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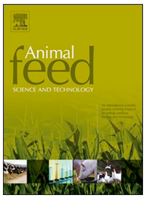

Chemical composition, protein quality and nutritive value of commercial soybean meals produced from beans from different countries: A meta-analytical study

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ABSTRACT

Soya bean meal (SBM) is the most important source of protein and indispensable amino acids in non-ruminant diets worldwide. The chemical composition, protein quality and nutritive value of commercial SBM depend on numerous factors, including seed variety, environmental conditions during growing, harvesting and storage of the beans and the procedure used for oil extraction. A meta-analytical approach was conducted to quantify the relation between the country of origin of the beans [Argentina (ARG), Brazil (BRA), USA and India (IND)] and the chemical composition, protein quality and nutritive value of the SBM. The data set used was obtained from 18 published papers from 2002 to 2018 with a total of 1944 samples of SBM. The data were analyzed using a mixed model with country of origin of the beans as a fixed effect and the study as a random effect. Origin of the beans had consistent and significant effects on most of the chemical variables of the corresponding SBM. The BRA SBM had more crude protein (CP), neutral detergent fiber, raffinose and iron but less sucrose, stachyose and K contents than the USA or the ARG SBM ($P < 0.05$). Per unit of protein, Lys, Met, Thr and Cys concentrations were greater for the USA and ARG meals than for the BRA and IND meals ($P < 0.05$). Protein dispersibility index (PDI), KOH solubility (KOH) and trypsin inhibitor activity were lower for the BRA and ARG meals than for the USA and IND meals ($P < 0.05$). Trypsin inhibitor activity was positively related with PDI ($r = 0.712$; $P < 0.001$) and KOH ($r = 0.886$; $P < 0.001$). Also, a significant relation was observed between PDI and KOH ($r = 0.614$; $P = 0.001$). Urease activity, however, was not related to any of the protein quality traits studied. Within the range of CP values (418–500 g/kg) studied a decrease in crude fiber increased ($P < 0.01$) the CP content of the SBM. In summary, the country of origin of the beans affected the chemical composition and nutritive value of the SBM. Consequently, matrices with different nutrient composition should be used for SBM of different origins in the formulation of diets for non-ruminant animals.

Abbreviations: AA, amino acid; AME_n, nitrogen-corrected apparent metabolizable energy; ANF, antinutritional factor; ARG, Argentina; BRA, Brazil; CF, crude fiber; CFAT, crude fat without HCl hydrolysis; CP, crude protein; DCFATh, digestible crude fat after HCl hydrolysis; DCP, digestible CP; dE, digestibility of the gross energy in percentage; DE, digestible energy; DM, dry matter; DSTA + SUG, digestible (starch + sugars); EE, ether extract; GE, gross energy; IND, India; I^2, heterogeneity index; KOH, protein solubility in KOH; N, nitrogen; NDF, neutral detergent fiber; NE, net energy; NFE, nitrogen-free extract; NIRS, near-infrared spectroscopy; PDI, protein dispersibility index; SBM, soybean meal; SE, standard error; SED, standard error of the difference; TI, trypsin inhibitor; TIA, trypsin inhibitor activity; UA, urease activity

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1. Introduction

Soya bean meal (SBM) is the most common protein source in non-ruminant diets, with USA, Brazil (BRA), Argentina (ARG) and India (IND) being the most important exporting countries. Most feed mill managers and nutritionists uses in feed formulation a matrix for SBM based on its crude protein (CP) content, independently of other characteristics of the beans. However, Westgate et al. (2000) and Karr-Lilienthal et al. (2004) reported that factors such as bean genotype, type of soil, environmental conditions during growing and harvesting seasons and storage affects the proximal analyses of soybeans. Moreover, the geographical area of production of the soybeans might affect the protein quality and nutrient content of the corresponding SBM (Grieshop et al., 2003; Ravindran et al., 2014; García-Rebollar et al., 2016; Lagos and Stein, 2017). However, the feed compound industry has paid little attention to the influence of the country of origin of the beans on the chemical composition, amino acid (AA) profile and protein quality of the SBM (Pfarr et al., 2018).

Trypsin inhibitors (TI) are the most important group of antinutritional factors (ANF) present in raw beans. These ANF are inactivated by heat, which allows the use of increased levels of SBM in animal feeding. An excess of heat, however, increases the incidence of Maillard reactions, reducing the digestibility of Lys and other AA and the nutritive value of the SBM (Fontaine et al., 2007; González-Vega et al., 2011). Because the analyses of TI and Maillard reactions are tedious, time consuming and expensive, indirect methods such as urease activity (UA), protein dispersibility index (PDI) and protein solubility in KOH (KOH) are preferred by the industry to evaluate indirectly the quality of the protein fraction of the SBM. Notice, however, that urea is not an ANF in pigs and poultry and in fact, its presence in the SBM does not affect animal productivity. However, urease, an enzyme present in raw beans, is inactivated by heat at a rate that resembles that of TI (Balloun, 1980; Waldroup et al., 1985). Consequently, high UA values are indicative of under-processing and of an excess of TI remaining in the meal. Urease activity, does not have negative values and consequently, values close to zero might indicate either adequate processing or over-cooking of the meal. Because of its low cost, however, UA is the method preferred by the soybean crushing industry to evaluate the quality of the protein fraction of the SBM. The PDI and KOH methods estimate the solubility of the protein fraction of the SBM and indirectly, its denaturation, with high values indicating under-processing and low values indicating over-processing of the meal (Araba and Dale, 1990; Parsons et al., 1991; Serrano et al., 2013).

The meta-analysis procedure is used as a statistical tool to compare the chemical composition and nutritive value of any particular ingredient. The technique combines data from independent studies conducted under variable conditions and allows the statistical analysis of published data with a greater analytical power (St-Pierre, 2001; Sauvant et al., 2008). Consequently, the meta-analysis approach facilitates the transformation of research results into an applicable knowledge by taking into account in a systematic way, the unavoidable heterogeneity among studies.

The research reported herein studied the influence of the origin of the beans (Argentina, Brazil, USA and India) on the chemical composition, protein quality and nutritive value of commercial SBM collected from 18 independent published papers, using the meta-analytical approach.

2. Material and methods

2.1. Description of the data

A literature search was conducted to identify manuscripts published between 2002 and 2018 in which the chemical composition and protein quality of SBM of different origins were compared. The manuscripts were scrutinized based on the following criteria: 1) peer reviewed papers, 2) research in which the origin of the beans was clearly stated and documented, 3) experiments in which the origin of the beans was used as main effect and in which at least two different origins of the beans were compared in the same research and 4) studies in which the methods used to determine the composition and protein quality of the SBM were reported. Under this set of conditions, a total of 16 papers (Park et al., 2002; Karr-Lilienthal et al., 2004; Thakur and Hurburgh, 2007; De Coca-Sinova et al., 2008; Mateo and Conejos, 2009; Goerke et al., 2012; Wang et al., 2011; Frikha et al., 2012; Serrano et al., 2012; Ravindran et al., 2014; Li et al., 2015; García-Rebollar et al., 2016; Guzmán et al., 2016; Lagos and Stein, 2017; Cámara et al., 2017; Li et al., 2017) were identified. In addition, the information on the chemical composition and AA content of samples collected and reported by Evonik (2010, 2016) for the last 17 years, was also incorporated in the study. A data set containing 1944 SBM samples from the four main producer countries (ARG = 481, BRA = 531, USA = 819 and IND = 113) was extracted from these manuscripts. The data were compiled and subsequently entered into the meta-analytical process (Table 1). The number of samples analyzed in these 18 manuscripts varied from more than 100 [n = 610 in Evonik (2010); n = 515 in García-Rebollar et al. (2016); n = 403 in Evonik (2016); n = 123 in Thakur and Hurburgh (2007) and n = 108 in Cámara et al. (2017)] to less than 10 [n = 6 in de Coca-Sinova et al. (2008); Mateo and Conejos (2009) and Guzmán et al. (2016); n = 4 in Serrano et al. (2012) and n = 3 in Park et al. (2002) and Wang et al. (2011)]. The chemical analyses conducted were dry matter (DM), ash, CP, ether extract (EE), sucrose, stachyose, raffinose, crude fiber (CF), neutral detergent fiber (NDF), macro-minerals (Ca, P, K, Mg and Na), trace minerals (Zn, Mn, Fe and Cu), AA (Arg, Cys, His, Iso, Leu, Lys, Met, Phe, Thr, Trp and Val) and key protein quality indicators [UA, PDI, KOH and TI activity (TIA)]. Not all papers selected included a complete set of analyses for all the samples. The most analyzed variables in these studies were moisture and CP (n = 18), AA (n = 17; wet chemistry in 15 studies and near-infrared spectroscopy (NIRS) technology in two studies), ash (n = 14), CF (n = 13) and NDF (n = 12). The less analyzed variables were sucrose and oligosaccharides (n = 10) and trace minerals (n = 5). Within the protein quality variables studied, the number of analyses were 11 for KOH, 10 for PDI and UA and 9 for TIA. A summary of the data, including sample size by bean origin, and the means, SD and range of all these values are shown in Table 2 for

Table 1
Variables available in the reports used in the meta-analysis.

			Proximal analyses[a]										Protein quality[b]			
Reference	Number of samples	Soybean meal origin[c]	Ash	CP	EE[d]	Sucrose	Oligo[e]	CF	NDF	Macro minerals[f]	Trace-minerals[g]	AA[h]	UA	PDI	KOH	TIA
Park et al., 2002	3	BRA, USA, IND	–	+	+	–	–	+	–	–	–	Wet	+	+	+	–
Karr-Lilienthal et al., 2004	17	All	–	+	+	–	–	–	+	All	All	Wet	+	+	+	–
Thakur and Hurburgh, 2007	123	All	+	+	+	–	–	+	–	–	–	Wet	–	–	+	–
de Coca-Sinova et al., 2008	6	ARG, BRA, USA	+	+	+	+	+	–	+	–	–	Wet	+	+	+	+
Mateo and Conejos, 2009	6	All	–	+	+	–	–	+	–	–	–	–	+	+	–	–
Evonik, 2010	610	All	–	+	–	–	–	–	–	–	–	Wet	–	–	–	–
Goerke et al., 2012	18	ARG, BRA, USA	+	+	+	–	+	–	+	–	–	Wet	–	+	–	+
Wang et al., 2011	3	BRA, USA, IND	+	+	+	–	–	+	–	Ca, P	–	Wet	–	–	+	–
Frikha et al., 2012	22	ARG, BRA, USA	+	+	+	+	+	+	+	–	–	Wet	+	+	+	+
Serrano et al., 2012	4	ARG, BRA, USA	+	+	+	+	+	+	–	Ca, P	–	Wet	+	+	+	+
Ravindran et al., 2014	55	All	+	+	+	+	–	+	+	All	All	Wet	+	–	+	+
Li et al., 2015	16	ARG, BRA, USA	+	+	+	+	+	+	+	Ca, P	–	Wet	–	–	–	–
Evonik, 2016	403	All	+	+	+	–	–	+	+	All	–	Wet	–	–	–	–
García-Rebollar et al., 2016	515	ARG, BRA, USA	+	+	+	+	+	+	+	All	All	NIRS	+	+	+	+
Guzmán et al., 2016	6	ARG, BRA, USA	+	+	+	+	+	+	+	–	–	Wet	+	+	+	+
Lagos and Stein, 2017	19	All	+	+	+	+	+	–	+	All	All	Wet	–	–	–	+
Cámara et al., 2017	108	ARG, BRA, USA	+	+	+	+	+	+	+	All	All	NIRS	+	+	+	+
Li et al., 2017	10	BRA, USA	+	+	+	+	+	+	+	Ca, P	–	Wet	–	–	–	–

[a] +: analyzed; −: not analyzed.

[b] Urease activity (UA), protein dispersibility index (PDI), KOH protein solubility (KOH) and trypsin inhibitor activity (TIA).

[c] Origin of the beans: Argentina (ARG), Brazil (BRA), USA and India (IND).

[d] Ether extract analyzed after acid hydrolysis. Park et al. (2002) did not specified the method used.

[e] Oligosaccharides (raffinose + stachyose).

[f] Macro-mineral analyzed (Ca, P, K, Mg and Na).

[g] Trace minerals analyzed (Zn, Mn, Fe and Cu).

[h] Wet chemistry (wet) or near-infrared spectroscopy (NIRS) method.

Table 2

Chemical composition of the soybean meals[a] (880 g DM/kg).

	n[b]	Mean	SD	Minimum	Maximum
Dry matter	55	891	13.1	869	928
Ash	44	65.1	4.43	56.4	78.7
Crude protein	58	464	18.1	418	500
Ether extract	46	16.6	5.05	8.30	29.4
Sucrose	34	61.7	12.7	32.7	85.9
Stachyose	30	43.4	13.7	12.4	64.7
Raffinose	27	11.9	3.26	5.98	19.8
Crude fiber	40	46.5	9.93	34.3	70.5
Neutral detergent fiber	34	96.8	17.7	71.6	131

[a] Publications used: Park et al., 2002; Karr-Lilienthal et al., 2004; Thakur and Hurburgh, 2007; De Coca-Sinova et al., 2008; Mateo and Conejos, 2009; Evonik, 2010; Goerke et al., 2012; Wang et al., 2011; Frikha et al., 2012; Serrano et al., 2012; Ravindran et al., 2014; Li et al., 2015; Evonik, 2016; García-Rebollar et al., 2016; Guzmán et al., 2016; Lagos and Stein, 2017; Cámara et al., 2017; Li et al., 2017.

[b] Number of means per origin compared in all the studies.

proximate analyses, sugars and NDF, Table 3 for minerals, Table 4 for AA profile and Table 5 for protein quality variables. For comparative purpose, all data are expressed on 880 g DM /kg basis.

In addition, the apparent metabolizable energy for poultry corrected by nitrogen (AME_n) of the SBM, was estimated according to the prediction equations recommended by the WPSA (1989) for roosters and by the CVB (2018) for broilers and roosters. Because the information provided on the chemical composition of the SBM in these 18 studies was not complete in all the manuscripts, the energy was estimated using the average values for SBM. The prediction equation used to estimate the AME_n of the SBM according to the WPSA, 1989WPSA (1989) was:

$$AME_n \text{ (KJ/kg DM)} = 15.69 \times CP \text{ (g DM/kg)} + 19.41 \times CFAT \text{ (g DM/kg)} + 6.236 \times NFE \text{ (g DM/kg)}$$

Where CFAT was crude fat, analyzed using petroleum ether as an extraction solvent, without previous HCl hydrolysis step. When needed, the ratio between CFAT and CFAT after HCl hydrolysis of the SBM was estimated as 0.59 (CVB, 2018). The digestibility coefficient for CP used was 0.87 for all SBM samples. NFE represents the nitrogen-free extract.

The prediction equation used to estimate the AME_n for broilers, as indicated by the CVB (2018) was:

$$AME_n \text{ (MJ/kg)} = (18.03 \times DCP + 38.83 \times DCFATh + 17.32 \times D(STA + SUG)/1000$$

Where DCP, DCFATh, and D(STA + SUG) were the fecal digestible content of CP, crude fat after HCl hydrolysis and (starch + sugars), respectively, all of them express in g/kg. The digestibility coefficients for CP used in this predictive equation were (0.83, 0.84, 0.85 and 0.82 for ARG, BRA, USA and IND meals, respectively) as estimated from data reported by Frikha et al. (2012) and Ravindran et al. (2014). For the EE and starch + sugars, the digestibility coefficient for all SBM was estimated to be 0.71 and 0.60, respectively, as reported by the CVB (2018). The starch and verbascose content of the SBM was not analyzed in most of the 18 papers used in this meta-analyses. Consequently, it was estimated to be 8.0 and 0.5 g/kg, respectively (Kuo et al., 1988; Hou et al., 2009; CVB, 2018).

The predicted AME_n of the SBM for adult roosters, as recommended by the CVB (2018) was:

Table 3

Macro-mineral and trace mineral content of the soybean meals[a] (880 g DM/kg).

	n[b]	Mean	SD	Minimum	Maximum
Macro-minerals (g/100 g)					
Ca	32	0.345	0.0747	0.160	0.466
P	32	0.640	0.0531	0.564	0.766
K	21	2.19	0.129	2.02	2.52
Mg	21	0.318	0.0516	0.255	0.494
Na	20	0.0271	0.0275	0.006	0.109
Trace minerals (mg/kg)					
Zn	14	52.1	8.4	41.4	77.0
Mn	14	44.3	10.4	29.7	70.8
Fe	14	220	239	92.9	919
Cu	14	14.7	2.47	9.0	18.7

[a] Publications used: Park et al., 2002; Karr-Lilienthal et al., 2004; Thakur and Hurburgh, 2007; De Coca-Sinova et al., 2008; Mateo and Conejos, 2009; Goerke et al., 2012; Wang et al., 2011; Frikha et al., 2012; Serrano et al., 2012; Ravindran et al., 2014; Li et al., 2015; Evonik, 2016; García-Rebollar et al., 2016; Guzmán et al., 2016; Lagos and Stein, 2017; Cámara et al., 2017; Li et al., 2017.

[b] Number of means per origin compared in all the studies.

Table 4
Amino acid profile (% crude protein) of the soybean meals[a].

	n[b]	Mean	SD	Minimum	Maximum
Arg	45	7.28	0.164	6.92	7.69
Cys	52	1.44	0.084	1.26	1.65
His	45	2.73	0.119	2.54	3.11
Ile	48	4.54	0.235	3.92	5.73
Leu	45	7.66	0.140	7.21	7.98
Lys	52	6.16	0.186	5.51	6.60
Met	52	1.36	0.056	1.26	1.52
Phe	42	5.09	0.111	4.86	5.41
Thr	52	3.85	0.123	3.31	4.09
Trp	42	1.40	0.138	1.21	1.97
Val	45	4.78	0.172	4.23	5.22
Σ Five key AA[c]	42	14.2	0.277	13.5	14.8

[a] Publications used: Park et al., 2002; Karr-Lilienthal et al., 2004; Thakur and Hurburgh, 2007; De Coca-Sinova et al., 2008; Mateo and Conejos, 2009; Evonik, 2010; Goerke et al., 2012; Wang et al., 2011; Frikha et al., 2012; Serrano et al., 2012; Ravindran et al., 2014; Li et al., 2015; Evonik, 2016; García-Rebollar et al., 2016; Guzmán et al., 2016; Lagos and Stein, 2017; Cámara et al., 2017; Li et al., 2017.

[b] Number of means per origin compared in all the studies.

[c] Lys, Met, Cys, Thr and Trp.

Table 5
Protein quality indicators of the soybean meals[a].

	n[b]	Mean	SD	Minimum	Maximum
UA[c]	32	0.037	0.056	0.000	0.280
PDI[d]	28	15.6	7.71	8.8	45.7
KOH[e]	36	78.7	5.60	67.7	87.7
TIA[f]	29	2.80	0.940	1.19	5.23

[a] Publications used: Park et al., 2002; Karr-Lilienthal et al., 2004; Thakur and Hurburgh, 2007; De Coca-Sinova et al., 2008; Mateo and Conejos, 2009; Goerke et al., 2012; Wang et al., 2011; Frikha et al., 2012; Serrano et al., 2012; Ravindran et al., 2014; Li et al., 2015; Evonik, 2016; García-Rebollar et al., 2016; Guzmán et al., 2016; Lagos and Stein, 2017; Cámara et al., 2017; Li et al., 2017.

[b] Number of means per origin compared in all the studies.

[c] Urease activity (mg N/g).

[d] Protein dispersibility index (%).

[e] KOH protein solubility (%).

[f] Trypsin inhibitor activity (mg/g).

$$AME_n \text{ (MJ/kg DM)} = [7{,}690 - 7.69 \times \text{ash (g DM/kg)} + 6.464 \times \text{CP (g DM/kg)} + 29.43 \times \text{CFAT (g DM/kg)} - 16.09 \times \text{CF (g DM/kg)}]/1000$$

In addition, the net energy (NE) content of the SBM for pigs, was calculated according to the equations proposed by Noblet et al. (2003), as follows:

a)Gross energy (GE, MJ/kg DM) = [4094 + 14.73 × CP (%) + 9.25 × CF (%) + 52.4 × EE (%) − 44.6 × ash (%)]/239

Where EE is ether extract without previous HCl hydrolysis.

b)dE (%) = [92.2 − 1.01 × CF (%) + 94.8 – 0.71 × NDF (%) + 95 – 0.71 × NDF (%)]/3

Where dE is the digestibility of the gross energy (GE).

From these data, the NE of the SBM was estimated from its digestible energy (DE) value applying the coefficients of 0.9135 for DE to AME and of 0.605 for AME to NE. For comparative purposes, all the AME_n and NE all values for the SBM samples are presented on 880 g DM/kg basis.

2.2. Chemical analyses

The chemical composition of the SBM was determined using diverse procedures, although in most cases the methods recommended by the AOAC International (2005) were used. Crude protein content was determined by combustion (method 990.03) or Kjeldahl (method 988.05), AA profile was analyzed either directly by HPLC (method 982.30E or similar methodology) or by NIRS technology (Redshaw, 2010). Ether extract was measured after previous HCl hydrolysis in all cases. The NDF was analyzed sequentially as indicated by Van Soest et al. (1991) and CF by sequential extraction with diluted acid and alkali (method 962.09 of the

AOAC International) in most cases. Several methods (Múzquiz et al., 1992; Sánchez-Mata et al., 1998; Cervantes-Pahm and Stein, 2010) based on similar principles, were utilized for sucrose and oligosaccharides determination. Minerals and trace elements were assessed following the AOAC International procedures. Urease activity (mg N/g) was determined as indicated by Boletín Oficial del Estado (1995) in five of the studies (de Coca-Sinova et al., 2008; Frikha et al., 2012; Serrano et al., 2012; García-Rebollar et al., 2016; Cámara et al., 2017), AOCS (1980) in the study of Karr-Lilienthal et al. (2004), AOAC Association of Official Analytical Chemists, 1980 in the Ravindran et al. (2014) study, AOAC International (1984) in the Mateo and Conejos (2009) study, and the Caskey and Knapp (1944) approach in the study of Park et al. (2002). The most common methodologies used for the determination of PDI and TIA, were those described by the AOCS (2000) and Hamerstrand et al. (1981), respectively, and the procedure reported by Araba and Dale (1990) was the preferred method for KOH determination. The differences in methodology used to analyze the chemical composition of the meals, among studies, were taken into account by including the individual study as a random effect in the model.

2.3. *Statistical analysis*

The difference in sample size among studies was high and consequently, the data were weighed taking into account the number of observations for the estimation of treatment effect. Because the information available was not complete, it was not possible to consider the unequal standard deviations in the analysis of the data. In all cases, the dependent variable for each trait was the average value obtained by soybean origin. The effect of bean origin on the value of each of the SBM traits studied, was analyzed by using a mixed model (SAS Institute, 2008) with bean origin as fixed effect and the study as random effect. Least square means by soybean origin were compared using the Tukey test. The heterogeneity among studies (I^2) was estimated as the percentage of the total variation caused by the variability among the studies.

In addition, a meta-regression study was performed to evaluate the relation between CP and fiber (CF and NDF) content, and between CP and the AA concentration per unit of CP of the samples. A mixed model (SAS, 2008), with origin of the bean as fixed effect, the study as a random effect, and the concentration of CP as a linear covariate, was used. The interaction between soybean origin and CP content of the SBM was also included in the model and used to test if the effect of CP content of the SBM differed among soybean origins. Finally, the correlations among the procedures used to evaluate the protein quality of the SBM, were also calculated.

The number of studies that included SBM samples from India was limited ($n = 9$ and lower than those which included comparisons of SBM from the other three origins ($n = 15$ for ARG and $n = 18$ for BRA and USA meals). Consequently, the standard error (SE) of the difference (SED) was higher for the comparisons that included IND meals than for the comparisons in which IND origin was not considered. Consequently, two distinct SED values were included in the corresponding tables, with SED1 values corresponding to the comparison between Indian meals and the meals of the other three origins and SED2 values corresponding to the comparisons among USA, ARG and BRA meals.

3. Results

The highest variability among studies ($I^2 > 50\%$) was observed for DM and stachyose contents, and the lowest ($I^2 < 10\%$) for ash and CF contents. For the minerals, the I^2 value was highest for P and lowest for Mg. For the AA profile, the highest variability was observed for His and Cys and the lowest for Ile and Leu.

The effects of soybean origin on the proximal analyses and on the sugars and fiber contents of the SBM are shown in Table 6. Soybean origin affected significantly most of the chemical values of the meals reported. Crude protein content was greatest for the BRA SBM and lowest for the ARG SBM ($P < 0.05$). Soybean meals from the IND beans contained less EE than SBM from beans of the

Table 6
Chemical composition (g/kg) of the soybean meals (880 g DM/kg).

		SBM origin[b]								Range			
Trait	n[a]	ARG	BRA	USA	IND	SED1[c]	SED2[d]	P-value	I^2[e]	ARG	BRA	USA	IND
Dry matter	55	891	891	891	892	1.43	0.70	0.751	57.4	874 – 923	869 – 928	880 – 923	880 – 924
Ash	44	65.4^{y}	62.9^{x}	65.4^{y}	74.8^{z}	1.37	0.57	< 0.001	9.74	56.4 – 69.9	58.0 – 69.6	57.3 – 69.9	68.8 – 78-7
Crude protein	58	455^{x}	470^{z}	464^{y}	$463^{x,y,z}$	4.51	1.98	< 0.001	24.2	420 – 468	418 – 500	422 – 486	441 – 495
Ether extract	46	16.6^{z}	17.8^{z}	16.7^{z}	11.1^{y}	1.75	0.56	0.004	25.7	12.5 – 29.2	8.73 – 29.4	8.30 – 27.8	10.5 – 16.9
Sucrose	34	64.1^{y}	52.4^{x}	69.9^{z}	41.9^{w}	3.09	0.98	< 0.001	43.5	43.9 – 75.6	32.7 – 62.3	51.4 – 85.9	49.6 – 53.7
Stachyose	30	41.5^{y}	38.0^{x}	47.7^{z}	$39.7^{x,y,z}$	4.61	0.74	< 0.001	74.2	15.2 – 58.7	12.4 – 46.4	22.4 – 64.7	50.9 – 50.9
Raffinose	27	11.5^{y}	13.3^{z}	9.5^{x}	$17.0^{y,z}$	2.26	0.37	< 0.001	22.8	6.0 – 16.0	7.9 – 17.0	7.0 – 14.5	19.8 – 19.8
Crude fiber	40	43.2^{x}	50.3^{y}	38.8^{w}	65.5^{z}	3.18	1.31	< 0.001	2.08	36.1 – 49.3	38.7 – 68.3	34.3 – 51.1	60.2 – 70.5
NDF	34	95.7^{y}	108^{z}	86.9^{x}	130^{z}	9.31	2.84	< 0.001	13.7	72 – 107	84 – 131	72 – 131	100 – 127

$^{x,\ y,\ z,\ w}$Means within a row lacking of a common superscript differ significantly ($P < 0.05$).

[a] Number of means per origin compared in all the studies.

[b] ARG = Argentina, BRA = Brazil and IND = India.

[c] SED1 = Standard error of the difference between India and the three other origins.

[d] SED2 = Standard error of differences among Argentina, Brazil and USA meals.

[e] I^2 = heterogeneity index.

Table 7
Macro-minerals and trace minerals content of the soybean meals (880 g DM/kg).

		SBM origin[b]								Range			
Trait	n[a]	ARG	BRA	USA	IND	SED1[c]	SED2[d]	P-value	I^2[e]	ARG	BRA	USA	IND
Macro-mineral (g/100 g)													
Ca	32	0.337^{y}	0.313^{y}	0.391^{z}	0.436^{z}	0.0398	0.015	< 0.001	2.64	0.233 – 0.378	0.160 – 0.456	0.322 – 0.444	0.371 – 0.467
P	32	0.669^{z}	0.620^{y}	0.675^{z}	0.570^{x}	0.0187	0.0066	< 0.001	21.4	0.590 – 0.755	0.565 – 0.697	0.600 – 0.766	0.564 – 0.600
K	21	2.32^{z}	2.12^{x}	2.21^{y}	2.02^{x}	0.0612	0.0215	< 0.001	16.7	2.14 – 0.52	2.02 – 2.28	2.09 – 2.40	2.02 – 2.13
Mg	21	0.308	0.346	0.313	0.364	0.0547	0.0213	0.262	0	0.255 – 0.316	0.257 – 0.494	0.273 – 0.321	0.330 – 0.376
Na	20	0.0298	0.0298	0.0283	0.0180	0.0141	0.0051	0.844	12.1	0.009 – 0.063	0.009 – 0.059	0.006 – 0.109	0.007 – 0.014
Trace mineral (mg/kg)													
Zn	14	47.6^{y}	53.9^{z}	53.6^{z}	$55.2^{y,z}$	5.6	1.9	0.029	2.54	41.4 – 50.6	50.5 – 56.6	48.0 – 77.0	54.2 – 57.1
Mn	14	46.5	36.7	39.7	46.9	10.1	3.7	0.110	0	40.7 – 51.5	29.7 – 70.8	33.4 – 45.9	44.0 – 56.3
Fe	14	112^{x}	181^{y}	$125^{x,y}$	843^{z}	53.5	19.1	< 0.001	0.26	93 – 120	132 – 194	102 – 157	598 – 919
Cu	14	15.2	14.0	15.4	16.9	1.6	0.6	0.122	2.53	11.2 – 16.3	9.0 – 15.2	14.3 – 18.7	15.5 – 16.6

$^{x,\ y,\ z,\ w}$Means within a row lacking a common superscript differ significantly ($P < 0.05$).
[a] Number of means per origin compared in all the studies.
[b] ARG = Argentina, BRA = Brazil and IND = India.
[c] SED1 = Standard error of the difference between India and the three other origins.
[d] SED2 = Standard error of differences among Argentina, Brazil and USA meals.
[e] I^2 = heterogeneity index.

other three origins ($P < 0.05$). Sucrose and stachyose concentrations were highest ($P < 0.05$) for the SBM from USA and lowest for the SBM from BRA and IND. An opposite trend was detected for raffinose, that was higher for the BRA and IND meals than for the ARG and USA meals ($P < 0.05$). Crude fiber and NDF concentrations were greater for the IND and BRA meals than for the ARG meals and greater for all than for the USA meals ($P < 0.05$). The effects of soybean origin on the mineral content of the SBM are shown in Table 7. Soybean origin affected Ca, P and K concentration of the SBM but Mg and Na contents were not affected. Calcium content was greater in the IND and USA meals than in the ARG and BRA meals ($P < 0.05$). Phosphorus concentration was greater for the USA and ARG meals than for the IND meals, with the BRA meals being intermediate ($P < 0.05$). The highest level of K was observed for the ARG meals and the lowest for the BRA and IND meals ($P < 0.05$). Country of origin of the beans affected Zn and Fe content of the meals, with the lowest values reported for the ARG meals ($P < 0.05$). The highest Fe content was observed for the IND meals followed by the BRA meals ($P < 0.05$). No differences among soybean origins were detected for Mn and Cu contents.

The abundance of the key indispensable AA profile of the SBM (% of CP) varied significantly with the country of origin of the beans (Table 8). In general, the AA profile for non-ruminant species was more favorable for the ARG and USA meals than for the BRA

Table 8
Amino acid profile (% of crude protein) of the soybean meals.

		SBM origin[b]								Range			
Trait	n[a]	ARG	BRA	USA	IND	SED1[c]	SED2[d]	P-value	I^2[e]	ARG	BRA	USA	IND
Arg	45	7.25	7.30	7.29	7.34	0.048	0.020	0.085	3.55	6.92 – 7.37	6.92 – 7.69	7.23 – 7.53	7.13 – 7.44
Cys	52	1.45^{z}	1.42^{y}	1.47^{z}	1.35^{x}	0.014	0.006	< 0.001	28.6	1.28 – 1.58	1.26 – 1.53	1.33 – 1.65	1.27 – 1.53
His	45	2.75^{z}	2.71^{x}	2.73^{y}	2.76^{xy}	0.015	0.006	< 0.001	56.5	2.56 – 2.85	2.54 – 2.87	2.59 – 3.11	2.67 – 2.90
Ile	48	4.55^{xy}	4.58^{y}	4.53^{x}	4.58^{xy}	0.043	0.018	0.031	7.11	4.19 – 4.67	4.25 – 4.75	4.26 – 4.74	3.92 – 5.73
Leu	45	7.63	7.65	7.61	7.65	0.042	0.018	0.160	1.08	7.53 – 7.95	7.43 – 7.98	7.39 – 7.91	7.21 – 7.78
Lys	52	6.19^{yz}	6.12^{x}	6.23^{z}	6.12^{xy}	0.033	0.015	< 0.001	24.7	5.51 – 6.39	5.79 – 6.39	6.05 – 6.60	5.78 – 6.30
Met	52	1.37^{y}	1.33^{x}	1.38^{z}	1.32^{x}	0.012	0.005	< 0.001	16.7	1.33 – 1.46	1.26 – 1.43	1.30 – 1.52	1.27 – 1.42
Phe	42	5.08^{xy}	5.15^{z}	5.04^{x}	$5.13^{y,z}$	0.031	0.013	< 0.001	7.98	4.86 – 5.22	5.03 – 5.41	4.90 – 5.15	4.87 – 5.21
Thr	52	3.89^{z}	3.84^{y}	3.88^{z}	3.78^{y}	0.027	0.012	< 0.001	14.2	3.76 – 4.00	3.65 – 4.00	3.74 – 4.09	3.31 – 3.88
Trp	42	1.39^{xy}	1.37^{x}	1.41^{y}	1.39^{xy}	0.030	0.012	0.026	18.7	1.23 – 1.56	1.21 – 1.62	1.26 – 1.67	1.31 – 1.97
Val	45	4.82^{z}	4.78	4.78	4.74	0.033	0.014	0.050	23.4	4.49 – 5.14	4.55 – 5.08	4.49 – 5.22	4.23 – 5.02
Σ Five key AA[f]	42	14.3^{y}	14.1^{x}	14.4^{z}	14.0^{x}	0.058	0.024	< 0.001	14.6	14.0 – 14.8	13.5 – 14.3	14.1 – 14.8	13.9 – 14.6

[a] Number of means per origin compared in all the studies.
[b] ARG = Argentina, BRA = Brazil and IND = India.
[c] SED1 = Standard error of the difference between India and the three other origins.
[d] SED2 = Standard error of differences among Argentina, Brazil and USA meals.
[e] I^2 = heterogeneity index.
[f] Lys, Met, Cys, Thr and Trp.

Table 9

Calculated average nitrogen-corrected apparent metabolizable energy (AME_n) and net energy (NE) of the soybean meal (SBM) estimated according to the prediction equations.

	SBM origin[a]			
	ARG	BRA	USA	IND
AME_n (MJ/kg 880 g DM/kg)				
WPSA, 1989WPSA (1989)	9.24	9.36	9.35	9.08
CVB (2018)[b]	8.57	8.77	8.98	8.26
CVB (2018)[c]	8.80	8.82	8.93	8.32
NE (MJ/kg 880 g DM/kg)				
Noblet et al. (2003)	8.21	8.21	8.29	7.91

$^{x, y, z, w}$Means within a row lacking of a common superscript differ significantly ($P < 0.05$).

[a] ARG = Argentina, BRA = Brazil and IND = India.

[b] Equation for all feedstuffs for broilers.

[c] Equation for SBM for adult roosters.

and IND meals. In this respect, Lys content per unit of protein (%) was highest for the USA meals and lowest for the BRA and IND meals, with the ARG meals being in an intermediate position ($P < 0.05$). Also, Thr content was higher for the USA and ARG meals than for the BRA and IND meals ($P < 0.05$). A similar trend was observed for Met, Cys and Val and for the sum of the five key AA. The Ile, Leu and Trp profiles, however, were not affected by the origin of the beans.

The average AME_n (MJ/kg) content for poultry of the SBM, calculated using the prediction equation recommended by the WPSA (1989) and using the chemical values reported in this research, were 9.24, 9.36, 9.35 and 9.08 for the ARG, BRA, USA and IND SBM, respectively (Table 9). When the prediction equation recommended for broilers by the CVB (2018) was used, the calculated values were 8.57, 8.77, 8.98 and 8.26 for the ARG, BRA, USA and IND SBM, respectively. The average AME_n contents of the SBM, estimated using the equation for adult rooster of the CVB (2018), were 8.80, 8.82, 8.93 and 8.32 for ARG, BRA, USA and IND, respectively. For pigs, the predicted NE content of the SBM, using the approach of Noblet et al. (2003) and the chemical analyses reported in this research, were 8.21, 8.21, 8.29 and 7.91 MJ/kg for ARG, BRA, USA and IND meals, respectively).

Soybean origin affected all protein quality indicators of the SBM, except UA (Table 10). Soybean meals from USA and IND beans had the greatest ($P < 0.05$) PDI and KOH solubility values. TIA values were highest for the USA meals ($P < 0.05$). The Pearson correlation coefficients among protein quality indicators, irrespective of bean origin, are shown in Table 11. Trypsin inhibitor activity was positively related ($P < 0.05$) with PDI (r = 0.712) and KOH (r = 0.886). Urease activity was low for all samples and was not related to any of the other protein quality estimates reported.

Table 10

Meta-analysis of the protein quality indicators of the soybean meals.

		SBM origin[b]								Range			
Trait	n[a]	ARG	BRA	USA	IND	SED1[c]	SED2[d]	P-value	I^2[e]	ARG	BRA	USA	IND
UA[f]	32	0.012	0.023	0.024	0.046	0.019	0.007	0.158	0.41	0 – 0.040	0 – 0.150	0.000 – 0.130	0.031 – 0.280
PDI[g]	28	14.0^{y}	13.5^{y}	17.8^{z}	$20.9^{y,z}$	4.85	0.93	< 0.001	21.3	10.3 – 23.9	8.9 – 17.6	8.8 – 45.7	9.6 – 33.6
KOH[h]	36	76.6^{y}	78.2^{y}	82.1^{z}	$79.3^{y,z}$	1.33	0.60	< 0.001	27.1	69.7 – 84.3	68.1 – 83.3	72.7 – 87.7	67.7 – 86.1
TIA[i]	29	2.47^{y}	$2.76^{y,z}$	3.18^{z}	$2.96^{y,z}$	0.44	0.14	< 0.001	13.0	1.19 – 5.10	2.07 – 5.23	1.61 – 3.50	2.37 – 2.45

$^{x, y, z, w}$Means within a row lacking a common superscript differ significantly ($P < 0.05$).

[a] Number of means per origin compared in all the studies.

[b] ARG = Argentina, BRA = Brazil and IND = India.

[c] SED1 = Standard error of the difference between India and the three other origins.

[d] SED2 = Standard error of differences among Argentina, Brazil and USA meals.

[e] I^2 = heterogeneity index.

[f] Urease activity (mg N/g).

[g] Protein dispersibility index (%).

[h] KOH protein solubility (%).

[i] Trypsin inhibitor activity (mg/g).

Table 11
Matrix of Pearson correlation coefficients among protein quality indicators of the soybean meals[a].

	Urease[b]	PDI[c]	KOH[d]	TIA[e]
PDI				
n[f]	25			
R	0.257			
P-value	0.216			
KOH				
N	29	25		
R	0.069	0.614		
P-value	0.721	0.001		
TIA				
N	22	21	22	
R	0.210	0.712	0.886	
P-value	0.348	< 0.001	< 0.001	

[a] Includes data on correlation between each pair of variables using exclusively those reports with complete pairs of observations.
[b] Urease activity (mg N/g).
[c] Protein dispersibility index (%).
[d] KOH protein solubility (%).
[e] Trypsin inhibitor activity (mg/g).
[f] Number of means per origin compared in all the studies.

Table 12
Linear effects[a] of crude protein content of SBM on selected variables correct by the study influence (values in g/kg).

Trait	Regression coefficient	SE	*P*
Crude fiber	−0.230	0.072	0.003
Neutral detergent fiber	−0.675	0.18	0.013
Amino acid			
Cys	−0.011	0.0052	0.051
Met	−0.0073	0.0045	0.101
Thr	−0.032	0.0095	0.001
Σ Five key AA[b]	−0.052	0.020	0.012

[a] $P < 0.05$.
[b] Lys, Met, Cys, Thr and Trp.

The regression coefficients for the linear effects of CP content of the meal on the concentration of those nutrients (CF, NDF, Cys, Met, Thr and Σ five key AA) that reached significance ($P < 0.05$), are shown in Table 12. The quadratic effect of CP concentration on nutrient composition of the SBM was not significant for any of the variables studied. Within the range of values studied (418–500 g CP/kg), the meta-regression analysis predicted a decrease of 18.9 and 55.4 g/kg for CF and NDF as the CP content of the SBM increased. Also, within the range of CP values studied, Cys (0.90 g/kg), Met (0.60 g/kg), Thr (2.62 g/kg) and the sum of the five key AA (4.26 g/kg) decreased as the CP content of the meal increased from 418 to 500 g/kg. An interaction ($P < 0.05$) between soybean origin and CP content of the SBM was detected for Met profile; the decrease in Met per unit of CP (g/kg) observed (2.54 g/kg CP) was greater for the ARG meals than for the average of the meals from the other three origins. Based on the data shown in Table 12, the content in Cys, Thr and of the sum of five key AA content of the SBM, independent of bean origin, could be estimated from CP values using the following equations:

a) $\text{Cys} = 1.92 - 0.011 \times \text{CP}$

b) $\text{Thr} = 5.40 - 0.032 \times \text{CP}$

c) $\Sigma\ \text{Five key AA} = 16.5 - 0.052 \times \text{CP}$

Where Cys, Thr, Σ five key AA (Lys, Met, Cys, Thr and Trp) and CP contents of the SBM are given in g/kg.

4. Discussion

4.1. Influence of the origin of the beans on the chemical composition

The proximal analyses and the nutritive value of the SBM, across the country of origin of the beans, were within the range reported in the literature (Karr-Lilienthal et al., 2005; Thakur and Hurburgh, 2007; Ravindran et al., 2014; García-Rebollar et al., 2016; Lagos and Stein, 2017; Cámara et al., 2017). Park and Hurburgh (2002) reported greater CP content for the USA meals than for the BRA and ARG SBM. In most studies, however, the CP content of the SBM was higher for the BRA meals than for the USA meals (i.e., Thakur and Hurburgh, 2007; Frikha et al., 2012; Ravindran et al., 2014; Cámara et al., 2017), consistent with practical data observations reported from European feed mills. García-Rebollar et al. (2016), in a study involving 515 SBM samples, reported higher CP content for the USA and BRA meals than for the ARG meals. Similar information was provided by Grieshop and Fahey (2001) and Karr-Lilienthal et al. (2004). The inconsistencies reported on the CP content of the SBM, depending on the origin of the beans, suggest that the protein values of commercial SBM are more variable than commonly accepted. Differences in seed genotype (Zarkadas et al., 2007), planting area of the beans within countries (Wilcox and Shibles, 2001; Karr-Lilienthal et al., 2005), environmental conditions during the growing and harvesting seasons (Rotundo et al., 2016; Pfarr et al., 2018) and year crop (Ravindran et al., 2014; Cámara et al., 2017) affect the CP content of the beans and consequently, of the resulting SBM. Within the four countries considered, differences in CP content and on the chemical constituents of the beans, might depend on the latitude (day length, humidity and temperature) of the area of production, with higher CP content in beans produced close to the ecuator, consistent with data of Cromwell et al. (1999); Grieshop et al. (2003); Medic et al. (2014); Miller-Garvin and Naeve (2015) and García-Rebollar et al. (2016). In addition, the CP content of the SBM depends at a high extent, on the proportion of hulls removed from the beans at the crushing plant before oil extraction or on the amount of hulls added back to the meal after the crushing process. In this respect, the SBM produced in Argentina had less CP than the SBM produced in Brazil or in the USA (Thakur and Hurburgh, 2007; García-Rebollar et al., 2016). Moreover, the BRA SBM are often marketed on “profat bases” (CP + EE) which means that the CP content is 17.8 g/kg lower for the “profat SBM” than for the meals marketed based on its CP content, exclusively.

As an average, the CF and NDF contents of the SBM were higher for the BRA and IND meals than for the USA and ARG meals, data that are consistent with most published research (Thakur and Hurburgh, 2007; Frikha et al., 2012; Ravindran et al., 2014; Evonik, 2015a, b; Lagos and Stein, 2017). As indicated for CP, differences in fiber content of the SBM among countries depend not only on the amount of hulls added to the meal but also on the geographical planting area and the climatic conditions occurring during the growing season (Medic et al., 2014). An interesting observation, based on the data of the current review, was that the BRA meals had more CP but also more CF and NDF than the USA and the ARG meals. This finding is opposite to the general belief that fiber content of the SBM is inversely related to CP content. However, within each individual country, the negative correlation between CP and NDF content of the SBM, was quite evident and consistent with the data reported in the current research.

Sucrose and stachyose concentrations were higher and raffinose concentration was lower for the USA and ARG meals than for the BRA and IND meals, consistent with data of Frikha et al. (2012); García-Rebollar et al. (2016); Lagos and Stein (2017) and Cámara et al. (2019). Sucrose is a highly digestible carbohydrate (≥78%) that when present in the meal, increases the energy content and the palatability of the feed (Coon et al., 1990; Hou et al., 2009; Mateos et al., 2019). Consequently, sucrose is a desirable component of SBM, especially in piglet diets (Berrocoso et al., 2013 Berrocoso et al., 2014; Jiang et al., 2018). Wolf et al. (1982) and Kumar et al. (2010) reported that most of the differences in sucrose content among countries were due to the latitude (day length) and to the average temperature of the area of production of the beans during the growing season, with higher proportion of sucrose in those beans produced in the cooler locations.

The oligosaccharides present in SBM (raffinose, stachyose and small amounts of verbascose) are not digested in the gastrointestinal tract (GIT) of non-ruminant species, acting as an ANF and reducing the nutritional value of the meal in young animals (Choct et al., 2010). Stachyose, composed of two α-D-galactose units, one α-D-glucose unit and one D-fructose units, is the most abundant oligosaccharide present in SBM, independently of the country of origin of the beans. Stachyose accumulates in the seed during the late phase of maturation, serving for the transport or storage of carbohydrates in mature seeds (Obendorf et al., 2009). Although not digested in non-ruminant species, most of the oligosaccharides present in SBM are fermented in the large intestine, and when fed in limited proportions, they might yield valuable energy (Coon et al., 1990). Moreover, stachyose is considered often as a potential prebiotic substance, with benefits on health and growth in humans an in non-ruminant species (Grizard and Barthomeuf, 1999; Conway, 2001; Bouhnik et al., 2004; Wang et al., 2007). Consequently, depending on the type and age of the animal, and on the level of inclusion of SBM, stachyose might not behave necessarily as an ANF. In addition, the short-chain fatty acids, end products of oligosaccharides fermentation, might reduce the pH of the large intestine, which in turn might benefit GIT health (Coon et al., 1990).

The ash and the macro-minerals contents of the SBM, across the country of origin of the beans, were within the range reported in the literature (Harmon et al., 1969; Batal et al., 2010; NRC, 2012; Tahir et al., 2012). Comparative data on the mineral content of SBM from the four key producer countries, however, are scarce and often contradictory (Karr-Lilienthal et al., 2004; García-Rebollar et al., 2016; Ravindran et al., 2014; Cámara et al., 2017; Lagos and Stein, 2017). In the current study, the mineral concentration of the SBM varied with the origin of the beans, with P, Ca, K and Fe contents showing the most striking differences among countries. In this respect, P content was higher for the USA and ARG meals than for the BRA meals and higher for all of them than for the IND meals, reflecting differences in mineral content of the soil as well as on the amount of phosphate used in the fertilization of the crops. Calcium content was higher for the USA and IND meals than for the South American meals, an observation that was unexpected based on the similar average Ca content of the beans reported for these countries by several institutions (CIGI, 2010; FEDNA, 2010; NRC, 2012). The data presented might reflect that extra amounts of Ca are added to the meals as a flow agent under some circumstances (Batal et al., 2010; Karr-Lilienthal et al., 2004; Sotak-Peper et al., 2016). The K content of the SBM was higher for the ARG meals than for the BRA and IND meals, with the USA meals being in an intermediate position. The Fe content of the SBM was greatest for the IND meals than for the BRA meals and higher for both than for the ARG and USA meals.

The variability reported for most macro- and trace minerals of the SBM, was probably related to differences in soil characteristics, rate of fertilization and absorption capability of the soya plant (Westgate et al., 2000; Huerta and Martin, 2002). For example, the soils of the main soybean planting areas of Brazil are acidic, with high Al and Fe contents (Huerta and Martin, 2002; Jensen, 2010). At low pH, the phosphate ions present in the soil react with Al to form less soluble compounds (Brennan et al., 1994) which limits P absorption by the plant and reduces its accumulation in the seed. Moreover, low soil pH favors Fe and Al absorption. Consequently, the BRA SBM, that are mostly produced in very acidic soils, are expected to have more Al and Fe and less P content than the USA and ARG SBM, consistent with the results reported herein. In this respect, Sieburth et al. (1952) observed that P from aluminum phosphate was relatively unavailable for the bird. Moreover, Rossi et al. (1990) reported that when added to the diet, Al forms complex compounds with phosphates, reducing P availability in the laying hen. However, no data is available in the literature showing differences in availability of the P contained in SBM from BRA or from other origins.

The extra amounts of ash and of some trace minerals such as Fe, present in some cases in SBM samples, might be a result of contamination from the soil or occurring at the crushing plant (Karr-Lilienthal et al., 2004). This observation might explain the high ash and Fe content reported for the IND meals, reflecting the high soil contamination of the beans that might happen during harvesting in this country.

4.2. Influence of the origin of the beans on the amino acid profile

The AA profile of the SBM varied with the country of origin (i.e., geographical area of production) of the beans, in agreement with most published reports (Goldflus et al., 2006; Thakur and Hurburgh, 2007; Medic et al., 2014; Lagos and Stein, 2017). Evonik (2010; 2016) and Frikha et al. (2012) reported that USA and ARG meals had more Lys, total Sulphur AA and Thr per unit of protein than the BRA and IND meals. In fact, Ravindran et al. (2014); García-Rebollar et al. (2016); Lagos and Stein (2017) and Cámara et al. (2017, 2019) observed that the concentration (% of CP) of the five critical AA of the SBM, was similar for the USA and ARG meals and significantly higher for both than for the BRA and IND meals. We do not have a clear explanation for the differences in AA profile of the SBM because of country of origin of the beans but the results agree with data reported by Premier Atlas (2014); Evonik (2015a, b) and Cámara et al. (2017). Several authors (Medic et al., 2014; Mourtzinis et al., 2017; Pfarr et al., 2018) reported that the AA profile of the SBM is affected by the protein concentration of the seed. In fact, most reports indicate that the relative abundance of certain AA such as Lys, Met, Cys, Trp and Thr, that are often limiting growth in non-ruminant species, was reduced as the protein concentration in the seed increased. Overall, the information provided herein confirms that the nutritive value of the SBM of different origins should be based on CP content but also taking into consideration differences in the AA profile of the protein fraction of the meals.

4.3. Influence of the origin of the beans on the energy content

The energy content of the SBM depends primarily on the amount and digestibility of the protein fraction (Thakur and Hurburgh, 2007; Serrano et al., 2012) but also on their sucrose (Berrocoso et al., 2014; Ravindran et al., 2014), oligosaccharide (Coon et al., 1990) and fiber (Dilger et al., 2004; Ravindran et al., 2014) contents. However, most of the prediction equations used to generate energy values for SBM for feed formulation, including that of the WPSA, 1989WPSA (1989), does not take into account the digestibility of the protein fraction or the variability in sucrose and fiber content of the SBM. In most published research, USA SBM has higher CP digestibility (Lagos and Stein, 2017; Aguirre et al., 2019a, b), more sucrose (Lagos and Stein, 2017; Cámara et al., 2019) and oligosaccharides (García-Rebollar et al., 2016) and less NDF (García-Rebollar et al., 2016) contents than the ARG, BRA and IND SBM. Consequently, the recommended energy values for SBM, calculated according to prediction equations that do not take into consideration differences in CP digestibility or in the composition of the NFE fraction of the SBM, should be taken cautiously (Mateos et al., 2019).

The AME_n (MJ/kg) of the SBM for poultry, using the average chemical values reported in the current meta-analysis and calculated using the prediction equation recommended by the WPSA (1989), ranged from 9.08 for the IND meals to 9.36 MJ/kg for the BRA meals. Values reported in the literature for high CP SBM (> 460 g CP/kg), independent of the origin of the beans, range from 9.04 MJ/kg (CVB, 2018) to 10.06 MJ/kg (Premier Atlas, 2019). In the current research, the AME_n of the BRA (470 g CP/kg) and USA (455 g CP/kg) SBM, estimated using the WPSA, 1989WPSA (1989) prediction equation, were similar (9.36 and 9.35 MJ/kg, respectively), reflecting the higher CP (470 g/kg) but not the potential lower digestibility of the protein fraction and the lower sucrose content of the BRA meal compared with the USA meals (de Coca-Sinova et al., 2008; Ravindran et al., 2014; Aguirre et al., 2019a, b). When the AME_n of the SBM was estimated based on the CVB (2018) prediction equation for broilers, in which these two variables were taken into account, a change in order was found, with values of 8.77 and 8.98 MJ/kg for the BRA and USA meals, respectively. When the AME_n of the SBM was estimated based on the CVB (2018) prediction equation for roosters, in which the ash and CF content of the SBM are taken into consideration, the values obtained are 8.82 and 8.93 for BRA and USA meals, respectively. In this respect, Ravindran et al. (2014) reported average AME values, in an in vivo experiment with broilers, of 9.58 and 9.80 MJ/kg for the BRA and USA meals, respectively. The information provided suggests that the prediction equation of WPSA (1989) which is based on CP, EE and NFE contents, exclusively, under-evaluate the real contribution of the USA meals to the energy content of the diet, compared with the South American and IND meals.

The NE (kcal/kg) content of the SBM for pigs, estimated using the predictive equation of Noblet et al. (2003) and the chemical analyses reported in this research, varied from 7.91 for the IND SBM to 8.29 for USA SBM. These values are within the range reported in the literature for commercial SBM of unknown bean origin [i.e., 7.74, 8.25, 8.42, 8.48 and 8.54 MJ/kg for Rostagno et al. (2017); INRA (2018); CVB (2018); FEDNA (2017) and NRC (2012), respectively]. The prediction equation of Noblet et al. (2003) is based primarily on the fiber content of the meals, which explain the high NE value of the USA SBM which has less CF and NDF than the other SBM sources. Because the prediction equation of Noblet et al. (2003) does not take into account the sucrose content of the SBM, the NE values reported might under-estimate the real energy contribution of the USA meals compared to that of the SBM of other origins.

4.4. Influence of the origin of the beans on protein quality indicators

In the current research, the UA values of the SBM, independent of bean origin, were in most cases below the threshold (0.05 mg N/g) recommended for high quality meals (van Eys, 2012; Serrano et al., 2013). Notice, however, that UA was higher for the IND meals than for the average of the meals of the other three origins, although, because of the high variability reported, the differences observed did not reach significance.

Balloun (1980); Batal et al. (2000) and van Eys (2012) suggested that correctly processed SBM should show PDI and KOH values within a range of 15–30% and of 75–85%, respectively. The feed industry accepts that high PDI and KOH values are indicative that the beans were under-processed, with a high proportion of the original TI present in the original beans remaining in the resulting meal. On the other hand, low PDI and KOH values might reflect a high incidence of Maillard reaction, which results eventually from the formation of indigestible Lys × sugar complexes. In the current research, PDI values differed among origins and were higher for the IND meals than for the South American meals, with USA meals being intermediate (average values of 20.9, 17.8, 13.5 and 14.0% for the IND, USA, BRA and ARG meal, respectively). Notice, however, that over 60% of the samples from South American origin evaluated in this survey had a PDI equal or below current industry recommendations, indicative, at least in theory, of potential over-processing of these meals. However, Frikha et al. (2012) reported that the correlation between the PDI value and the apparent ileal digestibility of CP of 22 SBM from USA, BRA and ARG origins was not significant ($P > 0.10$). Similarly, the KOH values of the SBM reported in the current study varied widely among origins with higher values for USA meals than for ARG and BRA meals, and with IND meals being in an intermediate position (average values of 76.6, 78.2, 82.1 and 79.3 for the ARG, BRA, USA and IND meals, respectively). Notice, however, that more than 40% of the South American meals analyzed in this research, showed KOH values equal or below current industry recommendations. In fact, 67% of the USA samples showed KOH values over 85%, which is the maximum value recommended by different authors for well processed SBM (Moizzudin, 2003; van Eys, 2012).

The PDI values reported were more variable than the KOH values, in agreement with data of Karr-Lilienthal et al. (2004); Serrano et al. (2013) and García-Rebollar et al. (2016). The higher variability of the PDI values does not support the recommendation of Hsu and Satter (1995) and Dudley-Cash (2001) on the preferred use of this procedure as an indicator of protein quality of SBM. In this respect, Serrano et al. (2013) reported that the PDI values of seven samples of ARG SBM decreased from 21.9–17.7% after four months of storage under laboratory conditions, whereas KOH values were not affected.

The TIA of the SBM was within the range reported in the literature for commercial SBM (USSEC, 2008; van Eys, 2012; Ravindran et al., 2014). When the SBM were sorted by the area of origin of the beans, significant differences among countries were observed, with average values (mg/g) of 3.18, 2.96, 2.76 and 2.47 for USA, IND, BRA and ARG meals, respectively. The higher TIA values observed for the USA SBM compared with those of the other SBM, are consistent with the higher PDI and KOH values reported. We do not have a clear explanation for the higher PDI, KOH and TIA of the USA meals compared with the ARG and BRA meals. The data suggest that less heat was applied to the USA meals than to the South American meals. In this respect, the BRA and ARG beans produced in the North part of these two countries, are harvested with a high moisture content and are usually heated using air dryers to reduce the moisture content to 13 or 14% before for safe storage before processing for oil extraction (Hill et al., 1996). This previous extra heat applied to reduce the moisture content of the beans, might be responsible, at least in part, for the lower solubility and TIA content of the South American meals. In addition, over-heating of the beans or of the meals because of poor storage and transport conditions, might also reduce KOH, PDI and TIA values of the SBM. The information available suggests that the relatively high TIA, PDI and KOH but low urease of the USA meals, are compatible with SBM with high CP and AA digestibility. In this respect, Frikha et al. (2012) in a study involving 22 commercial samples of SBM from ARG, BRA and USA origin reported a positive correlation between TIA (within the 1.8–4.2 mg/g range) and CP, Ly and Cys digestibility. García-Rebollar et al. (2016) suggested that the higher KOH value (up to 85%) recommended by the industry for the evaluation of the protein quality of the SBM, should be greater than currently accepted for commercial SBM, especially for the meals of USA origin. In any case, the potential influence of seed genotype, environmental conditions during growing, harvesting and storage, and the effects of the heat applied during crushing on protein solubility, and consequently on PDI and KOH values of the resulting SBM, should not be ruled out.

The correlations among protein quality indicators of the SBM reported in the current research were significant in all cases, except for UA that did not correlate with any of the other protein quality variables. García-Rebollar et al. (2016) in a study involving 515 samples of SBM from ARG, BRA and USA reported a significant ($P < 0.001$) but low correlation between UA and PDI ($r = 0.323$), KOH ($r = 0.293$) and TIA ($r = 0.379$). In the current research, most of the meals had UA values close to zero. Consequently, the majority of the UA values used to correlate UA and CP digestibility belonged to samples that were either very well processed or over-processed, resulting in poor correlation between both parameters.

4.5. Correlations among protein quality indicators and amino acid profile

The abundance of key essential AA (% of CP), including Cys, Met and Thr, decreased linearly as the CP content of the meals increased, in agreement with most published research (Thakur and Hurburgh, 2007; Medic et al., 2014; Miller-Garvin and Naeve, 2015). Krober and Cartter (1966), however, did not observe any trend for the abundance of Met with increases in CP content of the beans. Moreover, García-Rebollar et al. (2016) observed that Lys and Met abundance decreased as the CP content of the meal increased for SBM of USA origin but had no effects for the ARG and BRA meals. Pfarr et al. (2018) reported that the incidence of a series of stresses that affected the growth of the beans during the growing period, influenced not only the protein concentration of the seed but also the relative abundance of key indispensable AA. The authors reported that shading tended to increase the relative abundance of Lys, Met, Cys and Thr to a greater extent than was expected based on the regression studies the authors carried out. All this information suggests that the AA concentration of the SBM could not be predicted accurately from the CP content of the meal, and indicates the need of direct measurement of the AA concentration in the meals from beans of different countries to fully optimize the AA balance of diets for animal feeding.

5. Conclusions

Country of origin of the beans affects the chemical composition, protein quality and nutritive value of the corresponding meals. On average, BRA meals had more CP, NDF and raffinose content than the Argentina and USA meals, whereas the Indian meals show the highest ash, raffinose and NDF content. USA meals had more sucrose and stachyose but less raffinose and more indispensable AA content per unit of protein than BRA and IND meals, with ARG meal being intermediate. The USA SBM had higher TIA, KOH solubility and PDI than the ARG and BRA SBM. The information provided suggests that the range of PDI, KOH and TIA values recommended by the industry to evaluate the quality of the protein fraction of commercial meals of different origins should be taken with caution. In spite of its lower CP content, the SBM from the USA had similar or even higher energy content for poultry and swine than the SBM from Brazil, suggesting higher protein digestibility of the USA meals. Trypsin inhibitor activity was positively correlated with PDI and KOH. No correlations were found between UA and any of the other protein quality indicators studied, confirming that UA values do not predict accurately the quality of the protein fraction of SBM currently available in the market. Data from the meta-analysis suggest that the chemical composition, protein quality and nutritive value of the SBM depend on the country of origin of the bean. Consequently, different matrices should be used in feed formulation for commercial SBM obtained from beans of different origins.

CRediT authorship contribution statement

M.A. Ibáñez: Formal analysis, Supervision. **C. de Blas:** Formal analysis, Supervisión. **L. Cámara:** Writing - review & editing. **G.G. Mateos:** Writing - review & editing.

Declaration of Competing Interest

The authors confirm that there are not conflicts of interest in this research.

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