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Influence of the origin of the beans on the chemical composition and nutritive value of commercial soybean meals

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ABSTRACT

Commercial samples of soybean meal (SBM) from USA (n = 180), Brazil (BRA; n = 165) and Argentina (ARG; n = 170) were collected from 2007 to 2015 to study the effects of the origin of the beans on chemical composition, crude protein (CP) quality and nutritive value of the meals. Samples were collected at the country of origin or at the arrival of vessels from these countries to Europe. On a dry matter (DM) basis, USA and BRA meals had more CP than ARG meals (532, 532 and 517 g/kg, respectively; $P < 0.001$). On a CP basis, Lys content was higher (6.17, 6.07 and 6.11% CP; $P < 0.001$) in USA than in BRA meals, with ARG meals being intermediate. USA meals had more sucrose (84, 64 and 78 g/kg) and stachyose (64, 53 and 57 g/kg) but less neutral detergent fibre (90, 118 and 102 g/kg) and raffinose (11, 16 and 14 g/kg) than BRA and ARG meals ($P < 0.001$). Ether extract was highest for the BRA meals ($P < 0.05$). Mineral content depended on SBM origin, with BRA meals having more Fe but less Ca, P and K than USA and ARG meals ($P < 0.001$). The AME_n for poultry and net energy for pigs, estimated from published equations, were higher ($P < 0.001$) for the USA meals than for the South American meals. Protein quality indicators varied also with SBM origin. Urease activity was lowest for ARG meals, but the differences were of little practical interest. Protein dispersibility index, KOH protein solubility and trypsin inhibitor activity were higher ($P < 0.001$) for the USA meals than for the BRA and ARG meals. Heat damage indicator, a variable that measures indirectly the incidence of Maillard reactions, was lowest in the USA meals ($P < 0.001$). The correlations among chemical analyses, protein quality indicators and nutritive value traits were numerous and depended on the origin of the beans. The correlation between CP (g/kg DM) and Lys (% CP) contents was negative ($P < 0.001$) for the USA SBM, positive ($P < 0.001$) for the BRA SBM and not significant ($P > 0.10$) for the ARG SBM. In summary, chemical composition, protein quality and nutritive value of the SBM varied widely with the origin of the beans. At equal CP content, USA meals had less fibre,

Abbreviations: AA, amino acid; AID, apparent ileal digestibility; AME_n, apparent metabolisable energy, N corrected; ANF, antinutritional factor; ARG, Argentina; BRA, Brazil; CF, crude fibre; CP, crude protein; CV, coefficient of variation; DE, digestible energy; DM, dry matter; EE, ether extract; HDI, heat damage indicator; KOH, KOH protein solubility; N, nitrogen; NDF, neutral detergent fibre; NE, net energy; NFE, nitrogen-free extract; PDI, protein dispersibility index; SBM, soybean meal; TI, trypsin inhibitor; TIA, trypsin inhibitor activity; TSAA, total sulfur amino acids; UA, urease activity.

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more sucrose and Lys and better protein quality than South American meals. Consequently, nutritionists should consider the country of origin of the beans when preparing matrices for evaluating the nutritive value of commercial SBM.

1. Introduction

Soybean meal (SBM) is the main protein source in non-ruminant diets, with USA, Brazil (BRA) and Argentina (ARG) as the major exporter countries. Most nutritionists analyse moisture, crude fibre (CF), crude protein (CP) and urease activity (UA) of the SBM for estimating the nutritive value but usually little attention is paid to the influence of the origin of the beans on the characteristics and nutrient content of the meals. Factors such as bean genotype, planting area, soil type, agricultural practices, and environmental conditions during the growing season and storage, affect the chemical composition of the soybeans (Westgate et al., 2000; Karr-Lilienthal et al., 2004) and consequently the CP, fibre, sugars and mineral content and the nutritive value of the SBM (Grieshop et al., 2003; Ravindran et al., 2014; García-Rebollar et al., 2014). In addition, Frikha et al. (2012) and Ravindran et al. (2014) reported that the amino acid (AA) profile of the SBM varied with the origin of the beans, with USA and ARG meals having more Lys, total sulphur AA (TSAA) and Thr per unit of protein than BRA meals.

Trypsin inhibitors (TI) are the most important antinutritional factors (ANF) present in raw beans. Their inactivation by heat, reduces pancreas weight and increases pancreatic enzyme activity, improving the nutritive value of the meals (Balloun, 1980; Krogdahl and Holm, 1983). However, an excess of heat increases the incidence of Maillard reactions, reducing nutritive value (Fontaine et al., 2007; González-Vega et al., 2011). The determination of TI and Maillard reactions in SBM is tedious, time consuming and expensive. Urease activity, protein dispersibility index (PDI) and protein solubility in KOH (KOH) are the main methods used by the industry for evaluating indirectly the quality of the protein of the SBM. Because of cost and easy implementation, UA is widely used as an indicator of the presence of TI in SBM. 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) and therefore, high UA is indicative of under-processing of the beans and of an excess of TI remaining in the meal. A low UA, however, indicates either adequate or over-cooking of the meal, because the UA scale does not have negative values. Consequently, when the UA is the only criteria used for determining SBM quality, over-processed meals may pass undetected.

Globulins (glycinin and β-conglycinin) are the predominant storage proteins of soybeans. Globulins are soluble in their native state but their solubility decrease with heat processing. The PDI and KOH measure the solubility of the protein in water and 0.2% KOH solution, respectively. Both methods estimate the extent of denaturation of the protein fraction of the SBM, with high values indicating under-processing and low values indicating over-processing. Araba and Dale (1990) and Parsons et al. (1991) reported that KOH was a good indicator of protein quality. Anderson-Haferman et al. (1992), however, concluded that KOH was not accurate enough to assess under-processed meals. On the other hand, Hsu and Satter (1995), Batal et al. (2000) and Dudley-Cash (2001) suggested that PDI was a more consistent and sensitive indicator of adequate heat processing of SBM than UA or KOH. The heat damage indicator (HDI) quantifies via NIRS technology the effects of heat treatment on the availability of the AA. Most HDI of commercial meals ranges between 0 and 40, with the value of 12 representing the most frequent value in SBM (Evonik, 2010). High HDI values are indicative of damaged protein because of excessive heat treatment.

The aim of the research that is described herein was to study the influence of the origin of the beans (USA, BRA and ARG) on chemical composition, AA profile, protein quality and nutritive value of 515 commercial samples of SBM collected for nine consecutive years.

2. Materials and methods

2.1. Sample procurement

Representative samples (1–3 kg) of SBM were collected from USA (n = 180), BRA (n = 165) and ARG (n = 170) by specialized quality control personnel either at the country of origin (50% of samples) or at the arrival of the vessels to Europe. Only samples processed locally that eventually could reach the European market, were included in the study. Samples were collected for nine consecutive years and the number of samples per country varied with the year of collection (Table 1). The USA SBM were obtained from crushing plants located in the Mississippi river area (n = 96) and the East Coast (n = 36), or at the arrival at the ports of Tarragona and A Coruña (Spain), Hamburg (Germany), Rotterdam (The Netherlands) and Brest (France) of vessels loaded in New Orleans (n = 48). Samples from BRA were collected directly at the country of origin (n = 63), mostly from feed mills in the states of Porto Alegre and Sao Paulo, or in Europe (n = 102) from cargoes loaded at Paranaguá, Santos and Ilheus and unloaded at Brest (France), Hamburg (Germany) and Bilbao and Tarragona (Spain). Samples from ARG were collected from six different local crushing plants (n = 64) or in Europe (n = 106), at the arrivals of cargoes loaded at Rosario and Bahia Blanca to the ports of Marin and Huelva (Spain), Lisbon (Portugal) and Hamburg (Germany). In all cases, samples identity was preserved during the process, with identification of the technician in charge of the sampling, location and date of collection and details on dates and ports of departures and arrivals of the vessels.

Table 1
Number of soybean meal samples collected per year by country of origin.

	2007	2008	2009	2010	2011	2012	2013	2014	2015	Total
USA	55	40	18	11	16	9	10	7	14	180
BRA[a]	23	35	28	21	16	12	8	9	13	165
ARG[b]	50	36	23	13	10	10	10	7	11	170
Total	128	111	69	45	42	31	28	23	38	515

[a] Brazil.
[b] Argentina.

2.2. Laboratory analyses

2.2.1. Proximal composition and chemical determination

At arrival to the laboratory, samples were stored in hermetic plastic containers at 12 ± 2 °C and a relative humidity of 60 ± 3% until analyses (less than 30 days in storage). Individual samples were divided in three portions using a seed divider. Laboratorios Finca Mouriscade (Pontevedra, Spain) conducted all chemical determinations, except for AA content and HDI that were conducted at Evonik central lab (Hanau, Germany) (portions 1 and 2). The third portion was stored in the lab for further utilization. The samples were ground using a hammer mill (Model Z-I, Retsch, Stuttgart, Germany) fitted with a 0.50 mm screen and analysed for moisture by oven-drying (method 930.15), ash with a muffle furnace (method 942.05) and nitrogen (N) by Kjeldahl (method 988.05) as described by the AOAC International (2005). Crude protein content was calculated as N × 6.25. Ether extract (EE) was analysed by Soxhlet after 3 *N* HCl hydrolysis (method 4.b) as described by Boletín Oficial del Estado (1995). Sucrose and oligosaccharides (stachyose and raffinose) were determined as indicated by de Coca-Sinova et al. (2008). Crude fibre content was determined by sequential extraction with diluted acid and alkali (method 962.09; AOAC International, 2005) and the neutral detergent fibre (NDF) as described by van Soest et al. (1991). All samples were analysed in duplicate in the same lab by the same technician. Data are presented on dry matter (DM) bases.

The apparent metabolisable energy, corrected for N (AME_n) of the SBM was estimated from the chemical analyses as indicated in the European Table of Energy Values for Poultry Feedstuffs (WPSA, 1989): AME_n (MJ/kg DM) = 15.69 × CP (g/kg DM) + 29.51 × EE (g/kg DM) + 6.236 × NFE (g/kg DM), where NFE represents the nitrogen-free extract. Net energy (NE) for pigs was calculated according to the equation proposed by Noblet et al. (2003). Briefly, the digestibility of the gross energy was calculated as follows: (92.2 – 1.01 × CF (%) + 94.8 – 0.71 × NDF (%) + 95 – 0.71 × NDF (%))/3. The NE, on DM bases, was estimated from the digestible energy (DE) by applying the coefficients of 0.913 (DE to AME) and 0.605 (AME to NE) proposed for SBM.

Macrominerals and trace elements were analysed as described by Hermida et al. (2006). Briefly, the ash was dissolved in HCl an diluted to 200 ml with Milli-Q water and filtrated. Phosphorus was measured at 430 nm (AOAC International, 1995). Sodium and K were determined by emission spectroscopy at 589.0 and 766.5 nm, respectively, using an air-acetylene flame and Ca and Mg by atomic absorption spectroscopy at 422.7 and 285.2 nm, respectively. Zinc, Fe, Cu and Mn were determined by atomic absorption spectroscopy using single element hollow cathode lamps and air-acetylene flame at 213.9, 248.3, 324.7 and 279.5 nm, respectively. The contents in indispensable AA and Cys, were determined by NIRS (Fontaine et al., 2001). Briefly, two ring cups were filled with the finely ground material and scanned between 1100 and 2500 nm in 2 nm steps. The absorbance at each wavelength was expressed as log (1/R) using a ceramic plate as reference.

2.2.2. Protein quality indicators

Urease activity (mg N/g) was determined as indicated by Boletín Oficial del Estado (1995) and KOH as described by Araba and Dale (1990). The PDI was measured according to method Ba 10–65 of the AOCS (2000) using a Hamilton blender (Model G936, VOS Instrument, Zaltbommel, The Netherlands), and TI activity (TIA), expressed in mg/g DM, according to the method of Hamerstrand et al. (1981). The HDI was determined using the AMINORED method as proposed by Evonik (2010).

2.3. Statistical analyses

Data were analysed as a completely randomized design using the GLM procedure of SAS (SAS Institute Inc., 1990). The main effect of the model was the country of origin of the SBM. Year crop and heat conditions applied during the extraction process of the beans were considered random effects and were not included in the model. Therefore, the inherent variability caused by bean genotype, environmental conditions, storage time and heat processing variables applied to the beans, was assumed to be part of the experimental error. When the model was significant, the Tukey test was used to make pairwise comparisons between treatment means. In addition, the Pearson correlation (r) analyses and the REG procedure of SAS (SAS Institute Inc., 1990) were conducted to determine the relation between the different variables studied. A value of 0.05 was considered significant and values between 0.05 and 0.10 were considered a tendency.

Table 2
Chemical composition (g/kg) and AME_n for poultry and ME and NE for pigs (MJ/kg) of the soybean meals[a] (on dry matter basis).

	Average					Coefficient of variation (%)			Range		
	USA	BRA	ARG	S.E.M.	P-value	USA	BRA	ARG	USA	BRA	ARG
Determined											
Dry matter	885	884	886	0.703	0.265	0.76	1.25	1.07	868–910	863–920	863–925
Ash	75.7[x]	71.8[y]	74.9[x]	0.432	<0.001	8.83	7.12	6.47	61.0–105.7	62.3–108.5	64.2–93.3
Crude protein	532[x]	532[x]	517[y]	1.120	<0.001	2.32	2.85	3.11	504–565	497–571	484–553
Ether extract	19.1[y]	20.3[x]	19.0[y]	0.413	0.040	31.5	26.2	24.6	8.2–36.8	8.0–36.3	6.7–33.6
Sucrose	84.3[x]	64.3[z]	77.6[y]	0.810	<0.001	12.7	13.9	13.0	58.7–109.6	28.0–91.1	22.0–101.5
Stachyose	63.9[x]	52.5[z]	56.5[y]	0.440	<0.001	8.40	10.1	9.50	43.2–82.6	36.5–73.4	37.3–71.0
Raffinose	10.9[z]	15.8[x]	13.5[y]	0.230	<0.001	25.9	17.2	14.2	6.0–1.86	9.0–25.7	9.0–20.1
Crude fibre	43.3[z]	61.4[x]	52.0[y]	0.850	<0.001	12.7	19.4	26.8	30.3–66.0	39.3–94.3	29.4–96.8
NDF[b]	90[z]	118[x]	102[y]	1.380	<0.001	12.1	16.3	20.8	54–127	74–165	73–178
Calculated											
AME_n[c], MJ/kg	10.97[x]	10.90[y]	10.78[z]	0.018	<0.001	1.76	2.10	2.23	10.54–11.50	10.45–11.63	10.27–11.26
AME[d], MJ/kg	16.40[x]	15.90[z]	16.16[y]	0.023	<0.001	1.60	1.81	1.88	15.65–16.96	15.27–16.74	15.24–16.77
NE[e], MJ/kg	9.92[x]	9.62[z]	9.76[y]	0.018	<0.001	1.60	1.81	1.88	9.47–10.26	9.24–10.13	9.22–10.14

[x,y,z] Within a row, means without a common superscripts differ (P < 0.05).
[a] n = 180, 165 and 170 for USA, Brazil and Argentina SBM, respectively.
[b] Neutral detergent fibre.
[c] Apparent metabolisable energy corrected by nitrogen. Calculated according to the European tables of energy values for poultry feedstuffs WPSA (1989).
[d] Apparent metabolisable energy. Calculated according to Noblet et al. (2003).
[e] Net energy. Calculated according to Noblet et al. (2003).

Table 3
Macromineral (g/100 g) and trace mineral (mg/kg) content of the soybean meals.[a]

	Average					Coefficient of variation (%)			Range		
	USA[c]	BRA[d]	ARG[e]	S.E.M.	P-value	USA	BRA	ARG	USA	BRA	ARG
Macrominerals											
Ca	0.43[x]	0.33[z]	0.37[y]	0.007	<0.001	30.9	16.2	16.1	0.24–0.91	0.19–0.56	0.24–0.57
P	0.77[x]	0.70[y]	0.76[x]	0.005	<0.001	5.49	6.02	9.44	0.65–0.89	0.58–0.82	0.53–0.92
K	2.41[y]	2.29[z]	2.54[x]	0.019	<0.001	7.74	9.87	8.36	1.98–2.84	1.33–3.00	2.00–3.29
Mg	0.323	0.322	0.316	0.004	0.458	11.0	16.7	13.6	0.249–0.458	0.237–0.484	0.238–0.410
Na	0.026[y]	0.032[x]	0.031[x]	0.001	0.001	50.6	44.8	37.4	0.004–0.068	0.004–0.079	0.004–0.057
Trace minerals											
Zn	56.6[x]	56.9[x]	50.9[y]	0.390	<0.001	8.15	6.61	8.83	47.7–73.9	45.1–73.1	42.4–84.4
Mn	40.5[y]	35.0[z]	46.5[x]	0.562	<0.001	14.4	19.0	12.6	27.0–54.3	19.7–54.0	31.5–61.5
Fe	136[y]	195[x]	121[y]	5.007	<0.001	39.2	36.1	23.0	80–335	95–647	51–252
Cu	16.6[x]	15.3[y]	16.4[x]	0.220	<0.001	13.3	18.3	12.4	11.2–28.6	8.9–22.3	12.4–25.9

[x,y,z] Within a row, means without a common superscripts differ (P < 0.05).
[a] n = 180, 165 and 170 for USA, Brazil (BRA) and Argentina (ARG) SBM, respectively.

3. Results

3.1. Chemical analyses

On a DM basis, CP was higher (P < 0.001) for the USA and BRA meals than for the ARG meal (Table 2). Brazilian meals had more EE (P < 0.05) than USA and ARG meals but the differences were of limited practical interest. Sucrose and stachyose were higher and raffinose, CF and NDF lower, for the USA than for the BRA SBM, with the ARG SBM being intermediate (P < 0.001). The calculated (MJ/kg DM) AME_n for poultry (11.0 vs. 10.9 and 10.8) and NE for pigs (9.92 vs. 9.62 and 9.76) were higher (P < 0.001) for the USA than for the BRA and ARG SBM.

Calcium, P and K content was greater (P < 0.001) for the USA and ARG meals than for the BRA meals (Table 3). Origin of the beans affected also trace mineral contents, with the biggest differences observed for Fe, that was higher for the BRA meals than for the USA and ARG meals (195, 136 and 121 mg/kg DM, respectively; P < 0.001).

The content in indispensable AA and Cys varied with the country of origin of the beans, reflecting differences in CP content of the SBM (Table 4). In g/kg DM, Lys (32.8, 31.6 and 32.3), Thr (20.8, 20.4 and 20.7) and Trp (7.3, 7.1 and 7.2) were higher (P < 0.001) for the USA than for the ARG meals, with the BRA meals being intermediate. As a result, the concentration of the five key AA was higher for the USA and BRA SBM than for the ARG SBM (76.9, 75.1 and 74.0 g/kg DM, respectively; P < 0.001).

Table 4
Amino acid (AA) content (g/kg DM) of the soybean meals.[a]

	Average					Coefficient of variation (%)			Range		
	USA	BRA	ARG	S.E.M.	P-value	USA	BRA	ARG	USA	BRA	ARG
Indispensable AA											
Arg	39.0[x]	38.8[x]	37.5[y]	0.095	<0.001	2.62	3.36	3.46	36.6–41.5	35.3–42.1	34.6–40.5
His	14.2[x]	14.1[x]	13.9[y]	0.031	<0.001	2.14	2.90	3.29	13.4–15.0	13.1–15.2	12.8–15.0
Iso	24.1[x]	24.1[x]	23.4[y]	0.060	<0.001	2.62	3.54	3.34	22.6–26.2	21.4–26.4	21.8–25.1
Leu	40.5[x]	40.4[x]	39.3[y]	0.096	<0.001	2.47	3.34	3.30	38.3–43.4	37.3–43.9	36.3–42.1
Lys	32.8[x]	32.3[y]	31.6[z]	0.074	<0.001	2.07	3.45	3.22	30.9–34.5	29.7–35.1	29.3–33.5
Met	7.3[x]	7.1[y]	7.1[y]	0.016	<0.001	1.93	2.98	3.22	6.9–7.7	6.7–7.6	6.6–7.5
Phe	27.0[x]	27.2[x]	26.2[y]	0.067	<0.001	2.69	3.43	3.50	25.5–29.8	24.8–29.5	24.2–28.3
Thr	20.8[x]	20.7[y]	20.4[z]	0.043	<0.001	2.08	2.88	3.07	19.9–22.1	19.4–22.3	19.0–21.6
Trp	7.3[x]	7.2[y]	7.1[z]	0.017	<0.001	2.11	3.26	3.40	6.8–7.7	6.7–7.9	6.6–7.6
Val	25.3[x]	25.2[x]	24.7[y]	0.056	<0.001	2.23	2.99	3.24	23.9–27.0	23.0–27.2	22.9–26.4
Dispensable AA											
Cys	8.0[x]	7.8[y]	7.8[y]	0.021	<0.001	2.69	3.17	4.12	7.4–8.5	7.4–8.5	7.1–8.5
$\sum$ Five key AA[b]	76.9[x]	75.1[x]	74.0[y]	0.185	<0.001	3.14	3.02	3.16	72.3–85.0	70.1–81.1	69.2–78.7
$\sum$ Ten key AA[c]	246.9[x]	245.1[x]	238.9[y]	0.552	<0.001	2.25	3.10	3.26	233.4–260.4	227.9–264.5	222.3–255.9

[x,y,z] Within a row, means without a common superscripts differ (P < 0.05).
[a] n = 180, 165 and 170 for USA, Brazil (BRA) and Argentina (ARG) SBM, respectively.
[b] Lys, Met, Cys, Thr and Trp.
[c] Arg, His, Iso, Leu, Lys, Met + Cys, Phe, Thr, Trp and Val.

Table 5
Amino acid (AA) profile (% crude protein) of the soybean meals.[a]

	Average					Coefficient of variation, %			Range		
	USA	BRA	ARG	S.E.M.	P-value	USA	BRA	ARG	USA	BRA	ARG
Indispensable AA											
Arg	7.32[x]	7.30[y]	7.24[z]	0.005	<0.001	0.92	1.04	0.79	7.18–7.64	6.92–7.62	7.06–7.49
His	2.67[y]	2.66[z]	2.68[x]	0.002	<0.001	1.06	1.25	1.04	2.60–2.73	2.52–2.83	2.60–2.75
Iso	4.53	4.54	4.52	0.004	0.010	1.05	1.47	0.76	4.47–4.77	4.19–4.79	4.47–4.67
Leu	7.60	7.60	7.59	0.005	0.179	0.87	1.13	0.71	7.03–7.94	7.35–8.01	7.48–7.80
Lys	6.17[x]	6.07[z]	6.11[y]	0.005	<0.001	1.03	1.32	1.07	5.99–6.39	5.81–6.35	5.91–6.32
Met	1.37[x]	1.33[y]	1.37[x]	0.002	<0.001	1.59	1.33	1.32	1.28–1.41	1.29–1.41	1.31–1.41
Phe	5.07[y]	5.11[x]	5.06[y]	0.005	<0.001	1.17	1.39	1.06	4.98–5.35	4.86–5.35	4.97–5.24
Thr	3.92[y]	3.89[z]	3.94[x]	0.002	<0.001	0.81	0.78	0.77	3.85–4.04	3.84–4.03	3.86–4.03
Trp	1.37[y]	1.35[z]	1.37[x]	0.002	<0.001	1.47	1.44	1.30	1.33–1.43	1.30–1.43	1.33–1.42
Val	4.76[y]	4.75[z]	4.77[x]	0.003	<0.001	0.90	0.95	0.66	4.55–4.93	4.50–4.94	4.70–4.88
Dispensible AA											
Cys	1.51[x]	1.48[y]	1.51[x]	0.003	<0.001	2.73	2.33	2.77	1.36–1.58	1.38–1.57	1.41–1.59
$\sum$ Five key AA[b]	14.3[x]	14.1[y]	14.3[x]	0.013	<0.001	0.99	0.90	0.87	14.0–14.8	13.8–14.7	14.0–14.6
$\sum$ Ten key AA[c]	46.3[x]	46.1[y]	46.2[y]	0.027	<0.001	0.73	0.80	0.60	45.8–48.0	45.4–48.1	45.5–47.2

[x,y,z] Within a row, means without a common superscripts differ (P < 0.05).
[a] n = 180, 165 and 170 for USA, Brazil (BRA) and Argentina (ARG) SBM, respectively.
[b] Lys, Met, Cys, Thr and Trp.
[c] Arg, His, Iso, Leu, Lys, Met + Cys, Phe, Thr, Trp and Val.

3.2. Amino acid profile and protein quality indicators

The AA profile of the SBM varied with the origin of the beans (Table 5). On CP bases, Lys content was higher for the USA than for the ARG meals and higher for both than for the BRA meals (6.17, 6.11 and 6.07% CP; $P < 0.001$). Similarly, TSAA, Thr, Trp and Val concentrations were greater ($P < 0.001$) for the USA and ARG SBM than for the BRA SBM. As a result, the concentration of five critical AA (Lys, Met + Cys, Thr and Trp) in the protein fraction was higher for the USA and ARG meals than for the BRA meal (14.3 and 14.3 vs. 14.1% CP; $P < 0.001$).

Protein quality indicators differed among SBM (Table 6). Urease activity ($P < 0.001$) was higher for the USA and BRA meals than for ARG meals. The PDI (19.5, 15.0 and 16.0%), KOH (86.1, 82.0 and 81.2%) and TIA (3.5 vs. 2.9 and 2.8 mg/g DM) were higher and the HDI (9.0 vs. 16.0 and 12.5) was lower for the USA than for the BRA and ARG meals ($P < 0.001$).

Table 6
Protein quality indicators of the soybean meals.[a]

	Average					Coefficient of variation (%)			Range		
	USA[c]	BRA[d]	ARG[e]	S.E.M.	P-value	USA	BRA	ARG	USA	BRA	ARG
UA[b]	0.022[x]	0.026[x]	0.014[y]	0.002	<0.001	154	115	146	0.00–0.25	0.00–0.19	0.00–0.14
PDI[c]	19.5[x]	15.0[y]	16.0[y]	0.324	<0.001	23.9	21.3	25.8	9.7–32.2	7.0–26.2	7.3–32.5
KOH[d]	86.1[x]	82.0[y]	81.2[y]	0.328	<0.001	4.67	5.34	4.86	77.7–95.7	67.9–93.0	71.4–91.3
TIA[e]	3.5[x]	2.9[y]	2.8[y]	0.053	<0.001	22.1	18.9	20.2	1.4–5.5	1.8–4.7	1.4–4.6
HDI[f]	9.0[z]	16.0[x]	12.5[y]	0.371	<0.001	44.5	29.9	37.1	0.0–19.0	5.0–39.0	1.0–39.0

[x,y,z] Within a row, means without a common superscripts differ (P < 0.05).
[a] n = 180, 165 and 170 for USA, Brazil (BRA) and Argentina (ARG) SBM, respectively.
[b] Urease activity (mg N/g).
[c] Protein dispersibility index (%).
[d] KOH protein solubility (%).
[e] Trypsin inhibitor activity (mg/g DM).
[f] Heat damage indicator (Evonik, 2010). Values varied from 0 (low damage of CP) to 40 (high damage of CP).

3.3. Dispersion of the analytical data and correlations among chemical variables

In g/kg DM, ash and CP content varied from 61.0 to 108.5 (CV = 7.9%) and from 484 to 571 (CV = 3.1%), respectively (Table 2). Sucrose, stachyose and raffinose contents ranged from 22 to 110 g/kg (CV = 17.2%), 37 to 83 g/kg (CV = 12.5%) and 6 to 26 (CV = 24.4%), respectively. The highest CV (27.8%) was recorded for EE. The calculated (MJ/kg DM) AME_n for poultry and NE for swine of the SBM varied from 10.3 to 11.6 (CV = 2.15%) and from 9.2 to 10.3 (CV = 2.18%), respectively. When the data were sorted by the origin of the beans, the CV tended to decrease for all traits, with values of 2.3, 2.9 and 3.1% for CP, 12.7, 13.9 and 13.0% for sucrose, 8.4, 10.1 and 9.5% for stachyose, (12.1, 16.3 and 20.8%) for NDF and 31.5, 26.2 and 24.6% for EE, for USA, BRA and ARG meals, respectively.

Among the macro-minerals, the highest variation, independent of the origin of the beans, was observed for Na and Ca that ranged (g/100 g) from 0.004 to 0.079 (CV = 44.8%) and from 0.19 to 0.91 (CV = 25.2%), respectively and the lowest for P (range from 0.53 to 0.92; CV = 8.3%) and K (range from 1.33 to 3.29; CV = 9.9%) (Table 3). For trace minerals, the highest variability (51–647 mg/kg; CV = 41.5%) was observed for Fe. When the SBM were sorted by the origin of the beans, the CV were 30.9, 16.2 and 16.1% for Ca, 5.5, 6.0 and 9.4% for P, 7.7, 9.9 and 8.4% for K, and 39.2, 36.1 and 23.0% for Fe, for USA, BRA and ARG meals, respectively.

Among the AA, the CV was lowest for Thr (2.8%) and highest for Cys (3.5%), with Lys (3.2%) and Met (3.0%) in an intermediate position. When the samples were sorted by the country of origin, the dispersion of values decreased, and the CV were similar for all origins (Table 4).

Numerous correlations affecting most of the chemical and protein quality variables studied were detected and therefore, we will focus exclusively on those correlations that were highly significant (P < 0.001) and had a Pearson coefficient (*r*) higher than 0.4 (Tables 7–10). When the data were analysed irrespective of the origin of the beans, the most significant correlations (P < 0.001) detected were between CF and NDF ($r = 0.836$), CF and CP ($r = -0.415$) and sucrose and stachyose ($r = 0.673$) (Table 7). Moreover, sucrose content was negatively correlated with raffinose ($r = -0.537$), CF ($r = -0.549$) and NDF ($r = -0.583$). When the data were sorted by the country of origin of the beans, the relation among the variables were still evident but depend on the origin of the beans. The more stable correlation was for CF and NDF ($r = 0.637$, 0.757 and 0.789 for the USA, BRA and ARG meals). A negative correlation between CP and sucrose ($r = -0.562$) was detected for the USA meals but not for the South American meals. In contrast, a significant negative correlation between CP and NDF was detected for the BRA ($r = -0.435$) and ARG ($r = -0.645$) meals but not for the USA meals. Moreover, the correlation between sucrose and stachyose was higher for the BRA and ARG meals than for the USA meals ($r = 0.524$, 0.661 and 0.269, respectively).

The correlations among minerals were numerous but of limited practical interest (Table 8). In fact, all the coefficients, except that between P and K ($r = 0.422$; P < 0.001) and Cu and Mn ($r = 0.426$; P < 0.001) were below 0.4. Similarly, when the SBM were sorted by the country of origin of the beans, the only relations of interest (P < 0.001) observed were between P and K ($r = 0.452$ and 0.432) and Na and Fe ($r = 0.393$ and 0.412) for the USA and BRA meals.

3.4. Dispersion of the analytical data and correlations among amino acid profile and protein quality indicators

The range and CV of the AA profile (% CP) of the SBM, across the origin of the beans, was relatively low for most AA but had important economic consequences (Table 5). For example, as a percentage of CP content, Lys and Cys varied from 5.81 to 6.39 (CV = 1.3%) and from 1.36 to 1.59 (CV = 2.8%), respectively. When the data on AA profile were sorted by the country of origin of the beans, the CV was reduced with the lowest values observed for Thr (0.81, 0.78 and 0.77%) and Lys (1.03, 1.32 and 1.07%) and the highest for Cys (2.73, 2.33 and 2.77%), for USA, BRA and ARG meals, respectively. For all AA the CV was lower for the USA meals than for the South American meals.

Table 7
Pearson coefficient of correlation (r) among chemical parameters of the soybean meals.

Origin	CP[a]	EE[b]	Sucrose	Stachyose	Raffinose	CF[c]
All (n = 515)						
CP	1					
EE	−0.031[NS]	1				
Sucrose	−0.168[***]	−0.130[**]	1			
Stachyose	0.076[NS]	−0.162[***]	0.673[***]	1		
Raffinose	0.088[+]	0.085[+]	−0.537[***]	−0.398[***]	1	
CF	−0.412[***]	−0.001[NS]	−0.549[***]	−0.498[***]	0.245[***]	1
NDF[d]	−0.302[***]	0.062[NS]	−0.583[***]	−0.535[***]	0.351[***]	0.836[***]
USA (n = 180)						
CP	1					
EE	0.042[NS]	1				
Sucrose	−0.562[***]	−0.127[NS]	1			
Stachyose	0.003[NS]	−0.286[***]	0.269[***]	1		
Raffinose	0.179[*]	0.061[NS]	−0.512[***]	−0.223[**]	1	
CF	−0.047[NS]	−0.041[NS]	−0.381[***]	−0.175[*]	0.122[NS]	1
NDF	0.047[NS]	0.119[NS]	−0.442[***]	−0.235[**]	0.271[***]	0.637[***]
Brazil (n = 165)						
CP	1					
EE	−0.138[+]	1				
Sucrose	−0.085[NS]	0.038[NS]	1			
Stachyose	−0.067[NS]	0.105[NS]	0.524[***]	1		
Raffinose	−0.112[NS]	0.090[NS]	−0.111[NS]	−0.070[NS]	1	
CF	−0.536[***]	−0.187[*]	−0.129[NS]	−0.124[NS]	−0.163[+]	1
NDF	−0.435[***]	−0.089[NS]	−0.280[***]	−0.221[**]	0.008[NS]	0.757[***]
Argentina (n = 170)						
CP	1					
EE	−0.092[NS]	1				
Sucrose	0.104[NS]	−0.166[+]	1			
Stachyose	0.176[*]	−0.170[*]	0.661[***]	1		
Raffinose	0.437[***]	−0.149[+]	0.072[NS]	0.276[**]	1	
CF	−0.710[***]	0.002[NS]	−0.447[***]	−0.322[***]	−0.336[***]	1
NDF	−0.645[***]	0.037[NS]	−0.323[***]	−0.314[**]	−0.314[***]	0.789[***]

NS, no significant.
[+] $P < 0.10$.
[*] $P < 0.05$.
[**] $P < 0.01$.
[***] $P < 0.001$.
[a] Crude protein.
[b] Ether extract.
[c] Crude fibre.
[d] Neutral detergent fibre.

The variability across all beans of the protein quality indicators was highest for UA (0.00–0.245 mg N/g; CV = 141.4) and lowest for KOH (67.9–95.7%; CV = 5.6%) (Table 6). When the SBM were sorted by the country of origin, the CV of all the indicators decreased and in general, were slightly lower for the BRA meals than for the USA and ARG meals.

Across bean origin, the coefficient of correlation between CP content (g/kg DM) of the SBM and the concentration of the indispensable AA (% CP) was highly significant ($P < 0.001$) for most key AA, except Lys (Table 9). When the SBM were sorted by the origin of the bean, the r values showed a significant ($P < 0.001$) negative relation for the USA meals, but not for the South American meals. The data indicated that the AA profile of the South American meals did not change with increases in CP content of the SBM.

The significance, R^2 and the RSD of the regression equations between CP and Lys, Met and TSAA contents (g/kg DM) of the SBM indicate that the content of these AA could be estimated from the CP content (Figs. 1–3). The estimation was more precise for Lys (RSD = 0.404; $R^2 = 0.853$; $P < 0.001$) than for Met (RSD = 0.124; $R^2 = 0.666$; $P < 0.001$) and TSAA (RSD = 0.298; $R^2 = 0.596$; $P < 0.001$) (Fig. 1A–C). Moreover, when the SBM were sorted by the country of origin of the beans, the R^2 values of the correlation between CP and Lys (g/kg SBM) increased from 0.853 to 0.879 and 0.914 for BRA and ARG SBM (Fig. 1C and D) but decreased to 0.834 for USA SBM (Fig. 1B).

The regression equation between CP and Met content (g/kg DM) across the origin of the beans is shown in Fig. 2A. The data showed a very significant correlation ($P < 0.001$) between both variables but the correlation coefficient ($R^2 = 0.666$) was lower than that found for Lys. When the correlation was studied across the origin of the beans the coefficient was significant but small ($R^2 = 0.096$; $P < 0.001$). When the SBM were sorted by the country of origin of the beans, the significance of the correlation between Met and CP (g/kg SBM), was maintained in all cases SBM ($P < 0.001$). However, the R^2 increased from 0.666 to 0.835 and 0.849 for the BRA and ARG meals (Fig. 2C and D) but decreased to 0.572 for the USA meals (Fig. 2C). When

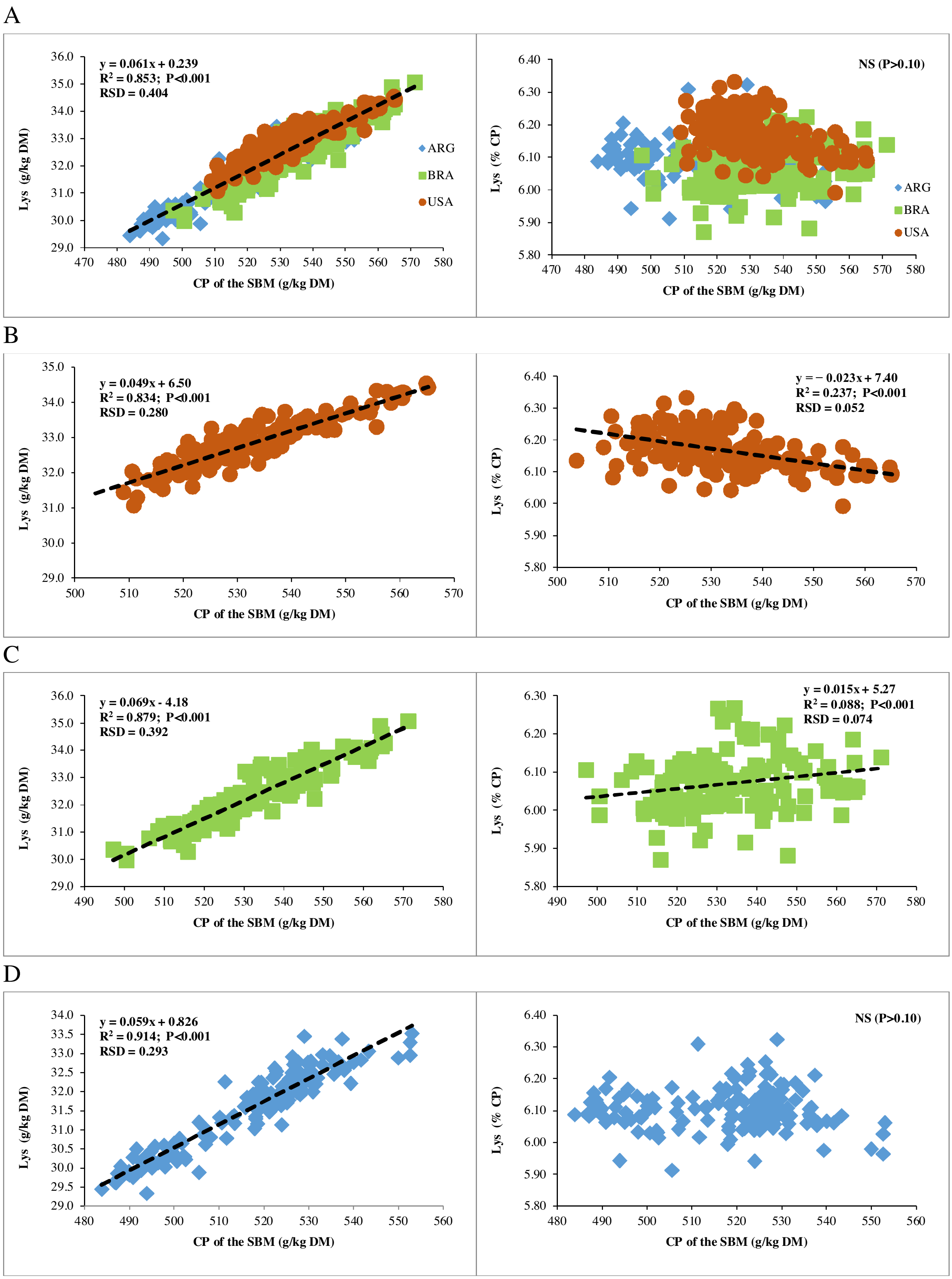

Fig. 1. Regression equations between CP content of the SBM (g/kg DM) and Lys content (g/kg SBM) and profile (% CP) for all SBM (A), or SBM from USA (B), Brazil (C) and Argentina (D) origin.

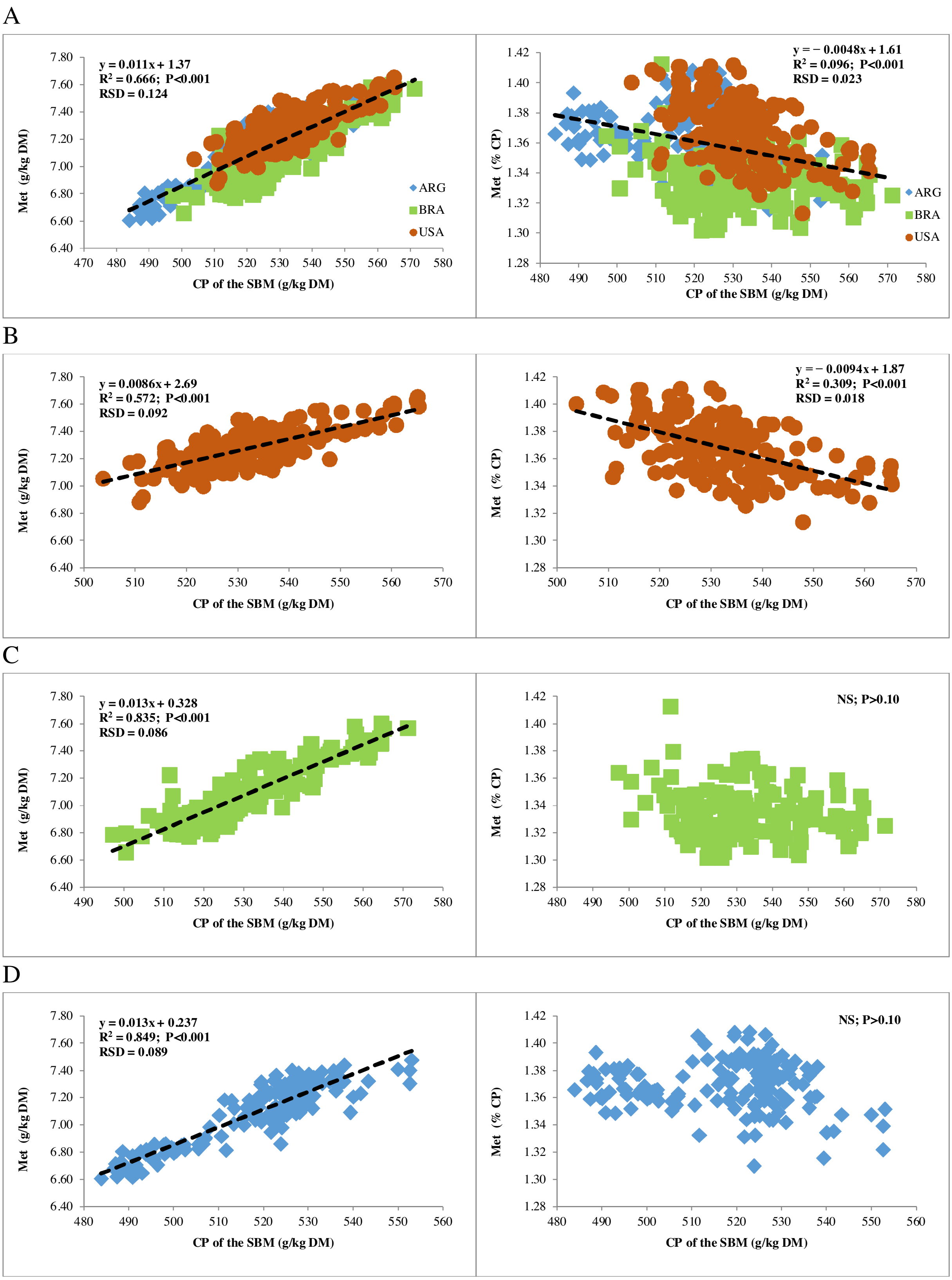

Fig. 2. Regression equations between CP content of the SBM (g/kg DM) and Met content (g/kg SBM) and profile (% CP) for all SBM (A), or SBM from USA (B), Brazil (C) and Argentina (D) origin.

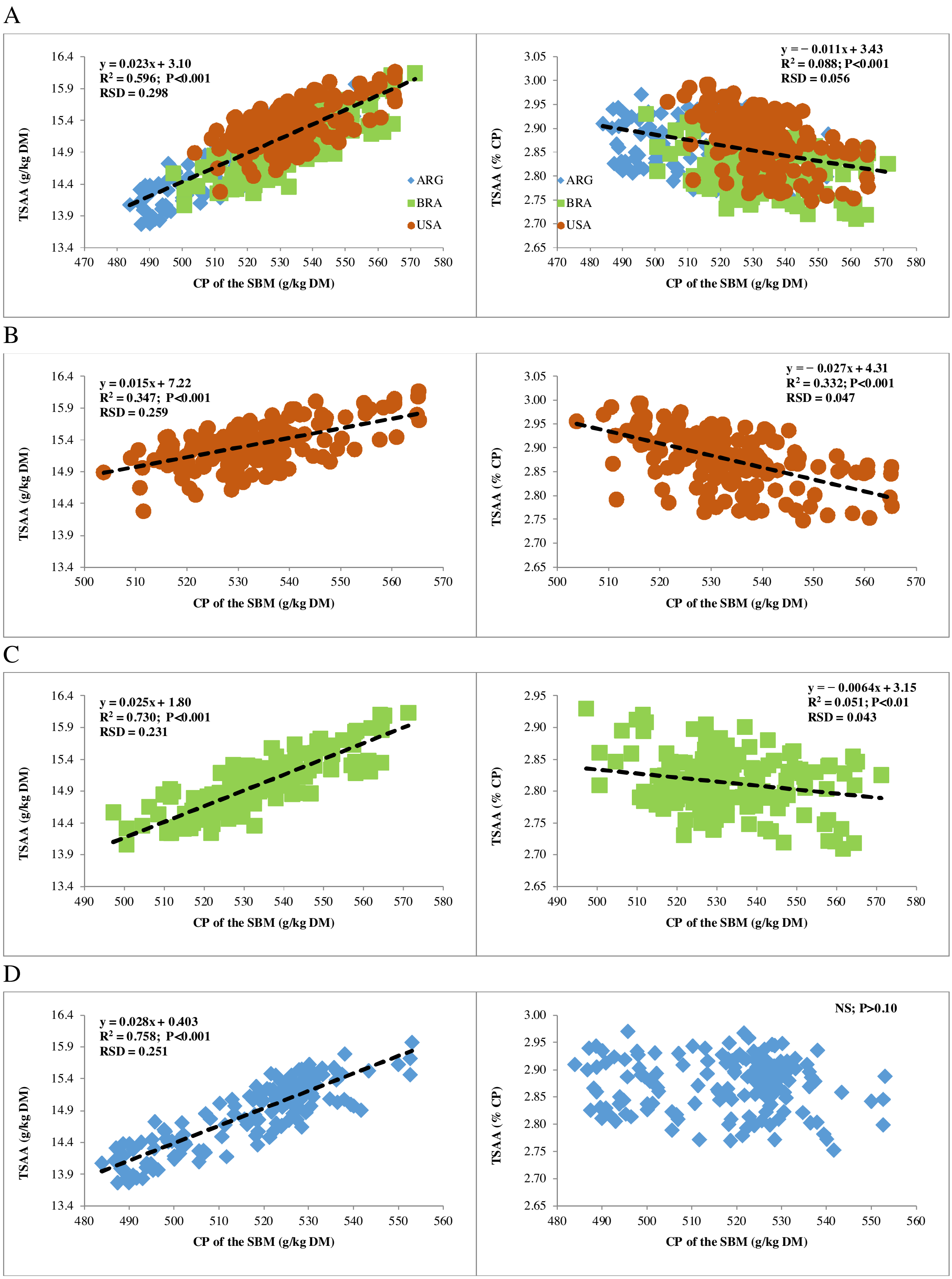

Fig. 3. Regression equations between CP content of the SBM (g/kg DM) and TSAA content (g/kg SBM) and profile (% CP) for all SBM (A), or SBM from USA (B), Brazil (C) and Argentina (D) origin.

Table 8
Pearson coefficient of correlation (*r*) among minerals of the soybean meals.

Origin	Ca	P	K	Na	Mg	Zn	Mn	Fe
All								
Ca	1							
P	0.235***	1						
K	0.042NS	0.422***	1					
Na	−0.088+	−0.142+	−0.199***	1				
Mg	0.023NS	0.236***	−0.153**	0.036NS	1			
Zn	0.004NS	−0.111*	−0.247***	0.018NS	0.191***	1		
Mn	0.259***	0.396***	0.272***	−0.105*	0.028NS	−0.209***	1	
Fe	−0.136**	−0.371***	−0.338***	0.350***	0.081NS	0.202***	−0.279***	1
Cu	0.228**	0.175***	0.103NS	0.050NS	−0.156**	−0.087NS	0.426***	−0.060NS
USA								
Ca	1							
P	0.269**	1						
K	−0.028NS	0.452***	1					
Na	−0.031NS	−0.196*	−0.285**	1				
Mg	−0.014NS	0.032NS	−0.221*	0.139NS	1			
Zn	−0.123NS	0.231*	0.160NS	0.048NS	0.024NS	1		
Mn	0.273**	0.150NS	0.070NS	0.035NS	0.051NS	0.326***	1	
Fe	−0.65NS	−0.278**	−0.261**	0.393***	−0.022NS	0.062NS	−0.078NS	1
Cu	0.278**	0.064NS	−0.111NS	0.245*	−0.076NS	0.065NS	0.297**	0.092NSS
BRA								
Ca	1							
P	−0.061NS	1						
K	−0.061NS	0.432***	1					
Na	−0.005NS*	−0.018NS	−0.280***	1				
Mg	0.184*	0.386***	−0.006NS	0.078NS	1			
Zn	0.173*	−0.076NS	−0.002NS	0.044NS	0.334***	1		
Mn	0.316***	0.006NS	−0.136NS	0.013NS	−0.019NS	0.015NS	1	
Fe	0.132NS	−0.101NS	−0.159+	0.412***	0.200*	0.011NS	0.154+	1
Cu	0.057NS	−0.023NS	−0.065NS	0.026NS	−0.243**	−0.228**	0.560***	0.060NS
ARG								
Ca	1							
P	−0.055NS	1						
K	−0.102NS	0.187*	1					
Na	0.110NS	−0.057NS	−0.004NS	1				
Mg	−0.132NS	0.368***	−0.322***	−0.122NS	1			
Zn	−0.003NS	0.036NS	−0.129NS	−0.118NS	0.138NS	1		
Mn	0.202*	0.371***	−0.019NS	−0.318***	0.273**	0.094NS	1	
Fe	0.163+	−0.160+	0.100NS	−0.006NS	−0.265**	−0.097NS	−0.189*	1
Cu	0.173+	0.165+	0.292**	0.038NS	−0.042NS	0.119NS	0.211*	0.051NS

NS, no significant.
+ $P<0.10$.
* $P<0.05$.
** $P<0.01$.
*** $P<0.001$.

Table 9
Pearson coefficient of correlation (*r*) between crude protein (g/kg DM) and amino acid profile (% CP) of the soybean meals.

	Lys	Met + Cys	Thr	Trp
All (n = 515)	0.010NS	−0.296***	−0.355***	−0.201***
USA (n = 180)	−0.487***	−0.576***	−0.463***	−0.445***
Brazil (n = 165)	0.297**	−0.225**	−0.141NS	−0.028NS
Argentina (n = 170)	−0.026NS	−0.069NS	−0.130NS	0.049NS

NS, no significant.
** $P<0.01$.
*** $P<0.001$.

the SBM were sorted by the country of origin of the beans, there was a significant correlation between CP (g/kg DM) and Met (%) for the USA meals ($R^2=0.309$; $P<0.001$) but not for the South American meals. Similar type of data was observed for the correlations between CP and TSAA contents (Fig. 3).

The *r* values among protein quality indicators across the origin of the beans, were highly significant in most cases (Table 10). The TIA, the most important ANF in SBM, was positively correlated ($P<0.001$) with PDI, KOH and UA and negatively with HDI, with the highest value ($r=0.657$) detected for PDI. Also, the correlations between PDI and KOH ($r=0.626$) and PDI and HDI ($r=-0.542$) were of interest ($P<0.001$). When the SBM were classified according to the origin of the beans,

Table 10
Pearson coefficient of correlation (*r*) between CP and protein quality indicators of the soybean meals.

Origin	CP	PDI	KOH	UA	TIA
All (n = 515)					
CP[a]	1				
PDI[b]	−0.040^{NS}	1			
KOH[c]	0.009^{NS}	0.626***	1		
UA[d]	−0.103*	0.323***	0.293***	1	
TIA[e]	0.177***	0.657***	0.584***	0.379***	1
HDI[f]	0.132**	−0.542***	−0.355***	−0.026^{NS}	−0.340***
USA (n = 180)					
CP	1				
PDI	−0.142^{+}	1			
KOH	−0.087^{NS}	0.522***	1		
UA	−0.044^{NS}	0.459***	0.417***	1	
TIA	−0.042^{NS}	0.704***	0.613***	0.641***	1
HDI	0.378***	−0.490***	−0.072^{NS}	−0.088^{NS}	−0.222**
Brazil (n = 165)					
CP	1				
PDI	−0.129^{NS}	1			
KOH	−0.174*	0.553***	1		
UA	−0.278***	0.311***	0.230**	1	
TIA	0.286***	0.288***	0.270***	0.103^{NS}	1
HDI	0.029^{NS}	−0.573***	−0.256**	−0.101^{NS}	−0.193*
Argentina (n = 170)					
CP	1				
PDI	−0.189*	1			
KOH	−0.279***	0.607***	1		
UA	−0.366***	0.255**	0.235**	1	
TIA	−0.050^{NS}	0.646***	0.541***	0.179*	1
HDI	0.104^{NS}	−0.221*	−0.269**	0.111^{NS}	−0.252**

NS, no significant.
$^{+}$P < 0.10.
*P < 0.05.
**P < 0.01.
***P < 0.001.
[a] Crude protein.
[b] Protein dispersibility index.
[c] KOH protein solubility.
[d] Urease activity.
[e] Trypsin inhibitor activity.
[f] Heat damage indicator (Evonik, 2010). Values varied from 0 (low damage of CP) to 40 (high damage of CP).

many of the correlations were maintained (P < 0.001) with the highest *r* values observed between PDI and TIA (*r* = 0.704, 0.288 and 0.646) and PDI and KOH (*r* = 0.522, 0.553 and 0.607) for USA, BRA and ARG meals, respectively. The significance and importance of the correlations among the protein quality traits were of less interest for the BRA meals than for the USA and ARG meals.

4. Discussion

Numerous reports compared different variables related to the composition and nutritive value of SBM from different countries. Thakur and Hurburgh (2007) analysed 165 SBM from six different origins but all the samples were collected in the same year crop. Grieshop and Fahey (2001) analysed a total of 133 soybean samples from BRA, India and USA, but they did not include any ARG bean in the survey. Karr-Lilienthal et al. (2004) conducted a complete set of analyses of soybeans and SBM from five different countries processed in the USA under uniform conditions, but the number of samples by country was limited (n = 3). Frikha et al. (2012) conducted an experiment in which SBM from USA, BRA and ARG were collected at Hamburg port and analysed for all major constituents, including apparent ileal digestibility (AID) of the AA, but only 22 samples were used. Similarly, Goerke et al. (2012) analysed all major nutrients and AID of the AA in piglets of 18 SBM from these three countries. Finally, Ravindran et al. (2014) provided information on the composition, AID of the AA and AME_n for poultry of 55 samples from the four main producing countries (USA, BRA, ARG and India) collected in feed mills in South East Asia from 2010 to 2012, although neither the oligosaccharides nor the PDI and HDI of the meals were determined. In the current research, 515 SBM samples, collected for nine consecutive years, were analysed for all major nutrients and protein quality indicators. Probably, the data of the current survey were more representative of the chemical composition and quality of the SBM of different origins than other important published surveys.

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

The proximal analyses and nutrient composition of the SBM were within the range reported in the literature (Karr-Lilienthal et al., 2005; Thakur and Hurburgh, 2007; Ravindran et al., 2014). Park and Hurburgh (2002) reported that CP content was higher for USA beans than for BRA and ARG beans. In the current research, however, the CP content was higher for the USA and BRA SBM than for the ARG SBM, in agreement with data of Grieshop and Fahey (2001) and Karr-Lilienthal et al. (2004). Moreover, most available studies (Thakur and Hurburgh, 2007; Frikha et al., 2012; Ravindran et al., 2014), reported that BRA SBM had more CP than USA SBM, consistent with practical observations in most feed mills in Europe. The inconsistencies reported on the CP content of the SBM are justified by differences in the genotype and planting area of the beans, as well as by the proportion of hulls added to the meal after oil extraction (Wilcox and Shibles, 2001; Karr-Lilienthal et al., 2005). For example, in the current research, only samples collected from crushing plants that eventually could arrive to Europe, were surveyed. Consequently, a high percentage of the samples (20%) was collected from the East Coast, an area of the USA that produces beans with a higher CP content than the average of the country (Cromwell et al., 1999; Grieshop et al., 2003; Medic et al., 2014; Miller-Garvin and Naeve, 2015). Moreover, no samples of SBM from the Northwestern states were included in the survey. On the other hand, the CP content of the SBM depends also on the proportion of hulls removed before oil extraction or added back to the meal, after the crushing process. In this respect, many BRA samples collected in France and Sao Paulo (Brazil), were "profat" (CP + EE) and thus, the protein content was lower than in traditional 47% CP "high-pro SBM".

Crude fibre and NDF were higher and sucrose lower for the BRA than for the USA meals, with ARG meals being intermediate, consistent with most published research (Thakur and Hurburgh, 2007; Frikha et al., 2012; Ravindran et al., 2014; Evonik, 2015a,b). The difference in fibre content of the SBM of these three countries depends not only on the amount of hulls added to the meal but also on the geographical area of the planting and growing seasons (Mateos et al., 2011; Li et al., 2015). It is of interest to notice that the BRA meals had more CP but also more CF and NDF than the ARG meals, opposite to the general believe that high fibre contents reflect SBM with low CP contents. Jung (1997) demonstrated that the NDF fraction of the ingredients might include heat-damaged proteins, which will overestimate the fibre content of these meals.

Sucrose and stachyose concentration was lower for the BRA meals than for the USA and ARG meals, consistent with data of Mateos et al. (2011) and Frikha et al. (2012). The differences in sucrose content were probably related to differences in the latitude and temperature of the planting areas of the beans, with higher proportion of sucrose when the crop is produced in cooler locations (Wolf et al., 1982; Kumar et al., 2010). On the other hand, stachyose accumulates in the seed during the late phase of maturation and serve as a storage or transport of carbohydrates in mature seeds (Obendorf et al., 2009).

Sucrose is a highly digestible carbohydrate that increases the energy content and the palatability of the feed and thus, it is a desirable component of SBM, especially in piglet diets (Berrocoso et al., 2014). The oligosaccharides (stachyose and raffinose) present in SBM, are not digested by the gastrointestinal tract, acting as ANF and reducing the nutritional value of the meal (Choct et al., 2010). However, oligosaccharides are easily fermented in the large intestine, and when fed in adequate proportions, they will yield valuable energy. In addition, the short-chain fatty acids, end products of oligosaccharides fermentation, reduce the pH of the large intestine, which might benefit gastrointestinal tract health. In this respect, SBM oligosaccharides are considered often, as potential prebiotic substances, with possible benefits on the health status and growth of non-ruminants (Grizard and Barthomeuf, 1999; Conway, 2001; Rycroft et al., 2001). Consequently, stachyose and raffinose do not behave as ANF under all circumstances.

The energy content of the SBM depends primarily on the quality of the protein fraction (Thakur and Hurburgh, 2007; Serrano et al., 2012, 2013b), the sucrose (Berrocoso et al., 2014; Ravindran et al., 2014) and the fibre (Dilger et al., 2004; Ravindran et al., 2014) content of the meals. Based on the results of the analyses conducted in the current survey, USA SBM should have higher energy content than South American SBM. In fact, the AME_n (MJ/kg DM) of the SBM for poultry, calculated as recommended by WPSA (1989), was as an average 10.97, 10.90 and 10.78, for the USA, BRA and ARG SBM, respectively, values that are within the range reported by others. For example, Ravindran et al. (2014) reported average AME values of 11.14, 10.89 and 10.45 MJ/kg DM for USA, BRA and ARG SBM, respectively. Different institutions (NRC, 1994; FEDNA, 2010; CVB, 2011; Rostagno, 2011; Premier Atlas, 2014) recommended for high-pro SBM (470 g CP/kg) energy values in the range of 10.51–11.32 MJ/kg DM.

Energy values of SBM calculated according to the WPSA (1989) predictive equation, should be taken cautiously because the estimation is based exclusively on the CP, EE and NFE content of the samples. Consequently, the equation does not take into consideration differences in the composition of the NFE or in the CP digestibility of the SBM. In this respect, USA SBM has more sucrose and oligosaccharides and less NDF content than BRA SBM. Moreover, Frikha et al. (2012) indicated that the AID of the AA increase with increases in the KOH value of the SBM. Consequently, the use of the WPSA (1989) equation might penalize the energy content of the USA SBM as compared with the BRA and ARG meals. In this respect, Premier Atlas (2014), a table of ingredient composition widely use in Europe, proposed AME_n values for poultry 0.25 MJ/kg higher for the USA SBM than for the BRA SBM, consistent with the results reported herein.

The NE content of the SBM for pigs, estimated as indicated by Noblet et al. (2003) was also higher for USA SBM than for BRA and ARG SBM (9.92, 9.62 and 9.76 MJ/kg DM). These values are slightly higher than values of 9.51, 9.58, 9.45 and 9.70 MJ/kg DM presented by Rostagno (2011), CVB (2011) and NRC (2012), respectively. Sotak-Peper et al. (2015) reported that the NE content of 22 SBM samples collected in the USA was quite uniform (average value of 10.32 MJ/kg DM) and 6–9%

higher than indicated in practical tables of ingredient composition. However, no South American SBM were included in this research.

The macro-minerals and trace minerals contents of the SBM were within the range reported in the literature (Harmon et al., 1969; Batal et al., 2010; NRC, 2012; Tahir et al., 2012) although most published data correspond to USA SBM. In fact, data comparing the mineral content of SBM from the three key producer countries are scarce and often contradictory (Karr-Lilienthal et al., 2004; Mateos et al., 2011; Ravindran et al., 2014). Origin of the bean affected in different ways the ash and mineral concentration of the SBM, with the most striking differences detected for P, Ca, K and Fe. Phosphorus content was higher for the USA and ARG meals than for the BRA meals, although the differences were of little practical interest. Calcium content was higher and more variable for the USA meals than for the South American meals. Moreover, Ca concentration was higher than expected based on the average Ca content of the beans reported by other authors (CIGI, 2010; FEDNA, 2010; NRC, 2012), reflecting that some extra Ca was probably added to the meals as a flow agent (Batal et al., 2010; Karr-Lilienthal et al., 2004). The K content was higher in the ARG than in the BRA meals with that of the USA meals being intermediate. The variability in content reported for most minerals, were perhaps due to differences in soil characteristics, fertilization rate used and in their availability to be absorbed by the plant (Westgate et al., 2000; Huerta and Martin, 2002). For example, the soils in the main soybean planting areas of Brazil are very rich in Al and Fe and poor in P (Huerta and Martin, 2002; Jensen, 2010). The availability of these minerals is affected by the pH of the soil. At low pH, the phosphate ions react with Al to form less soluble compounds (Brennan et al., 1994). However, low soil pH increases Fe and Al absorption. Consequently, the BRA SBM, that are mostly produced in very acidic soils, should have less P and more Al and Fe contents than the USA and ARG SBM, consistent with the results reported herein. In addition, total ash and some minerals, such as Ca and Fe, might appear in the meal as a result of contamination from the soil or the crushing plant (Karr-Lilienthal et al., 2004).

The AA content of the SBM, including Lys, Met and TSAA, increased as the CP content of the meals increased, in agreement with most published research (Cromwell et al., 1999; Frikha et al., 2012).

4.2. Influence of the origin of the beans on the amino acid profile and protein quality

The AA profile of the SBM varied with the origin of the beans, in agreement with most published reports (Goldflus et al., 2006; Thakur and Hurburgh, 2007; Medic et al., 2014). In fact, Mateos et al. (2011) and Ravindran et al. (2014) reported that per unit of CP, the concentration of the five critical AA was significantly higher for the USA and ARG meals than for the BRA meals. We do not have a clear explanation for the differences in AA profile because of country of origin of the beans but the results agree with data reported by Premier Atlas (2014) and AMINODat (2016). The information provided confirms that the quality and nutritive value of the SBM should be evaluated on CP content but taking into consideration the AA profile of the protein fraction.

Urease activity and PDI were more variable than KOH, in agreement with data of Karr-Lilienthal et al. (2004). The higher variability of PDI as compared with KOH does not support the recommendation of Hsu and Satter (1995) and Dudley-Cash (2001) on the preferred use of PDI as a key indicator of protein quality of SBM. Urease activity was lower for the ARG meals than for USA and BRA meals, although in most cases the values were below the threshold (0.05 mg N/g) recommended for high quality SBM (van Eys, 2012; Serrano et al., 2013a). The PDI values differed also among origins and were higher for the USA meals than for the South American meals. Balloun (1980), Batal et al. (2000) and van Eys (2012) suggested that PDI values for correctly processed SBM should be within the 15–30% range. In the current research, however, the USA, BRA and ARG meals had as an average PDI value of 19.5, 15.0 and 16.0%, respectively. Consequently, approximately 50% of the samples from South American origin had a PDI equal or below recommendations, indicative of potential over-processing of these meals. de Coca-Sinova et al. (2008, 2010), however, reported that the AID of CP and AA of different sources of SBM in broilers were high and independent of the low PDI values observed for some of the samples. Moreover, Frikha et al. (2012) reported that the correlation between PDI and AID of CP of 22 SBM from these three countries was not significant ($P > 0.10$). The data suggest that the current recommended range of values for PDI might need to be re-evaluated. In this respect, Serrano et al. (2013a) reported that the PDI of seven ARG samples of SBM decreased from 21.9 to 17.7% after 120 days of storage under laboratory conditions whereas KOH values was affected little. In the current research, the average length of storage (from sample collection to analysis) was probably higher for the ARG and BRA SBM than for the USA SBM, which might explain, at least in part, the differences in PDI observed among meals from the different countries.

In the current survey, KOH across SBM origins, ranged from 67.9 to 95.7%, with higher average values for the USA than for the BRA and ARG SBM. In fact, 59% of the USA samples showed a KOH above 85%, the maximum recommended value for SBM well processed (Moizzudin, 2003; van Eys, 2012). However, Frikha et al. (2012) reported a significant positive relation between KOH and the AID of key AA in a research comparing 22 SBM samples of the three origins. High PDI and KOH values might indicate low protein quality because a high proportion of the TI of the original bean remains in the meal after processing. But also, a high solubility value reflects reduced incidence of Maillard reactions. The data reported in this manuscript suggest that wider ranges for PDI (15–30%) and KOH (70–85%) could still reflect beans that were processed, and that the recommended range might not be valid under all circumstances. Consequently, current recommendations for PDI and KOH deserve further evaluation.

Trypsin inhibitor activity of the SBM was within the range reported in the literature for commercial SBM (USSEC, 2008; Mateos et al., 2011; van Eys, 2012; Ravindran et al., 2014). When the SBM were sorted by the origin of the bean, significant differences among countries were observed, with average values (mg/g DM) of 3.5, 2.9 and 2.8 for USA, BRA and ARG meals, respectively. Heat damage indicator, however, was significantly lower for the USA than for the BRA or ARG meals. The higher TIA but lower HDI of the USA meals, as compared with the BRA and ARG meals, might indicate that heat processing was less severe for USA meals, data that are consistent with the higher PDI and KOH of the USA meals. It is important to be aware that samples with relatively high TIA and KOH (indicative of the presence of antitrypsin activity) but relatively low HDI (indicative of reduced incidence of Maillard reactions) might reflect SBM with high CP and AA digestibility. In all cases, the potential influence of bean genotype and environmental conditions during the growing season on protein denaturation and solubility of the original bean and consequently on the PDI and KOH of the resulting SBM, should not be ruled out.

4.3. Dispersion of the analytical data and correlations among chemical variables

The dispersion of values of the different components of the SBM, across the origin of the beans, was similar to those reported by other authors (Hymowitz et al., 1972; NRC, 2012; AMINODat, 2016) for most of the variables studied. The highest variability was reported for EE, consistent with data of Evonik (2015a,b), although, the practical interest of the differences was of limited interest. In contrast, the variability for CP and AA data were less than that of other dietary components but still of great interest in practical diet formulation. Among the AA, the lowest variability was observed for Thr and Met and the highest for Arg and Cys, with Lys being intermediate, in agreement with data of García-Rebollar et al. (2014) and Evonik (2015a,b).

The correlation coefficients between CP and indispensable AA contents of the SBM varied with the AA considered and the country of origin of the beans. In general, the correlations were higher for Lys than for Met or Cys. Cromwell et al. (1999) reported that Lys in SBM increased by 0.063 percentage units for each percentage point increase in CP, in agreement with the results reported herein. The data of the current review indicate that when the origin of the bean is not known, the following equations could be used to estimate the Lys, Met and TSAA content of the SBM from the CP data.

$$\text{Lys} = 0.061 \times \text{CP} + 0.239(R^2 = 0.853; \text{RSD} = 0.404; P < 0.001);$$

$$\text{Met} = 0.011 \times \text{CP} + 1.37(R^2 = 0.666; \text{RSD} = 0.124; P < 0.001).$$

$$\text{TSAA} = 0.023 \times \text{CP} + 3.10(R^2 = 0.596; \text{RSD} = 0.298; P < 0.001)$$

With the contents in CP, Lys, Met and TSAA given in g/kg DM.

When the data were sorted by the origin of the beans, the significances were maintained and the correlation coefficients improved for all AA for the South American meals but not for the USA meals, an observation that should be considered when predicting the AA content of the SBM from its CP content. Similar type of data were obtained for Met and TSAA.

4.4. Dispersion of the analytical data on amino acid profile and correlations among protein quality indicators

Most published research reported that the content in the five most critical AA of SBM increased as the CP content of the meal sample decreased (Thakur and Hurburgh, 2007; Medic et al., 2014; Miller-Garvin and Naeve, 2015). The data reported herein, however, suggest that this assumption might not be correct because this depends on the origin of the beans (Burton et al., 1982; Westgate et al., 2000). In this respect, Krober and Cartter (1966) did not observe any trend for Met concentration with increasing in the protein content of the bean.

In the current survey, the correlations between CP (g/kg DM) and AA profile (% CP) of the SBM were of limited interest, especially when the origin of the beans was not considered. For example, across meals origins, Lys content per unit of CP was correlated with the CP content of the SBM. However, when the SBM were sorted by the origin of the beans, the three meals responded differently, showing a negative correlation for the USA meals, a positive correlation for the BRA meals and no effects for the ARG meals. Consequently, the practical interest of the correlations reported, without considering the country of origin of the meals might have limited value.

All the protein indicators of the SBM varied considerably among and within countries. As expected, the correlations among these indicators were significant in most cases, with coefficients that depended on the origin of the beans. As an example, the correlation between UA and TIA was higher for the USA meals than for the ARG and BRA meals, whereas those between TIA and PDI and TIA and KOH were higher for the USA and ARG meals than for the BRA meals. The information provided herein indicates that SBM from different countries belonged to different populations and consequently, comparative data on the quality of the protein of commercial samples should be taken cautiously.

5. Conclusions

The chemical composition, protein quality and nutritive value of commercial SBM depended on the country of origin of the beans. Soybean meals from USA showed better uniformity and had less fibre, more soluble sugars and higher indispensable AA content per unit of CP than BRA SBM, with SBM from ARG being intermediate. The USA SBM had higher TIA, KOH and PDI but lower HDI than the BRA SBM. All these data suggest that the quality of the protein and nutritive value of meals were higher for the USA meals than for the BRA and ARG meals. When the data were analysed independent of the origin of the beans, the *r* coefficients among chemical variables were significant in many cases, but the values depend on the country of origin of the beans. The most important significant correlations observed were for sucrose that was positively related to stachyose and negatively to raffinose and NDF. When the data were classified by the country of origin of the beans, negative correlations between CF and CP content were detected for the BRA and ARG meals but not for the USA meals. In addition, the relation between CP and Lys (% CP) of the SBM was negative for the USA meals but not significant for the BRA and ARG meals. Similarly, numerously significant correlations among protein quality indicators were observed but the *r* values varied widely depending on the origin of the meals. This survey explains SBM constituents in detail and demonstrate that significant differences exist in the composition and nutritive value of SBM from different origin. Feed mills should be aware of these differences when the nutritive value of commercial SBM are estimated.

Conflict of interest

There is no conflict of interest with this manuscript.

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