad154.
Wang Y, Ma XY, Li GW, Sun MM, Xu SY, Lin Y, et al. Effects of feeding levels on ileal amino acid digestibility of extruded full fat soybeans in non-gestating sows. J Anim Sci 2023d;18:skad052.
Yan H, Jin JQ, Yang P, Yu B, He J, Mao XB, et al. Fermented soybean meal increases nutrient digestibility via the improvement of intestinal function, anti-oxidative capacity and immune function of weaned pigs. Animal 2022;16:100557.
Yang M, Mao ZY, Jiang XM, Cozannet P, Che LQ, Xu SY, et al. Dietary fiber in a low-protein diet during gestation affects nitrogen excretion in primiparous gilts, with possible influences from the gut microbiota. J Anim Sci 2021;99:1–14.
Zhuo Y, Feng B, Xuan YD, Che LQ, Fang ZF, Lin Y, et al. Inclusion of purified dietary fiber during gestation improved the reproductive performance of sows. J Anim Sci Biotechnol 2020;11:47.
Zhuo Y, Zou XY, Wang Y, Jiang XM, Sun MM, Xu SY, et al. Nutritional values of cottonseed meal from different sources fed to gestating and non-pregnant sows. J Anim Sci 2023a;101:skad118.
Zhuo Y, Zou XY, Wang Y, Jiang XM, Sun MM, Xu SY, et al. Standardized ileal digestibility of amino acids in cottonseed meal fed to pregnant and non-pregnant sows. J Anim Sci 2023b;101:skad132.