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Prediction of digestible and metabolisable energy in soybean meals produced from soybeans of different origins fed to growing pigs

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The objective of this experiment was to determine the digestible energy (DE) and metabolisable energy (ME) in 22 sources of soybean meal (SBM) produced from soybeans from different countries and subsequently to establish equations for predicting the DE and ME in SBM based on their chemical composition. The 22 sources of SBM were all processed in Chinese crushing plants, but the soybeans used originated from China (n = 6), the US (n = 6), Brazil (n = 7) or Argentina (n = 3). The basal diet was a corn-based diet and 22 additional diets were formulated by mixing corn and 24.3% of each source of SBM. The average DE and ME in SBM from China, the US, Brazil and Argentina were 15.73, 15.93, 15.64 and 15.90 MJ/kg and 15.10, 15.31, 14.97 and 15.42 MJ/kg, respectively, and no differences among countries were observed. From a stepwise regression analysis, a series of DE and ME prediction equations were generated. The best-fit equations for SBM were DE = 38.44–0.43 crude fibre −0.98 gross energy +0.11 acid detergent fibre (R^2 = 0.67, p < 0.01) and ME = 2.74 + 0.97 DE −0.06 crude protein (R^2 = 0.79, p < 0.01). In conclusion, there were no differences in the DE and ME of SBM among the different soybean sources used in this experiment. The DE and ME of SBM of different origin can be predicted based on their chemical composition when fed to growing pigs.

Keywords: energy content; nutrient content; pigs; prediction; production location; soyabean oilmeal

1. Introduction

Soybean is the most common source of plant protein used in swine diets (Stein et al. 2008). In 2013, the countries with the greatest production were the US (89.5 million tons), Brazil (87.5 million tons), Argentina (54 million tons) and China (12.2 million tons) (ASA 2015). There are considerable quantities of these soybeans imported and processed in China, where the US, Brazil and Argentina are the three largest exporters of soybeans to China.

Soybean variety and growing and processing conditions may affect the composition of soybean meal (SBM) (Grieshop et al. 2003). The chemical composition and protein quality of SBM from different countries have been reported, e.g. by Karr-Lilienthal et al. (2005), Mateos et al. (2011) and Frikha et al. (2012). However, limited published information is available on comparison of digestible energy (DE) and metabolisable energy (ME) of SBM produced from soybeans grown in different countries, but processed

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*Corresponding author. Email: laichanghua999@163.com in China. Therefore, we hypothesised that there are differences in DE and ME of SBM produced from soybeans grown in different countries.

Recent research has been conducted to determine the effects of special processing of SBM, such as extruded-expelled SBM (Opapeju et al. 2006; Powell et al. 2011), high-protein, low-oligosaccharide SBM (Baker and Stein 2009; Baker et al. 2014) and fermented SBM (Rojas and Stein 2013). However, these special SBM only supply a niche market and the most common SBM is still conventional SBM processed using the solvent extraction procedure (Wang and Johnson 2001). Therefore, the objective of this study was to test the hypothesis that conventional SBM processed from soybeans grown in different countries have different DE and ME. The second objective was to develop prediction equations to predict DE and ME in SBM based on chemical composition.

2. Materials and methods

The experimental protocol used in this study was approved by the Institutional Animal Care and Use Committee at China Agricultural University (Beijing, China).

2.1. SBM sample collection

Twenty-two SBM samples were collected from 13 medium- and large-scale soybean processors located in the 8 provinces of China, which are the main SBM-producing areas. Information about the origin of the soybeans used to produce the SBM was obtained before collecting the SBM. The soybeans used to produce the 22 SBM originated from China (n = 6), the US (n = 6), Brazil (n = 7) and Argentina (n = 3).

All soybeans were dehulled before crushing, but in some cases, hulls were added back to the meal after crushing. Thus, there were 12 sources of regular SBM that had hulls added back to the meal (regular SBM) and 10 sources that had no hulls added after crushing (dehulled SBM). One source of SBM (source 12) had soapstock added after crushing, but the other sources contained no soapstock. Specific processing information, chemical composition and amino acid (AA) content of the 22 SBM are shown in Tables 1, 2 and 3, respectively.

2.2. Animals, diets and experimental design

Sixty-nine crossbred (Duroc × Landrace × Yorkshire) growing barrows (initial body weight for periods 1 and were 53.1 ± 3.7 kg and 63.6 ± 6.1 kg, respectively) were allotted to 1 of 23 diets using a two-period changeover design (Gill and Magee 1976). The basal diet was based on corn and 22 additional diets were formulated by mixing corn and 24.34% of each of the 22 sources of SBM (Table 4). All ingredients were ground through a 2.5 mm screen (hammer mill). The chemical composition of the experimental diets is shown in Table 5.

During each experimental period, all pigs were individually housed in stainless steel metabolism crates with a feeder and a nipple drinker. Crates were placed in an environmentally controlled room with the temperature maintained at 22 ± 2°C. Two equal-sized meals were fed daily at 08:30 h and 15:30 h at a rate of 4% of individual pig body weight. Water was freely available from a drinking nipple. The experimental period lasted 12 d, which included 7 d to adapt to diets and 5 d for collection of faeces and urine.

Table 1. Origin of soybean meal.

No.	Source of soybean	Plants*	Location of plants in China	Processing#
1	China	A1	Heilongjiang	Dehulled
2	China	B1	Heilongjiang	Regular
3	China	B2	Heilongjiang	Regular
4	China	C1	Heilongjiang	Regular
5	China	C2	Heilongjiang	Dehulled
6	China	A2	Hebei	Dehulled
7	US	D1	Jiangsu	Regular
8	US	E1	Shandong	Regular
9	US	E2	Shandong	Regular
10	US	F1	Henan	Regular
11	US	G	Shandong	Regular
12	US	H1	Tianjin	Regular†
13	Brazil	I1	Guangdong	Regular
14	Brazil	I2	Guangdong	Regular
15	Brazil	I3	Guangdong	Dehulled
16	Brazil	J	Guangdong	Dehulled
17	Brazil	K	Shandong	Regular
18	Brazil	H2	Tianjin	Dehulled
19	Brazil	H3	Jiangsu	Dehulled
20	Argentina	F2	Henan	Dehulled
21	Argentina	L	Shandong	Dehulled
22	Argentina	M	Shandong	Dehulled

Notes: *The same capital letter means that the soybeans were processed in the same facility; #Regular means that soybean hulls were added to the crushed meal and dehulled means that no hulls were added after crushing; †Soapstock was added to the crushed meal (only this plant).

2.3. Sample collection

Feed refusals and spillage were collected twice daily and subsequently dried and weighed. Faeces were collected in plastic bags immediately as they appeared in the metabolism crates and stored at −20°C. Urine was collected in buckets located under the metabolism crates. The buckets contained 10 ml of 6 N HCl for every 1000 ml of urine. The volume of collected urine was measured and 5% of the daily urinary collection was stored at −20° C. At the end of the collection period, faeces and urine were separately thawed and mixed within animal and a representative subsample was obtained for chemical analysis. Before analysis, faecal subsamples were dried at 65°C in a drying oven for 72 h and ground through a 1 mm screen.

2.4. Chemical analysis and calculations

All samples of SBM and diets used in this experiment were analysed for dry matter (DM) (AOAC 2007, Procedure 930.15), crude protein (CP) (AOAC 2007, Procedure 984.13), ash (AOAC 2007, Procedure 942.05), calcium (AOAC 2007, Procedure 927.02), phosphorus (AOAC 2007, Procedure 984.27) and ether extract (EE) (Thiex et al. 2003). Acid hydrolysed ether extract (AEE) was determined by acid hydrolysis using 3 N HCl followed by crude fat extraction using petroleum ether (AOAC 2007, Procedure 2003.06) on a Soxtec 2050 Automated Analyzer (FOSS North America, Eden Prairie, MN, USA). Crude fibre (CF), neutral detergent fibre (NDF) and acid

Table 2. Chemical composition of the different soybean meals (n = 22).

	Source of soybeans													
	China (n = 6)			US (n = 6)			Brazil (n = 7)			Argentina (n = 3)				
	Mean	Range	CV†	Mean	Range	CV	Mean	Range	CV	Mean	Range	CV	SEM$^{\#}$	p-Value
Gross energy [MJ/kg DM*]	19.59	19.23–19.99	1.40	19.27	18.94–19.66	1.31	19.45	19.18–19.72	1.14	19.72	19.59–19.90	0.83	0.10	0.06
DM [%]	89.68^{a}	89.03–90.92	0.80	89.80^{a}	89.41–90.22	0.32	89.61^{a}	89.42–90.06	0.23	88.73^{b}	88.49–89.09	0.36	0.19	0.02
Crude protein [% DM]	50.22	47.74–51.69	2.98	49.39	48.25–50.21	1.78	51.12	45.31–53.72	5.43	48.79	45.27–51.25	6.41	0.94	0.35
Ether extract [% DM]	0.83	0.23–1.27	44.11	1.20	0.69–1.91	38.34	0.95	0.29–1.32	37.43	1.13	0.49–1.57	49.92	0.18	0.44
AEE‡ [% DM]	1.21	0.77–1.34	18.01	1.66	1.16–2.18	20.84	1.52	0.78–1.81	24.20	1.68	1.19–2.04	26.42	0.15	0.12
NDF¶ [% DM]	14.77^{a}	12.08–19.45	20.02	14.75^{a}	13.14–19.37	15.56	14.37^{a}	11.74–19.47	17.57	9.82^{b}	9.68–10.07	2.18	1.09	0.04
ADF$^{\blacklozenge}$ [% DM]	5.99	4.14–8.07	27.76	7.22	5.72–11.33	28.27	7.40	5.87–11.86	28.20	4.86	4.17–5.28	12.44	0.82	0.19
Crude fibre [% DM]	5.24	3.64–6.95	23.84	5.81	5.30–6.34	6.02	6.19	4.19–9.9	30.61	4.51	4.4–4.66	3.05	0.57	0.27
Ash [% DM]	6.44	6.21–6.67	2.86	6.65	6.17–6.85	4.03	6.77	6.33–7.02	3.39	6.41	5.67–7.04	10.81	0.14	0.22
Calcium [% DM]	0.36	0.22–0.52	26.75	0.44	0.27–0.55	22.60	0.50	0.41–0.75	25.31	0.40	0.32–0.52	26.60	0.05	0.20
Phosphorus [% DM]	0.83^{a}	0.80–0.87	3.10	0.72^{b}	0.68–0.74	3.77	0.69^{b}	0.6–0.72	5.98	0.67^{b}	0.61–0.71	7.67	0.02	< 0.01
Sucrose [% DM]	5.20^{a}	4.65–5.75	8.21	5.94^{a}	4.78–7.12	13.63	3.72^{b}	2.97–5.08	19.64	4.99^{a}	4.93–5.07	1.48	0.28	< 0.01
Raffinose [% DM]	0.52^{b}	0.39–0.66	17.73	0.82^{a}	0.68–0.95	14.74	0.90^{a}	0.69–1.25	21.31	0.68^{ab}	0.56–0.88	26.55	0.07	< 0.01
Stachyose [% DM]	1.79^{b}	1.46–2.03	13.82	2.66^{a}	2.11–3.27	18.38	1.41^{b}	1.16–2.14	24.96	1.73^{b}	1.48–1.96	14.03	0.16	< 0.01

Notes: †CV, Coefficient of variation;*DM, Dry matter; ‡AEE, Acid hydrolysed ether extract; ¶NDF, Neutral detergent fibre; $^{\blacklozenge}$ADF, Acid detergent fibre; $^{\#}$SEM, Standard error of the mean; comparison of the mean of different source SBM; ^{a},^{b}Least square means within a row with different superscript letters are significantly different.

Table 3. Analysed amino acid composition of the tested soybean meals [in % of dry matter] (n = 22).

	Source of soybeans													
	China (n = 6)			US (n = 6)			Brazil (n = 7)			Argentina (n = 3)				
	Mean	Range	CV*	Mean	Range	CV	Mean	Range	CV	Mean	Range	CV	SEM#	*p*-Value
Indispensable amino acids														
Arginine	3.91^{a}	3.74–4.06	3.79	3.64^{ab}	3.36–3.80	4.68	3.65^{ab}	3.46–3.90	4.19	3.38^{b}	3.07–3.78	10.73	0.08	<0.01
Histidine	1.45	1.34–1.63	7.57	1.41	1.36–1.50	4.14	1.44	1.37–1.53	3.88	1.38	1.36–1.41	2.19	0.03	0.54
Isoleucine	2.18	2.04–2.41	6.34	2.16	1.91–2.33	6.62	2.25	2.05–2.39	5.73	2.09	1.97–2.17	5.19	0.06	0.33
Leucine	3.76	3.51–4.07	5.59	3.79	3.48–3.95	4.43	3.89	3.65–4.16	4.16	3.88	3.80–3.93	1.84	0.08	0.49
Lysine	3.32	3.19–3.46	3.77	3.26	3.08–3.36	3.29	3.22	3.06–3.47	4.28	3.12	2.90–3.33	6.76	0.06	0.27
Methionine	0.68	0.63–0.74	6.21	0.67	0.63–0.69	3.36	0.65	0.61–0.69	5.01	0.71	0.67–0.77	7.92	0.02	0.19
Phenylalanine	2.46	2.29–2.71	6.21	2.45	2.33–2.52	3.05	2.57	2.36–2.76	4.79	2.48	2.41–2.57	3.35	0.05	0.25
Threonine	2.04	1.90–2.40	9.34	2.02	1.76–2.25	8.21	2.03	1.82–2.24	7.50	1.93	1.86–1.98	3.11	0.07	0.81
Tryptophan	0.63	0.59–0.67	5.10	0.62	0.57–0.65	4.25	0.62	0.57–0.67	6.14	0.60	0.57–0.63	4.85	0.01	0.76
Valine	2.40	2.27–2.61	5.84	2.40	2.13–2.51	5.92	2.41	2.23–2.53	4.36	2.19	2.00–2.43	9.90	0.06	0.18
Dispensable amino acids														
Alanine	2.31	2.20–2.47	4.71	2.26	2.02–2.37	5.50	2.28	2.13–2.37	3.73	2.19	2.11–2.26	3.26	0.05	0.46
Aspartic acid	5.87	5.60–6.28	5.04	5.73	5.18–6.04	5.46	5.80	5.39–6.07	4.21	5.45	5.10–5.76	6.13	0.13	0.25
Cysteine	0.74^{a}	0.68–0.83	7.53	0.70^{ab}	0.65–0.73	4.73	0.68^{b}	0.64–0.72	4.32	0.67^{b}	0.64–0.70	4.68	0.02	0.04
Glutamic acid	8.46	8.16–9.01	4.17	8.29	7.75–8.78	5.11	8.23	7.46–9.15	6.95	8.46	8.13–8.65	3.41	0.20	0.77
Glycine	2.14	2.04–2.33	5.27	2.12	1.84–2.28	7.52	2.13	2.01–2.29	5.11	1.96	1.85–2.04	5.01	0.06	0.23
Proline	2.43	2.22–2.68	7.49	2.34	1.98–2.56	9.83	2.39	1.89–2.72	10.51	2.31	2.21–2.46	5.70	0.10	0.85
Serine	2.62	2.52–2.78	4.14	2.56	2.41–2.69	4.38	2.55	2.36–2.78	5.65	2.41	2.23–2.66	9.37	0.06	0.26
Tyrosine	1.94	1.84–2.03	3.54	1.87	1.70–2.03	6.66	1.88	1.73–2.04	6.84	1.90	1.82–1.95	3.63	0.05	0.73

Notes: *CV, Coefficient of variation; #SEM, Standard error of the mean; comparison of the mean of different source SBM; ^{a,b}Least square means within a row not sharing the same superscript are significantly different ($p < 0.05$).

Table 4. Ingredient composition of the experimental diets.

	Basal diet	Test diets (*n* = 22)
Corn	97.34	73.01
Soybean meal	0.00	24.34
Limestone	0.90	0.90
Dicalcium phosphate	0.90	0.90
Sodium chloride	0.30	0.30
Choline chloride	0.06	0.06
Vitamin and mineral premix*	0.50	0.50

Notes: *Supplied per kg of diet: vitamin A, 5512 IU; vitamin D_3, 2200 IU; vitamin E, 30 mg; vitamin K_3, 2.2 mg; vitamin B_{12}, 27.6 µg; riboflavin, 4 mg; pantothenic acid, 14 mg; niacin, 30 mg; choline chloride, 400 mg; folic acid, 0.7 mg; thiamine, 1.5 mg; pyridoxine, 3 mg; biotin, 44 µg; Mn (MnO), 40 mg; Fe ($FeSO_4 \cdot H_2O$), 75 mg; Zn (ZnO), 75 mg; Cu ($CuSO_4 \cdot 5H_2O$), 100 mg; I (KI), 0.3 mg; Se (Na_2SeO_3), 0.3 mg.

Table 5. Chemical composition of the experimental diets [% as-fed basis].

	Dry matter	Crude protein	EE*	AEE†	NDF‡	ADF¶	Crude fibre	Ash	Calcium	Phosphorus
Basal diet	86.93	7.82	2.44	2.79	10.66	2.07	2.41	3.17	0.67	0.46
SBM# diets										
1	87.43	17.05	1.86	2.41	9.52	2.63	2.69	4.70	0.78	0.50
2	87.44	16.67	2.14	2.46	10.51	3.31	2.56	4.36	0.73	0.47
3	87.40	16.33	2.30	2.66	10.75	3.15	2.83	4.33	0.72	0.49
4	87.17	16.34	1.99	2.47	10.95	3.50	2.54	4.22	0.69	0.43
5	87.13	16.99	2.12	2.53	10.48	2.42	1.94	4.32	0.66	0.48
6	87.36	17.60	2.28	2.78	10.31	2.64	1.88	4.29	0.70	0.47
7	87.27	16.40	2.12	2.43	11.61	3.09	2.68	4.18	0.59	0.44
8	87.31	16.65	2.02	2.42	11.36	2.97	2.72	4.37	0.66	0.44
9	87.30	16.62	2.44	2.75	11.41	2.83	2.51	4.24	0.77	0.44
10	87.25	16.69	2.61	3.01	10.92	3.09	2.36	4.07	0.68	0.43
11	87.24	15.94	2.58	2.97	12.86	3.31	2.92	4.36	0.69	0.45
12	87.56	16.71	2.80	3.18	11.91	2.99	2.93	4.36	0.71	0.46
13	87.21	15.88	2.28	2.61	15.04	4.40	3.55	4.27	0.68	0.21
14	87.32	17.11	2.27	2.72	13.10	3.20	3.84	4.37	0.61	0.44
15	87.41	17.31	2.16	2.55	11.72	2.81	2.74	4.37	0.72	0.46
16	87.39	17.11	2.47	2.88	14.06	3.33	3.29	4.24	0.68	0.44
17	87.35	16.57	2.51	2.83	14.06	3.36	3.48	4.12	0.68	0.65
18	87.15	17.22	2.30	2.82	11.77	3.08	2.95	4.21	0.74	0.46
19	87.59	17.05	2.26	2.78	10.68	2.90	2.66	4.26	0.63	0.44
20	87.44	16.98	2.30	2.66	13.52	2.94	2.43	4.30	0.66	0.45
21	87.55	16.49	2.34	2.75	12.33	2.99	2.81	4.35	0.69	0.37
22	87.57	15.77	2.15	2.48	11.80	2.61	2.60	4.19	0.67	0.42

Notes: *EE, Ether extract; †AEE, Acid hydrolysed ether extract; ‡NDF, Neutral detergent fibre; ¶ADF, Acid detergent fibre; #SBM, Soybean meal, sources are described in Table 1.

detergent fibre (ADF) were determined using filter bags and fibre analyser equipment (Fibre Analyzer, Ankom Technology, Macedon, NY, USA) following a modification of the procedure of Van Soest et al. (1991). The sucrose, raffinose and stachyose in the ingredients were analysed as described by Cervantes-Pahm and Stein (2010). The gross energy (GE) in ingredients, faeces and urine were analysed using an isoperibol calorimeter (Parr 6400 Calorimeter, Moline, IL, USA) with benzoic acid as a standard.

The GE in urine samples was measured after 4 ml of sample were dripped into two filter papers in a special crucible and dried for 8 h at 65°C in a drying oven (Zhang et al. 2014).

All samples of SBM were also analysed for AA according to Huang et al. (2014). Fifteen AA were determined after hydrolysis with 6 N HCl at 110°C for 24 h using an Amino Acid Analyzer (Hitachi L-8900, Tokyo, Japan). Methionine and cysteine were determined as methionine sulfone and cysteic acid after cold performic acid oxidation overnight and samples were then hydrolysed with 7.5 N HCl at 110°C for 24 h using an Amino Acid Analyzer (Hitachi L-8800, Tokyo, Japan). Tryptophan was determined after LiOH hydrolysis for 22 h at 110°C using HPLC (Agilent 1200 Series, Santa Clara, CA, USA).

The GE intake was calculated as the product of the GE of the diet and the actual feed intake over the 5 d collection period. The DE and ME of diets were calculated for each pig and diet using the direct procedure according to Adeola (2001). The DE and ME of each source of SBM were calculated using the difference method (Adeola 2001).

2.5. *Statistical analysis*

All data were subjected to analysis of variance using the Proc GLM procedure of SAS (SAS Institute Inc., Carry, NC, USA). The differences among each country (China, the US, Brazil and Argentina) were analysed using source as fixed effect and pig and period as random effects. To compare the differences among the four countries, the average data in each country were a fixed effect and pig and period were random effects. If significant differences were identified, the Student Newman–Keuls test was used to separate the means. In all analyses, the differences were considered significant if $p < 0.05$ and considered a trend at $p < 0.1$.

The chemical composition, DE and ME of the SBM were correlated using PROC CORR procedure. Prediction equations were developed by the PROC REG procedure of SAS to estimate the DE and ME of SBM (Sulabo and Stein 2013; Maison et al. 2015). The R^2, $C(p)$, Akaike information criterion (AIC), root mean square error (RMSE) and p-value of the model were calculated to compare these different equations. The prediction equation with $C(p)$ criterion closest to the number of predictors in the candidate model +1, the lowest AIC and the lowest RMSE were considered the optimal model.

3. Results

3.1. *Chemical composition of SBM sources*

The chemical composition of the SBM sources was variable (Table 2). The coefficient of variation (CV) of EE, AEE, NDF, ADF, CF, calcium and oligosaccharides was >10%. On a DM basis, the average CP in SBM from China, the US, Brazil and Argentina was 50.2%, 49.4%, 51.1% and 48.8%, respectively. The SBM from Argentina had less DM and NDF than the other three sources ($p < 0.05$). The phosphorus content in Chinese SBM was the highest among the four countries ($p < 0.01$), whereas the Chinese SBM contained the least raffinose ($p < 0.01$). The Brazilian SBM contained the least sucrose ($p < 0.01$) while the US SBM contained the highest stachyose ($p < 0.01$).

The concentration of AA varied among sources of SBM according to the origin of the beans (Table 3). The SBM from China had the greatest ($p < 0.05$) concentration of arginine and cysteine.

3.2. Energy concentration and energy digestibility

The DE and ME in the corn basal diet were 13.96 and 13.70 MJ/kg (Table 6), whereas the DE and ME in the 22 SBM sources ranged from 14.57 to 16.68 MJ/kg (mean = 15.77 MJ/kg) and from 14.25 to 16.07 MJ/kg (mean = 15.13 MJ/kg), respectively. There was a trend ($p < 0.1$) for the DE content to be different among sources of Chinese SBM. The GE in faeces, apparent total tract digestibility (ATTD) of GE, DE and ME were different ($p < 0.05$) among the six sources of SBM from the US. Differences among the seven Brazilian and among the three Argentinian SBM were not observed. Pigs fed the corn basal diet had less ($p < 0.05$) energy lost in the urine than pigs fed the SBM diets. The DE and ME in the SBM diets were greater ($p < 0.05$) than in the corn basal diet. SBM from source 12 had the greatest ($p < 0.05$) DE, whereas SBM source 13 had the least ($p < 0.05$, data are not shown) DE among the 22 SBM sources.

The average DE and ME in SBM produced from soybeans obtained from China, the US, Brazil and Argentina were 15.73, 15.93, 15.64 and 15.90 MJ/kg and 15.10, 15.31, 14.97 and 15.42 MJ/kg, respectively (Table 6). There was no difference among the different soybean origins in DE and ME content of the SBM.

3.3. Correlations and prediction equations of energy values

Correlation coefficients (r) between chemical characteristics and energy values of the 22 SBM samples are shown in Table 7. The concentration of CP was negatively correlated with the concentrations of EE, AEE, ADF and CF ($p < 0.05$). The EE content had a significant positive correlation with AEE content ($r = 0.85$, $p < 0.01$). The three measures of fibre in the SBM (NDF, ADF and CF) were negatively correlated with DE ($p < 0.05$). The DE had a significant positive correlation with ME ($r = 0.85$, $p < 0.01$).

Equations were developed to predict the DE and ME for SBM from their chemical characteristics (Table 8). CF was the best single predictor for DE of SBM, but the accuracy of the equations was improved if GE and ADF were included in the prediction. The best model for prediction of DE was Equation (3) (Table 8). The DE content can be used to predict the ME content, but if CP was included in the model, the R^2 was improved and led to a lower RMSE. The best ME prediction was reached with Equation (5) (Table 8).

4. Discussion

4.1. Chemical composition of SBM sources

Processing conditions (such as temperature, moisture, residence time and fineness) may result in SBM of varying residual oil content. The solvent extraction procedure has an extraction efficiency of 99% for separation of oil from the remainder of the soybean (Grieshop et al. 2003), which led to a relatively low residual oil content in the resultant SBM. However, there was no difference in the EE content among the different sources of SBM, which may be due to the fact that the high oil extraction efficiency minimised the variability among sources. The greater EE and AEE in SBM source 12 (data are not shown) may be a result of addition of soapstock to this source.

The concentration of CP in SBM from Brazil was greater than in SBM from China, the US and Argentina, which is in agreement with previous data (Thakur and Hurburgh 2007; Frikha et al. 2012). Differences in CP in the meals depend on the CP in the beans as

Table 6. Daily energy intake of the basal diet, soybean meal (SBM) diets and the energy concentration of the different SBM sources.

		Source of soybeans													
		China (n = 6)			US (n = 6)			Brazil (n = 7)			Argentina (n = 3)				
	Basal diet	Mean	Range	p-Value[‡]	Mean	Range	p-Value[‡]	Mean	Range	p-Value[‡]	Mean	Range	p-Value[‡]	SEM[◊]	p-Value[¶]
GE* intake [MJ/d]	35.95	34.99	33.83–36.24	0.96	35.35	34.33–37.37	0.90	35.77	33.51–38.03	0.54	35.04	33.14–37.36	0.25	0.79	0.87
GE in faeces [MJ/d]	3.98	3.75	3.52–4.07	0.24	3.72	3.40–4.40	0.02	3.97	3.63–4.33	0.49	3.69	3.58–3.81	0.78	0.11	0.17
GE in urine [MJ/d]	0.56	0.77	0.62–1.14	0.31	0.77	0.62–0.94	0.64	0.80	0.60–1.00	0.49	0.67	0.66–0.69	0.96	0.07	0.66
ATTD[#] of GE [%]	88.97	89.25	88.50–89.68	0.22	89.45	88.12–90.16	0.04	88.87	87.73–89.31	0.55	89.47	89.18–89.83	0.28	0.23	0.17
DE[†] in diet [MJ/kg]															
As-fed basis	13.96	14.30	14.17–14.47	0.07	14.35	14.10–14.53	0.02	14.28	14.02–14.38	0.17	14.34	14.29–14.41	0.19	0.04	0.46
Dry matter basis	16.05	16.37	16.21–16.56	0.05	16.43	16.16–16.59	0.04	16.34	16.07–16.46	0.23	16.38	16.34–16.46	0.23	0.04	0.50
ME[§] in diet [MJ/kg]															
As-fed basis	13.70	13.95	13.77–14.12	0.13	14.00	13.76–14.19	0.05	13.92	13.75–14.06	0.51	14.03	13.98–14.12	0.29	0.04	0.27
Dry matter basis	15.76	15.98	15.75–16.16	0.09	16.04	15.77–16.20	0.10	15.94	15.76–16.10	0.61	16.03	15.98–16.13	0.35	0.05	0.38
DE in SBM [MJ/kg]															
As-fed basis	–	15.73	15.22–16.43	0.07	15.93	14.92–16.68	0.02	15.64	14.57–16.07	0.18	15.90	15.72–16.20	0.19	0.16	0.46
Dry matter basis	–	17.54	17.10–18.07	0.31	17.74	16.68–18.49	0.03	17.45	16.27–17.89	0.20	17.92	17.74–18.19	0.33	0.17	0.28
ME in SBM [MJ/kg]															
As-fed basis	–	15.10	14.34–15.77	0.13	15.31	14.30–16.07	0.05	14.97	14.25–15.56	0.50	15.42	15.20–15.80	0.30	0.18	0.28
Dry matter basis	–	16.84	15.97–17.35	0.23	17.04	16.00–17.81	0.08	16.70	15.91–17.27	0.56	17.38	17.15–17.74	0.42	0.19	0.13

Notes: *GE, Gross energy; [#]ATTD, Apparent total tract digestibility; [†]DE, Digestible energy; [§]ME, Metabolisable energy; [‡]p-Value, Comparison of SBM sources from each country; [◊]SEM, Standard error of the mean, [¶]p-Value, Comparison of the mean of SBM sources from different countries.

Table 7. Correlation coefficients (r) between chemical characteristics and energy values of the tested soybean meal samples (n = 22).

	GE[#]	CP[†]	EE[‡]	AEE[§]	NDF[£]	ADF[◊]	CF[♦]	Ash	DE[+]	ME[¤]
GE	1.00									
CP	0.21	1.00								
EE	−0.39	−0.56**	1.00							
AEE	−0.40	−0.47*	0.85**	1.00						
NDF	−0.23	−0.34	0.18	0.04	1.00					
ADF	−0.23	−0.45*	0.33	0.29	0.84**	1.00				
CF	−0.42	−0.55**	0.29	0.27	0.69**	0.85**	1.00			
Ash	−0.09	0.65**	−0.18	−0.16	−0.06	0.04	0.02	1.00		
DE	−0.16	0.28	0.13	0.16	−0.46*	−0.48*	−0.63**	0.13	1.00	
ME	−0.14	0.06	0.27	0.23	−0.30	−0.27	−0.43*	−0.02	0.85**	1.00

Notes: [#]GE, Gross energy; [†]CP, Crude protein; [‡]EE, Ether extract; [§]AEE, Acid hydrolysed ether extract; [£]NDF, Neutral detergent fibre; [◊]ADF, Acid detergent fibre; [♦]CF, Crude fibre; [+]DE, Digestible energy; [¤]ME, Metabolisable energy; *$p < 0.05$, **$p < 0.01$.

Table 8. Linear regression equations for prediction of energy content based on the chemical composition of soybean meal fed to growing pigs*.

No.	Linear regression equations[◊]	R^2	RMSE[#]	$C(p)$[†]	AIC[§]	p-Value
1	DE [MJ/kg DM] = 18.86–0.21 CF [%]	0.40	0.37	14.29	−40.08	<0.01
2	DE [MJ/kg DM] = 35.94–0.29 CF [%] – 0.86 GE [MJ/kg DM]	0.62	0.30	4.90	−47.59	<0.01
3	DE [MJ/kg DM] = 38.44–0.43 CF [%] – 0.98 GE [MJ/kg DM] + 0.11 ADF [%]	0.67	0.28	4.01	−48.88	<0.01
4	ME [MJ/kg DM] = 1.21 + 0.89 DE [MJ/kg DM]	0.73	0.26	−1.32	−55.12	<0.01
5	ME [MJ/kg DM] = 2.74 + 0.97 DE [MJ/kg DM] – 0.06 CP [%]	0.79	0.23	−2.71	−58.23	<0.01

Notes: *Regression equations were developed based on stepwise regression analyses; [◊]DE, Digestible energy; CF, Crude fibre; GE, Gross energy; ADF, Acid detergent fibre; ME, Metabolisable energy; CP, Crude protein; [#]RMSE, Root mean square error is a measure of precision; [†]$C(p)$, Conceptual predictive statistic, the criterion used to determine candidate models that maximise explained variability (R^2) with as few variables as possible. Candidate models are those where $C(p)$ is close to the number of predictors in the candidate model + 1; [§]AIC, Akaike information criterion, which measures the fit of the model (smaller AIC is a better fit of the model).

well as the proportion of hulls removed or added during processing because CP content in SBM may be adjusted by addition of hulls. The SBM sources 13, 14 and 15 were collected from the same crushing plant, but source 13 had the greatest amount of hulls added during processing followed by source 14, whereas source 15 did not contain hulls. As expected, CP decreased and NDF, ADF and CF content increased as the amount of hulls added to the meal increased.

The concentration of NDF was the least for SBM samples from Argentina, which is likely because these three sources of SBM did not have hulls added after processing. However, the average CP in Argentinian SBM was least among the four countries. These results support the conclusion by Thakur and Hurburgh (2007), who reported that CP was less for soybeans from Argentina compared with soybeans from the US and Brazil.

The reduced concentration of sucrose and stachyose in SBM produced from beans grown in Brazil compared with SBM produced from beans grown in the US, China or Argentina is consistent with data of previous studies (Mateos et al. 2011; Frikha et al.

2012). These data are also in agreement with the hypothesis that an adverse relationship between CP and sucrose in soybeans exists (Baker et al. 2010; Yoon and Stein 2013).

The concentration of all AA of the SBM were in agreement with previous results (Thakur and Hurburgh 2007; Frikha et al. 2012).

4.2. *Energy concentration and energy digestibility*

The corn basal diet contained less CP than the SBM diets, which explained that less energy was lost from urine in the pigs fed the basal diet compared with pigs fed the SBM diets. In previous work, SBM diets contained more DE than a corn basal diet (Baker and Stein 2009; Rojas and Stein 2013; Baker et al. 2014) and the current results are in agreement with these observations. Previous data (Woodworth et al. 2001; Baker and Stein 2009; NRC 2012; Rojas and Stein 2013; Baker et al. 2014) reported a DE content of 14.3–16.0 MJ/kg and a ME content of 13.7–15.5 MJ/kg for conventional SBM, and results from this experiment are within this range.

The increased DE and ME in SBM source 12 compared with the other sources of SBM indicate that addition of soapstock to SBM may increase the energy value of SBM samples. This is likely a result of the increase in EE extract obtained in SBM if soapstock is added to the meal. In contrast, addition of hulls to the meal will reduce the DE and ME in the meal as observed for SBM source 13 compared with sources 14 and 15. However, the results may not always be consistent among different crushing plants.

Burkhalter et al. (2001) reported that the main composition in soybean hulls is total dietary fibre (TDF), in which most fibre is insoluble dietary fibre (IDF). The digestibility of nutrients and energy value decreased as the TDF and IDF increased (Zhang et al. 2013). Therefore, dehulled SBM contains less TDF than regular SBM, which will result in a higher DE content in dehulled SBM than that in regular SBM. Unfortunately, the variety and quantity of soybean hulls added into SBM are confidential to us. The TDF and IDF were not measured in the current experiment, and we are, therefore, not able to verify the conclusion.

The chemical composition of the SBM varied with the origin of the beans, but the DE and ME of the SBM samples were not affected by the origin of the soybeans, which contradicted our hypothesis. A possible reason for this observation is that the processing methods used in China were well controlled resulted in a consistent energy value among the SBM from different origins.

The ATTD of GE ranged 88.12% to 90.16%, which is in close agreement with previously reported value (Baker and Stein 2009; NRC 2012; Rojas and Stein 2013; Baker et al. 2014).

4.3. *Correlations and prediction equations of energy values*

Noblet and Perez (1993) generated a series of prediction equations for DE and ME based on complete diets; however, caution is essential when applying predictions to individual ingredients (NRC 2012). Our previous work generated correlation coefficients between chemical composition and energy values and subsequently established a series of energy prediction equations for corn (Li, Zang, et al. 2014), wheat milling by-products (Huang et al. 2014), peanut meal (Li, Piao, et al. 2014), corn germ meal (Ji et al. 2012) and corn gluten feed (Wang et al. 2014). Results of these previous studies indicate that correlations between chemical components of the ingredients and the DE and ME values are different among ingredients. Therefore, it is necessary to establish specific energy prediction equations for specific ingredients.

In the current study, the CP of SBM was negatively correlated with the concentrations of EE and AEE. Likewise, ADF and CF were negatively correlated with CP, which indicates that CP decreased with the addition of hulls. Grieshop et al. (2003) reported that the AEE analysis quantify all forms of lipids, whereas analysis for EE does not quantify phospholipid and sphingolipid content. Values for AEE are, therefore, expected to be greater than values for EE, which was also observed in this experiment, but the current data also indicate that values for AEE and EE are positively correlated. The observation that DE was negatively correlated with fibrous compounds is in agreement with previous data (Noblet and Perez 1993; Huang et al. 2014; Li, Piao, et al. 2014). Results of several experiments (Kang et al. 2004; Li, Piao, et al. 2014; Maison et al. 2015) indicated that ME is positively correlated with DE, which also was observed in the current experiment.

In the current experiment, prediction equations were developed from 22 SBM samples. Considering the statistical criterion of R^2, RMSE and AIC, Equation (3) may be the best fit to predict the DE of SBM. Equation (3) had the greatest R^2 and the least RMSE and AIC compared with the other equations. Equation (5) may be the best equation to predict ME. Considerable variation exists in the energy content (DE ranged 14.57–16.68 MJ/kg, ME ranged 14.25–16.07 MJ/kg) for conventional SBM. Therefore, it is necessary to establish DE and ME prediction equations based on the chemical compositions that can be easily measured. Under practical conditions, DE values are extensively available and the DE had a significant positive correlation with ME; therefore, the ME may be the better predictions for energy values when NE is unavailable. However, these equations should be validated using a separate set of SBM samples.

5. Conclusions

In summary, the concentration of DM, NDF, sucrose, raffinose, stachyose and some AA in the SBM varied with the origin of the beans. However, there were no differences in DE and ME of SBM according to origin of the beans. Addition of soapstock increased the DE of SBM, whereas addition of soy hulls to the meal reduced DE and ME. The DE of SBM may be predicted by analysing for CF, GE and ADF and ME can be predicted from DE and CP. Research to confirm the accuracy of these equations is needed.

Disclosure statement

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