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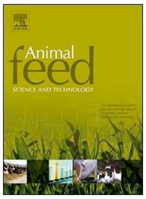

Digestible and metabolizable energy in soybean meal sourced from different countries and fed to pigs

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ABSTRACT

An experiment was conducted to compare the nutritional composition and the concentration of digestible energy (DE) and metabolizable energy (ME) of soybean meal (SBM) from the leading soybean producing countries in the world when fed to growing pigs. Five sources of SBM from Argentina, China, and the United States, and 4 sources from Brazil and India were used. A basal diet based on maize and 23 diets based on maize and each source of SBM were formulated. Twenty-four growing barrows (initial BW: 25.0 ± 1.7 kg) were allotted to a 24 × 7 Youden square design with 24 diets and 7 periods of 14 days. Pigs were individually housed in metabolism crates for total but separate collection of feces and urine. The coefficient of apparent total tract digestibility (CATTD) of gross energy (GE) and concentrations of DE and ME in each diet were calculated using the direct procedure and the DE and ME in each source of SBM were then calculated by difference. Results indicated that there was a tendency ($P < 0.10$) for Brazilian SBM (17.6 MJ/kg) to have greater concentration of GE than SBM from China and the United States (17.3 MJ/kg). The CATTD of GE in SBM from the United States (0.85), China (0.86), and Argentina (0.86) was greater ($P < 0.05$) than in SBM from India (0.83). Values for the concentration of DE and ME were calculated on a dry matter basis. Concentrations of DE and ME in Indian SBM were the least ($P < 0.05$) among countries, and Argentinian SBM had a greater concentration of DE and ME than SBM from the United States. There were no differences in the CATTD of GE among sources of SBM within each country and no differences in the concentration of DE or ME were observed among sources of SBM within Argentina or the United States. However, there were differences in the concentration of DE and ME among sources of SBM collected in India and in China, and a tendency ($P < 0.10$) for differences in the concentration of ME among sources of SBM collected in Brazil. Therefore, based on the four or five sources of SBM collected from each country it was concluded that SBM from Argentina and the United States were less variable than those from the other countries.

Abbreviations: ADF, acid detergent fiber; AA, amino acids; CATTD, coefficient of apparent total tract digestibility; CP, crude protein; DE, digestible energy; DM, dry matter; GE, gross energy; IDF, insoluble dietary fiber; ME, metabolizable energy; NDF, neutral detergent fiber; SDF, soluble dietary fiber; SBM, soybean meal; TDF, total dietary fiber; TIU, trypsin inhibitor units

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1. Introduction

In the 2018/19 crop year, 89 percent of the worldwide soybean production (323 million t) was concentrated in the United States, Brazil, Argentina, China, and India. Most soybeans are crushed to produce oil and soybean meal (SBM), thus, in the same year, 241 million t of SBM were produced (USDA, 2019). Soybean meal is the premier source of amino acids (AA) for pigs and poultry, but in addition to AA, SBM also provides energy to the diets (Stein et al., 2008). However different factors such as soil, weather, crushing methodologies, and length of soybean storage may affect the amount of energy and other nutrients that pigs can obtain from SBM (García-Rebollar et al., 2016). These variations may result in difficulties in feed formulation because variability in concentrations of digestible energy (DE) and metabolizable energy (ME) in SBM results in difficulties in predicting the amount of energy in the diets.

The apparent ileal digestibility and the standardized ileal digestibility of crude protein (CP) and AA were compared among sources of SBM from 3 or 5 different countries fed to pigs, and it was concluded that the digestibility of AA is dependent on the origin of the SBM (Karr-Lilienthal et al., 2004; Goerke et al., 2012; Lagos and Stein, 2017). However, there is limited information about the concentration of DE and ME in SBM produced in different geographical regions. When fed to broilers, the concentration of apparent ME in SBM from Argentina is lower than in SBM from the United States, greater than in SBM from India, and not different from the apparent ME of SBM from Brazil (Ravindran et al., 2014). Data from pigs indicate that there are no differences in the concentration of DE and ME in SBM from China, the United States, Brazil, and Argentina (Li et al., 2015), but there is no data comparing the concentration of DE and ME in SBM from the 5 major soybean-producing countries when fed to pigs. Therefore, the objective of this research was to test the hypothesis that the DE and ME in SBM from the United States, Brazil, Argentina, China, and India fed to pigs is not dependent on the origin.

2. Materials and methods

2.1. Animals and experimental design

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocol for this experiment. Pigs used in the experiment were the offspring of Line 359 boars mated to Camborough females (Pig Improvement Company, Hendersonville, TN, USA). Twenty-four growing barrows (initial BW: 25.0 ± 1.7 kg) were allotted to a 24 × 7 Youden square design with 24 diets and 7 periods of 14 days. Pigs were housed individually in metabolism crates (1.57 × 0.86 × 0.76 m) equipped with a feeder, a nipple waterer, and a slatted floor to allow for the total collection of urine and fecal materials. Under the slatted floor, a screen was placed followed by a pan to collect feces and urine samples, respectively. Thus, feces and urine were separately collected. The temperature and relative humidity were set at 22 °C and 50 %, respectively. Minimum and maximum values were daily recorded and the average ranged from 22.2–22.6 °C and 42–58% relative humidity.

Twenty-three sources of SBM were used. These sources were from batches used in a previous experiment (Lagos and Stein, 2017). Five samples were from the United States and selected from crushing plants located in South Dakota, Iowa, Illinois, Indiana, and Ohio. Eighteen additional samples were collected from Argentina (5), China (5), Brazil (4), and India (4). A maize diet and 23 diets based on a mixture of maize and each source of SBM were formulated (Tables 1 and 2). All SBM-containing diets contained amino acids, vitamins, and minerals that met or exceeded requirements of growing pigs (NRC, 2012).

Table 1
Ingredient composition of experimental diets (as-fed basis)[a].

Ingredient, g/kg	Diets	
	Soybean meal	Maize
Soybean meal	260.00	–
Maize	712.50	970.00
Limestone	10.00	8.00
Monocalcium phosphate	10.50	15.00
Salt	4.00	4.00
Vitamin micro-mineral premix[b]	3.00	3.00

[a] A maize diet and 23 diets using 23 different sources of soybean meal were formulated.

[b] The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kilogram of complete diet: Vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 as cholecalciferol, 2,208 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper sulfate and copper chloride; Fe, 126 mg as ferrous sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese sulfate; Se, 0.3 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc sulfate.

Table 2
Analyzed composition of experimental diets[a].

		Country				
Item	Maize	Argentina	Brazil	China	India	USA
Gross energy, [b] MJ/kg	15.8	16.1	16.2	15.9	15.9	16.0
Dry matter, g/kg	880.1	887.8	883.5	883.2	880.4	885.2

[a] Values are the average of 5 diets containing soybean meal from Argentina, China, and USA and 4 diets containing soybean meal from Brazil and India.
[b] As-fed basis.

2.2. Feeding and sample collection

Pigs were weighed at the beginning of each period and were fed 3.2 times their daily energy requirement for maintenance (0.82 MJ/kg $BW^{0.60}$; NRC, 2012), which was provided in 2 equal meals at 0800 and 1700 h. Diets were fed in a meal form and the amount of feed left in the feeders was removed and recorded daily to determine feed consumption for each pig. Throughout the study, pigs had free access to water. The initial 7 days of each period were considered the adaptation period to the diet, followed by a 5 day collection period. Urine was collected once a day in urine buckets over a preservative of 50 mL of hydrochloric acid from day 8–12, whereas fecal material was collected twice a day (0900 and 1500 h) according to standard procedures using the marker to marker approach (Adeola, 2001). The beginning of fecal collections was marked by adding chromium oxide to the morning meal on day 8, and the conclusion of fecal collection was marked by adding ferric oxide to the morning meal on day 12. The inclusion level of each marker was 0.4 % of the diet. Fecal samples and 20 % of the collected urine were stored at −20 °C immediately after collection.

2.3. Chemical analyses

At the conclusion of the experiment, urine samples were thawed and mixed within animal and diet, and a sub-sample was lyophilized (Kim et al., 2009). Fecal samples were thawed, dried in a 50 °C forced air drying oven for 7 days, and ground through a 1-mm screen (Wiley Mill Model 4; Thomas Scientific; Swedesboro, NJ, USA). All sources of SBM, diet, fecal, and urine samples were analyzed for gross energy (GE) using bomb calorimetry (Model 6400; Parr Instruments, Moline, IL, USA). Diets were analyzed for dry matter (DM; Method 930.15; AOAC Int., 2007) and all sources of SBM were analyzed for insoluble dietary fiber (IDF), soluble dietary fiber (SDF), and total dietary fiber (TDF) according to method 991.43 (AOAC Int., 2007) using the Ankom^{TDF} Dietary Fiber Analyzer (Ankom Technology, Macedon, NY, USA). Concentrations of acid detergent fiber (ADF) and neutral detergent fiber (NDF) were expressed inclusive of residual ash, and were analyzed using Ankom Technology method 12 and 13, respectively (Ankom 2000 Fiber Analyzer, Ankom Technology, Macedon, NY, USA). All sources of SBM were analyzed for CP (Method 990.03; AOAC Int., 2007) on an FP628 protein analyzer (Leco Corporation, St. Joseph, MI, USA), Lys [Method 982.30 E (a); AOAC Int., 2007], ash (Method 942.05; AOAC Int., 2007), and for acid hydrolyzed ether extract 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). All sources of SBM were also analyzed for sucrose, stachyose, and raffinose (977.2; AOAC Int., 2007) by extracting and quantifying the sugars using a high-performance liquid chromatography with an autosampler (Alcott, Norcross, GA, USA), a pump (Waters 510, Milford, MA, USA), a column (Dionex CarboPac PA1, Sunnyvale, CA, USA), and a pulsed amperometric detector (Dionex). Results were compared with known standards for sucrose (Chem Service, West Chester, PA, USA) and known standards for stachyose and raffinose (Sigma-Aldrich, St. Louis, MO, USA). Trypsin inhibitor units (TIU) were also determined in all SBM sources (Method Ba 12–75; AOCS, 2006).

2.4. Calculations and statistical analysis

Data for nutrient composition of SBM were adjusted to 880 g/kg of DM. The Lys:CP ratio in each source of SBM was calculated by dividing the concentration of Lys by the concentration of CP. The coefficient of apparent total tract digestibility (CATTD) of GE, concentration of DE, and concentration of ME in each diet were calculated using the following equations for the direct procedure:

$$\mathrm{CATTD} = \frac{\text{GE intake} - \text{GE in feces}}{\text{GE intake}}$$

$$\mathrm{DE, MJ/kg} = \frac{\text{GE intake} - \text{GE in feces}}{\text{Total feed intake}}$$

$$\mathrm{ME, MJ/kg} = \frac{\text{GE intake} - \text{GE in feces} - \text{GE in urine}}{\text{Total feed intake}}$$

Concentrations of DE and ME in maize were calculated by dividing the concentration of DE and ME in the maize diet by the inclusion rate of maize (i.e., 0.97). The concentration of DE and ME in each source of SBM were calculated by difference using the following equation modified from Adeola and Kong (2014):

Table 3
Protein digestibility, proximate composition, and concentration of carbohydrates and digestible protein in soybean meal from Argentina, Brazil, China, India, and the United States[1,2].

	Country						
Item	Argentina	Brazil	China	India	USA	SEM	*P*-value
GE,[3] MJ/kg	17.43^{xy}	17.61^{x}	17.33^{y}	17.39^{xy}	17.32^{y}	0.073	0.076
Dry matter, g/kg	891.5^{xy}	885.0^{y}	895.3^{x}	883.3^{y}	885.1^{y}	3.10	0.056
CP[3], g/kg	467.1^{b}	490.8^{a}	450.8^{c}	495.1^{a}	473.1^{b}	5.55	< 0.001
Lys, g/kg	29.56^{bc}	30.25^{ab}	28.50^{c}	31.24^{a}	30.68^{ab}	0.399	0.001
Lys:CP ratio[4]	0.0633^{b}	0.0616^{c}	0.0633^{b}	0.0631^{bc}	0.0649^{a}	0.00049	0.005
Ash, g/kg	68.94	67.26	63.45	68.78	67.16	2.834	0.636
AEE,[3] g/kg	16.73	14.85	12.46	11.94	16.65	2.727	0.602
IDF,[3] g/kg	163.9	172.7	171.4	185.5	168.1	10.41	0.574
SDF,[3] g/kg	11.63	13.72	9.04	6.46	5.24	4.149	0.616
TDF,[3] g/kg	175.5	186.7	180.7	192.9	173.6	12.70	0.842
ADF, [3] g/kg	36.87^{b}	54.25^{a}	56.00^{a}	64.06^{a}	36.85^{b}	4.984	0.002
NDF, [3] g/kg	71.84^{b}	93.56^{a}	94.55^{a}	99.59^{a}	72.45^{b}	7.224	0.030
Sucrose, g/kg	75.64^{b}	53.47^{c}	89.12^{a}	46.87^{c}	85.94^{ab}	4.376	< 0.001
Raffinose, g/kg	14.71^{b}	14.58^{b}	11.75^{b}	19.76^{a}	14.47^{b}	1.140	0.003
Stachyose, g/kg	52.29^{bc}	44.14^{c}	55.51^{b}	50.91^{bc}	64.71^{a}	2.961	0.002
TIU,[3] mg/kg	1.99^{c}	3.17^{ab}	2.92^{bc}	4.10^{a}	2.69^{bc}	0.330	0.006
CSID of CP[3,5]	0.911^{bc}	0.909^{bc}	0.919^{b}	0.899^{c}	0.938^{a}	0.0084	< 0.001
SID CP,[3,5] g/kg	426.2^{b}	447.8^{a}	414.2^{c}	445.2^{a}	443.1^{a}	4.28	< 0.001
SID Lys,[5] g/kg	26.7^{c}	27.6^{b}	26.3^{c}	28.4^{a}	28.4^{a}	0.25	< 0.001

$^{a-c}$Means within a row lacking a common superscript letter are different ($P < 0.05$).

$^{x-y}$Means within a row lacking a common superscript letter tend to be different ($P < 0.10$).

[1] Values are the LSMeans for 5 sources of soybean meal from Argentina, China and USA and 4 sources from Brazil and India. With the exception that for IDF, SDF, and TDF, only 4 sources of SBM from USA were used.

[2] All values were adjusted to 880 g/kg of DM except for the DM value.

[3] AEE, acid hydrolyzed ether extract; ADF, acid detergent fiber; CSID, coefficient of standardized ileal digestibility; CP, crude protein; GE, gross energy; IDF, insoluble dietary fiber; NDF, neutral detergent fiber; SDF, soluble dietary fiber; SID, standardized ileal digestible; TDF, total dietary fiber; TIU, trypsin inhibitor units.

[4] Lys:CP ratio was calculated by dividing the concentration of Lys by the concentration of CP.

[5] Data from Lagos and Stein (2017).

$$C_{SBM}, \text{MJ/kg} = \frac{C_{SBM,\ diet} - (C_{Maize} \times IR_{Maize})}{IR_{SBM}}$$

Where C indicates the CATTD of GE, the concentration of DE, or the concentration of ME in SBM, Maize, and the SBM diets, and IR indicates the inclusion rate of maize and SBM in the SBM diets (i.e., 0.71 and 0.26, respectively).

For nutrient composition, data were analyzed using the MIXED procedure of SAS-Institute Inc. (2016) using the source of SBM as the experimental unit and including country as the fixed effect in the model. Data for GE in feces, GE in urine, feed intake, DE, ME, and CATTD of GE in diets, as well as for concentrations of DE, ME, and CATTD of GE in SBM were analyzed using the MIXED procedure of SAS with pig as the experimental unit. The model included country as fixed effect and period as random effect. Correlations of chemical characteristics of SBM with concentrations of DE and ME (DM basis) were determined using the PROC CORR function of SAS. To determine if differences in DE, ME, and CATTD of GE within each country were significant, the MIXED procedure of SAS was also used but, the model included source within country as fixed effect and period as random effect. For all analysis, least squares means were calculated using the LS Means option and means were separated using the PDIFF option with Tukey's adjustment of SAS. Results were considered significant at $P \leq 0.05$ and a trend at $P \leq 0.10$.

3. Results

3.1. Chemical characteristics of soybean meals

No differences among countries were observed for concentrations of ash, acid hydrolyzed ether extract, IDF, SDF, or TDF (Table 3). Brazilian SBM tended ($P = 0.076$) to have greater concentration of GE than SBM from China and the USA. The concentration of CP in SBM from USA and Argentina was less ($P < 0.001$) than in SBM from India and Brazil, but greater ($P < 0.001$) than in SBM from China. The concentration of Lys in SBM from India was greater ($P = 0.001$) than in SBM from Argentina and China. Soybean meal from USA and Brazil also had a greater ($P = 0.001$) concentration of Lys than SBM from China. The Lys:CP ratio in SBM from USA was the greatest ($P = 0.005$) among countries, and Brazilian SBM had lower ($P = 0.005$) Lys:CP ratio than Argentinian and Chinese SBM. The concentration of ADF and NDF was greater ($P = 0.002$ and $P = 0.030$, respectively) in SBM from Brazil, China, and India than in SBM from Argentina or USA. Chinese SBM had a greater ($P < 0.001$) concentration of sucrose than Argentinian, Brazilian, and Indian SBM, and the concentration of sucrose in SBM from USA and Argentina was greater ($P < 0.001$)

Table 4

Digestible energy (DE), metabolizable energy (ME), and coefficient of total tract apparent digestibility (CATTD) of gross energy (GE) in experimental diets[1].

	Maize	Soybean meal					SEM	*P*-value
Item		Argentina	Brazil	China	India	USA		
GE intake, MJ/d	29.92^{c}	31.42^{bc}	32.36^{ab}	31.46^{ab}	32.15^{ab}	32.32^{a}	3.492	0.010
GE in feces, MJ/d	2.92^{c}	3.25^{bc}	3.71^{a}	3.25^{bc}	3.62^{a}	3.42^{ab}	0.217	0.002
GE in urine, MJ/d	0.52^{c}	0.83^{ab}	0.74^{bc}	0.82^{ab}	0.84^{ab}	0.89^{a}	0.091	0.032
DE, MJ/kg DM	16.05	16.21	16.17	16.11	16.01	16.16	0.143	0.236
ME, MJ/kg DM	15.74	15.72	15.75	15.63	15.52	15.66	0.156	0.200
CATTD GE	0.895^{ab}	0.892^{a}	0.882^{c}	0.892^{a}	0.883^{bc}	0.889^{abc}	0.0077	0.027

$^{a-c}$Means within a row lacking a common superscript letter are different ($P < 0.05$).

[1] Values are the LSMeans of 7 observations for maize diet, 35 observations for diets containing soybean meal from Argentina, China, and USA, and 28 observations for diets containing soybean meal from Brazil and India.

than in SBM from India and Brazil. Soybean meal from India and USA had the greatest ($P = 0.003$ and $P = 0.002$) concentration of raffinose and stachyose among countries, respectively. Chinese SBM also had greater ($P = 0.002$) concentration of stachyose than Brazilian SBM. Soybean meal from India had greater ($P = 0.006$) concentration TIU than SBM from USA, Argentina, and China and the concentration of TIU was greater ($P = 0.006$) in Brazilian SBM than in Argentinian SBM.

3.2. Energy concentration and digestibility of energy

Pigs fed diets containing SBM from USA consumed more ($P = 0.010$) GE than pigs fed diets containing SBM from Argentina, and pigs fed diets containing maize had less ($P = 0.010$) GE intake than pigs fed diets containing SBM from Brazil, China, India, and USA (Table 4). Pigs fed diets containing Indian or Brazilian SBM had greater ($P = 0.002$) concentration of GE in feces than pigs fed diets containing Chinese SBM, Argentinian SBM, or maize. Pigs fed diets containing SBM from USA had greater ($P = 0.032$) concentration of GE in urine than pigs fed diets containing SBM from Brazil or maize.

The concentration of DE and ME (DM basis) in diets containing SBM did not differ among countries, and the diets containing SBM were not different from the maize diet (Table 4). However, diets containing SBM from China and Argentina had greater ($P = 0.027$) CATTD of GE than diets containing SBM from India or Brazil and the CATTD in the maize diet was greater ($P = 0.027$) in the diet containing SBM from Brazil.

Values for the CATTD of GE were greater ($P = 0.026$) for SBM from Argentina, China, and USA than for SBM from India (Table 5). The DE and ME (DM basis) were lower ($P = 0.001$ and $P = 0.002$, respectively) in Indian SBM than in SBM from all other countries. Soybean meal from Argentina had greater concentration of DE (DM basis) than SBM from USA and China. The concentration of ME (DM basis) in SBM from Argentina was greater ($P = 0.002$) than in SBM from USA but not different from SBM from Brazil or China.

There was a tendency ($P = 0.078$) for a negative correlation (-0.84) between IDF and the CATTD of GE, and a negative correlation ($P = 0.011$ and $P = 0.018$) between IDF and DE (DM basis; -0.96) or ME (DM basis; -0.94; Table 6). The CATTD of GE was negatively correlated (-0.90; $P = 0.035$) with TDF, but positively correlated (0.91; $P = 0.031$) with sucrose. There was a negative correlation ($P = 0.053$) between the concentration of TIU and the CATTD of GE (-0.87), DE (DM basis; -0.96; $P = 0.010$), or ME (DM basis; -0.93; $P = 0.020$).

3.3. Variability within countries

Regardless of country, no differences in the CATTD of GE among the collected sources of SBM from each country were observed (Table 7). There were also no differences in the concentration of DE or ME among sources of SBM collected from Argentina or Brazil. However, there was a tendency ($P = 0.087$) for SBM source 3 from Brazil to have a lower ME (DM basis) than SBM source 4. No differences in the concentration of DE (DM basis) among Chinese sources of SBM were observed, but SBM source 1 had a lower ($P = 0.016$) concentration of ME (DM basis) than sources 2, 3, 4, and 5. The concentration of DE (DM basis) in SBM source 4 from India

Table 5

Concentration of digestible energy (DE) and metabolizable energy (ME) in dry matter (DM) basis and coefficient of total tract apparent digestibility (CATTD) of gross energy (GE) in soybean meal sources from Argentina, Brazil, China, India, and the United States[1].

Item	Argentina	Brazil	China	India	USA	SEM	*P*-value
CATTD	0.862^{a}	0.831^{bc}	0.857^{a}	0.827^{c}	0.854^{ab}	0.0232	0.026
DE, MJ/kg DM	17.32^{a}	16.81^{ab}	16.69^{b}	15.95^{c}	16.74^{b}	0.510	0.001
ME, MJ/kg DM	16.33^{a}	15.88^{ab}	15.77^{ab}	14.92^{c}	15.69^{b}	0.560	0.002

$^{a-c}$Means within a row lacking a common superscript letter are different ($P < 0.05$).

[1] Values are the LSMeans of 35 observations for soybean meal from Argentina, China, and the United States, and 28 observations for soybean meal from Brazil and India.

Table 6

Correlation coefficients between insoluble dietary fiber (IDF), total dietary fiber (TDF), sucrose, and trypsin inhibitor units (TIU) and the coefficient of apparent total tract digestibility (CATTD) of gross energy (GE) and the concentration (dry matter basis) of digestible energy (DE) and metabolizable energy (ME) in soybean meal[a].

Item	CATTD of GE		DE		ME	
	r	*P*-value	r	*P*-value	r	*P*-value
IDF	−0.836	0.078	−0.957	0.011	−0.938	0.018
TDF	−0.904	0.035	−0.767	0.130	−0.720	0.170
Sucrose	0.911	0.031	0.520	0.369	0.507	0.383
TIU	−0.873	0.053	−0.959	0.010	−0.934	0.020

[a] Only nutritional components in soybean meal that were significant or had a tendency for a correlation are shown.

Table 7

Digestible energy (DE), metabolizable energy (ME), and coefficient of total tract apparent digestibility (CATTD) of gross energy (GE) in sources of soybean meal from Argentina, Brazil, China, India, and the United States[1].

	Source							Variablity[2]	
Item	1	2	3	4	5	SEM	*P*-value	SD	CV
Argentina									
CATTD	0.839	0.865	0.863	0.887	0.852	0.0278	0.440	0.07	0.082
DE, MJ/kg DM	17.32	18.12	17.06	17.42	16.76	0.608	0.178	1.58	0.091
ME, MJ/kg DM	16.30	17.23	15.89	16.59	15.44	0.740	0.259	1.88	0.116
Brazil									
CATTD	0.818	0.831	0.818	0.855	–	0.0285	0.505	0.07	0.088
DE, MJ/kg DM	16.58	17.13	16.17	17.24	–	0.570	0.216	1.49	0.089
ME, MJ/kg DM	16.08	16.35	15.11	16.65	–	0.632	0.087	1.68	0.105
China									
CATTD	0.828	0.841	0.860	0.871	0.878	0.0313	0.516	0.08	0.091
DE, MJ/kg DM	15.54	16.56	17.28	17.03	17.09	0.696	0.209	1.84	0.110
ME, MJ/kg DM	14.09^b	15.76^a	16.76^a	16.38^a	15.82^a	0.760	0.016	2.10	0.134
India									
CATTD	0.813	0.827	0.806	0.862	–	0.0290	0.221	0.07	0.088
DE, MJ/kg DM	15.55^b	15.82^b	15.30^b	17.08^a	–	0.645	0.019	1.75	0.110
ME, MJ/kg DM	14.41^b	15.10^{ab}	14.30^b	15.98^a	–	0.727	0.016	1.94	0.130
USA									
CATTD	0.836	0.893	0.853	0.849	0.828	0.0283	0.105	0.07	0.087
DE, MJ/kg DM	16.37	17.63	16.72	16.22	16.74	0.628	0.139	1.64	0.098
ME, MJ/kg DM	15.61	16.29	15.69	15.17	15.49	0.509	0.277	1.30	0.083

$^{a-b}$Means within a row lacking a common superscript letter are different ($P < 0.05$).

[1] Values are the LSMeans of 6 or 7 observations per source.

[2] CV, coefficient of variation; SD, standard deviation.

was greater ($P = 0.019$) than in sources 1, 2, and 3 and ME (DM basis) in SBM source 4 from India was also greater ($P = 0.016$) than in sources 1 and 3, but not different from source 2. There were no differences in concentrations of DE or ME (DM basis) among sources of SBM from the USA. The coefficient of variation for DE and ME in SBM from USA, Argentina, and Brazil was lower than in SBM from China or India.

4. Discussion

4.1. Chemical characteristics of soybean meals

Although there are many factors that may affect the nutritional value of SBM, (e.g., variety, agronomic conditions, crushing procedure, transportation, etc.), in this research, the country of origin was the only factor that was evaluated because samples were collected from feed mills in Asia and Europe where imported SBM is used. Thus, the information available in this research is similar to the information a feed mill in Asia or Europe would have available when they purchase imported SBM.

Twenty four sources of SBM from Argentina, Brazil, China, India, and the United States were used to determine differences in the digestibility of CP and AA among countries (Lagos and Stein, 2017). In this experiment, the same sources of SBM were used with the exception that 4, instead of 5 sources of SBM from Brazil were included because of a limitation in the number of metabolism crates available. In previous experiments in which the nutritional value to pigs of SBM from different locations were compared, the samples obtained from each country varied between 2 and 7 samples (Karr-Lilienthal et al., 2004; Goerke et al., 2012; Li et al., 2015). Thus, by using 4 or 5 sources of SBM from each country in this experiment we attempted to use a sample size that has been accepted in the past to make conclusions about the nutritional value of SBM fed to pigs. However, it is recognized that having more samples is always better and stronger conclusions may be obtained if a greater sample size is used.

The ratio between Lys and CP concentration in the 23 SBM sources used in this study indicate that SBM was not over-processed or heat damaged as all values are above 0.60 (González-Vega et al., 2011). The concentration of TDF in ingredients is a better predictor of the digestibility of GE, DM, and organic matter than ADF and NDF concentrations (Anderson et al., 2012; Navarro et al., 2018), which is most likely because TDF also accounts for the soluble portion of the fiber (Agyekum and Nyachoti, 2017). Therefore, IDF, SDF, and TDF, which were not reported by Lagos and Stein (2017), were analyzed in all SBM sources. Despite the lack of differences in the concentration of IDF, SDF, and TDF among countries, there is a similar numeric pattern between IDF/TDF and ADF/NDF, with greater values in SBM from Brazil, China, and India than in SBM from Argentina or the United States. The reason the concentration of SDF differed may be that different quantities of soybean hulls were added to the SBM. Soybean hulls have high concentration of TDF, IDF, and SDF (689, 615, and 74 g/kg, respectively; Burkhalter et al., 2001). The relatively high concentration of SDF in soybean hulls results in high SDF in SBM if soybean hulls are not fully removed from soybeans or are added back to SBM. The observation that SBM from Brazil and India had lower concentration of sucrose than SBM from Argentina, China, and USA is likely because of the increased amount of sucrose synthesized in soybeans grown in cold locations (Kumar et al., 2010). Values for the concentration of sucrose in SBM used in this study concur with previous data (Sotak-Peper et al., 2015; García-Rebollar et al., 2016).

4.2. *Energy concentration and total tract digestibility of energy*

The concentration of DE and ME in SBM from Argentina, Brazil, China, and USA were lower than values reported by Li et al. (2015) and ME in SBM from USA was lower than values reported by Sotak-Peper et al. (2015). However, regardless of the country of origin, values for ME obtained in this experiment were greater than values in most feed ingredient composition books. Values from the current experiment, therefore, support the view that book values (i.e., values from Sauvant et al., 2004; NRC, 2012; Stein et al., 2016; Rostagno et al., 2017) generally underestimate the ME of SBM produced from current varieties of soybeans as has previously been demonstrated (Sotak-Peper et al., 2015). The reason for this underestimation may be that the composition of SBM has changed over time, possibly due to changes in the composition of soybeans, but it is also possible that the increased ME in SBM that has been determined in recent years simply reflects improved techniques for determination of ME values in feed ingredients.

The observation that SBM from India had the lowest concentration of ME among the five countries concurs with data from broiler chickens that indicated that the apparent ME in SBM from India is less than in SBM from USA, Argentina, and Brazil (Ravindran et al., 2014). This result is most likely caused by the greater concentration of TIU in SBM from India than in SBM from other countries, which compromises the digestibility of CP and AA. Indeed, SBM from India had reduced digestibility of CP compared with SBM from USA and China when fed to pigs (Lagos and Stein, 2017). Other factors likely affecting the concentration of DE and ME in SBM from India is the lower concentration of sucrose than in SBM from USA, Argentina, and China, and the greatest concentration of raffinose in Indian SBM than in SBM from other countries. Sucrose is highly digestible and was positively correlated to the CATTD of GE, which concurs with data from broilers indicating a positive correlation between sucrose and the digestibility and concentration of energy in SBM (de Coca-Sinova et al., 2008; Ravindran et al., 2014). However, raffinose is considered an anti-nutritional factor in diets for both pigs and poultry (Choct et al., 2010). Despite the lack of differences in the concentration of IDF or TDF among SBM from different countries, the negative correlation between IDF and DE or ME, and between TDF and the CATTD of GE, supports that fiber may act as a physical barrier for nutrient digestion (Abelilla and Stein, 2018). Likewise, the negative correlation between TIU and DE or ME concurs with the reduced concentration of DE and ME in SBM from India. The observation that the ME of SBM from Argentina is greater compared with SBM from USA is in contrast with data from poultry and pigs (Ravindran et al., 2014; Li et al., 2015), and was not expected because the digestibility and concentration of CP was greater in SBM from USA than in SBM from Argentina (Lagos and Stein, 2017). However, the CATTD of GE was greater in SBM from Argentina than in SBM from other countries, which in combination with a slightly greater GE resulted in the Argentinian SBM having the greatest DE and ME. The greater CATTD of GE and concentration of DE in SBM from Argentina than in SBM from USA may be a result of the greater SDF in SBM from Argentina, which is easily fermented in the hindgut of pigs, and thus, increasing the synthesis and absorption of volatile fatty acids from the large intestine (Agyekum and Nyachoti, 2017).

Only small variations in the concentration of DE and ME in SBM among Argentina, Brazil, China, and USA were observed, which concurs with data from Li et al. (2015), and indicates that importers of SBM may use common ME values for SBM from these countries. In contrast, SBM imported from India should be analyzed for TDF and TIU before usage to make sure that an acceptable product is purchased. However, only a small portion of SBM produced in India is exported (around 1.85 million t; USDA, 2019) and most Indian SBM is used locally. China imports soybeans from USA, Brazil, and Argentina for their crushing industry in addition to using locally produced soybeans, but the SBM from China used in this experiment was obtained from crushing plants that used only soybeans grown in China. However, due to the relatively low variability in the SBM among Brazil, Argentina, USA, and China, it is unlikely that the origin of the soybeans will have much effect on the ME value of the SBM produced in China, if similar crushing conditions are used. Because of the deficit of SBM in the Chinese feed industry, Chinese SBM is usually not exported to other countries.

4.3. *Differences in DE and ME values within countries*

Variability in the concentration of DE and ME within a country is important because it indicates the likelihood of receiving an ingredient from a specific country that is consistent in terms of the energy value. Based on the 4–5 different sources of SBM that were obtained from each country, it was observed that there are no differences in the concentration of ME among different sources of SBM from USA, which is in agreement with data from broiler chickens indicating that the least variability in concentration of apparent ME was observed among sources of SBM from USA, whereas Indian SBM had the greatest variability followed by Brazilian and Argentinian SBM (Ravindran et al., 2014). García-Rebollar et al. (2016) also reported a lower variability in the calculated apparent ME of SBM sources from USA than in SBM from Brazil or Argentina. However, when the concentration (DM basis) of DE and ME in SBM sources from 4 different zones of USA fed to pigs was compared, values from 1 zone were lower than in the others 3 zones (Sotak-Peper et al., 2015). The observation that the coefficient of variation for DE and ME in SBM from USA, Argentina, and Brazil is lower than in SBM from China or India indicates that if SBM from USA, Argentina, or Brazil is used, the likelihood of receiving a consistent product in terms of ME value is greater than if Chinese or Indian SBM is used.

5. Conclusions

Based on analysis of 4 or 5 sources of soybean meal from Argentina, China, Brazil, India, and USA, it was concluded that different sources of soybean meal differed in nutrient composition. The 4 sources of soybean meal from India had the greatest concentrations of raffinose, neutral detergent fiber, insoluble dietary fiber, and total dietary fiber, and the lowest concentration of sucrose, which resulted in lower concentrations of digestible energy and metabolizable energy compared with soybean meal from the other countries. This variability should be taken in account when diets for pigs are formulated. The variability in the digestibility of gross energy and the concentration of digestible energy and metabolizable energy in soybean meal from Argentina, Brazil, China, and USA was relatively low, although Argentinian soybean meal had an increased energy value compared with soybean meal from the USA, likely because of a greater concentration of soluble dietary fiber. Likewise, soybean meal from Argentina, USA, and Brazil had less variability among sources within each country than Chinese or Indian soybean meal.

Author statement

HHS conceptualized the experiment and organized logistics. DAL conducted the animal part and the laboratory analyses of the experiment. DAL and LVL analyzed the data, and wrote the first draft of the manuscript. HHS contributed with data interpretation and proofreading of manuscript. HHS also supervised the project. All authors edited and approved the final version of the manuscript.

Declaration of Competing Interest

The authors have no conflicts of interest.

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