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REVIEW

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Comparison of the quality of soybean meal and oil by soybean production origin

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Abstract
Previous reports indicate variable soybean quality parameters exported from different geographic regions. This review compares soybean and soybean co-products grown under diverse environmental conditions. While numerous studies have been conducted on whole soybean and soybean meal (SBM) composition by origin, similar analysis of soybean oil is lacking. This review has two objectives: 1) summarize soybean and SBM quality by origin using a meta-analysis approach, and 2) analyze collected crude degummed soybean oil samples that originate from the US, Brazil and Argentina for key quality attributes. Soybeans from Brazil have higher levels of protein ($P < 0.05$) than US soybeans, but US soybeans have lower heat damage ($P < 0.05$) and total damage ($P < 0.05$) than soybeans from Brazil. US and Brazil SBM have higher crude protein (CP) ($P < 0.05$) than SBM from Argentina. At equal CP content, US SBM had less fiber ($P < 0.0001$), more sucrose ($P < 0.0001$) and lysine ($P < 0.0001$) and better protein quality than South American SBMs. Methionine, threonine, and cysteine levels were similar in soybean protein from US and Argentina and higher than that in soybean protein from Brazil. Crude degummed soybean oil from Brazil had more ($P < 0.05$) free fatty acids, neutral oil loss, phosphorus, calcium and magnesium than crude degummed soybean oil from the US or Argentina. Our analysis suggests that environmental conditions under which soybeans are grown, stored, and handled can have a large impact on chemical composition and nutrient quality of soybean meal and soybean oil.

KEYWORDS
amino acids, glycine max, SBM, soybean oil, soybean protein

INTRODUCTION

Soybeans are one of the most traded agricultural products globally. Soybeans have been a major crop and oil and protein source in east Asia for thousands of years (Chen et al., 2022). However, soybeans only emerged as a major crop in western countries in the past 100 years. This was first driven by rising demand for vegetable oil and then as an economical, high-quality source of protein, particularly for animal feed. The United States (US), Brazil and Argentina are now the major producers and exporters of whole soybeans, soybean oil and soybean meal (SBM) with Asian (especially China) and western European countries serving as the major destinations for the whole soybean exports. Approximately 100 million tons of soybeans is consumed per year in China and over 90% of soybean usage in China is dependent on imported soybeans (Zhang, 2021). Greater than 60% of US and global soybean exports are destined for the Chinese market in recent years (2009–2021) followed by 12% exported to the EU and 3.6% to Mexico (Chen et al., 2022). Brazil and the US are the leading soybean exporters to China. The Brazilian soybean share in Chinese market has increased in the past several years due to US-China trade disputes (Chen et al., 2022; Zhang, 2021).

Worldwide demand for soybeans have reached nearly 353 million metric tons in 2020/21 with demand for soybeans rising along with global GDP growth (USDA, 2023).

As global soybean trade grows, greater attention is being placed on compositional differences by trade origin. Mounts et al. (1990) analyzed the quality of soybean shipments from Argentina, Brazil, Paraguay and the US shipped to five western European and three east Asian ports from 1985 to 1989. Data were collected on test weight, damaged seeds, foreign matter, splits, free fatty acids (FFA) of degummed oil, moisture, oil and protein content, phosphorus and total oxidation value of the oil. Soybeans from the US consistently showed a higher test weight than South American soybeans. Soybeans from Brazil had higher percentage of damaged seeds than those from the US with seeds from Argentina having lowest percentage of damaged seeds. US seeds had the highest percentage of foreign matter with those from Argentina containing the lowest. However, the Argentine soybean seeds had the highest percentage of split seeds. Seeds from the US had the lowest protein and highest oil levels compared to soybean seeds from four countries. The oil quality from US soybeans was highest and contained the lowest levels of FFA.

The world's demand for animal protein is expected to double by 2050 (Arrutia et al., 2020). Amino acid (AA) requirements in animal protein are likely to be supplied by oilseed press cake and solvent-defatted meal due to high protein levels and economic production globally and because they are naturally rich in high quality protein. Soybeans contain a higher percentage of CP on a dry weight (DW) basis (32%–43.6%) compared to rapeseed/canola [25%–30% DW] and sunflower (10%–27% DW). Soybean and rapeseed/canola also have fairly well-balanced AA composition, while sunflower is deficient in lysine (Lys) (Arrutia et al., 2020). The most efficient and common method of extracting soybean oil and defatted meal production is solvent extraction (Demarco & Gibon, 2020; Maciel et al., 2020) with oils from pressed seeds utilized in specialty markets.

It is well known by the soybean industry that seeds produced in different areas of the world with different cultivars, climatic conditions and different storage and handling can differ in important quality characteristics of unprocessed seeds, extracted oil and defatted meal for food and feed uses. However, these industry observations are not always supported by data evidence. All published and other sources of information on quality of soybeans and co-products from major sources and received at major destinations are covered in this review. To date there are eight key studies published in peer review journals comparing such soybean quality characteristics from the largest exporting countries, Brazil and the US and the data in these publications was subjected to meta-analysis with the results summarized in this review. There is insufficient data addressing compositional or quality differences in soybean oil by origin. To our knowledge, this analysis includes the first published comprehensive data of soybean oil quality differentiated by origin (US, Brazil and Argentina).

EXPERIMENTAL PROCEDURES

Meta-analysis of SBM quality

Since Brazil and the US are the top soybean exporters to China, we used a meta-analysis approach to quantify the relation between the country of origin and the SBM chemical composition, nutritional value, minerals and AA composition. Eight studies were included in the meta-analysis, which was performed using Revman 5.4 software (Cochrane Collaboration Network) (Table 1). The standardized mean difference was adopted for continuous variables and the heterogeneity among samples was determined based on the *P* value or I^2 values. A *P* value greater than 0.10 or I^2 value less than 50% indicated that the heterogeneity of the research was insignificant. A *P* value less than 0.10 or I^2 greater than 50% suggested significant heterogeneity between samples. The bias between studies was analyzed by funnel plots.

Soybean oil quality survey

There is insufficient data addressing compositional or quality differences in soybean oil by origin. To address this gap, a survey was conducted to collect samples of crude degummed soybean oil from the US, Brazil and Argentina. A total of 557 crude degummed soybean oil samples were collected from vessels and crushers and analyzed for quality factors in 2020/21 and 2021/22 (Table S1).

The samples were collected from two destination countries: India and South Korea. India is the largest importer of soybean oil, with Argentina being its main source of soybean oil (USDA FAS 2023). One 500 mL composite sample was taken from each ship tank available for sampling on each vessel, and sampling occurred randomly across the 3-year period (2020–2022). Each sample collected from individual ship tanks was considered a unique observation in the analysis.

Two crushing facilities in South Korea provided samples of US and Brazilian crude degummed soybean oil. Sampling of US crude degummed soybean oil samples occurred from January through April (in calendar years 2021 and 2022). Sampling of Brazilian crude degummed soybean occurred from August through November (in calendar years 2020 and 2021). Sampling occurred when the crushing facility could guarantee purity of origin (US or Brazil). One 500 mL crude degummed soybean sample per day was collected, at most 5 days a week during the

TABLE 1 The studies used for meta-analysis.

Study		Number of samples US	Brazil	Total
1	Galkanda-Arachchige et al. (2021)	5	5	10
2	García-Rebollar et al. (2016)	180	165	345
3	Cámara et al. (2017)	32	26	58
4	Lagos and Stein (2017)	5	5	10
5	Li et al. (2015)	6	7	13
6	Lopez et al. (2020)	5	4	9
7	Ravindran et al. (2014)	16	10	26
8	Park and Hurburgh (2002)	34	25	59

sampling period. In addition to soybean oil collected from crushing facilities, US exported soybean oil was collected from vessels at ports in South Korea. One 500 mL composite sample was taken from each ship tank available for sampling on the vessel. Each sample collected from individual ship tanks was considered a unique observation in the analysis.

These samples were analyzed for 11 oil quality parameters including Lovibond red color, FFA, neutral oil loss (NOL), iodine value, unsaponifiable matter, saponification value (mg KOH/g), Ca, Mg, Fe, P and chlorophyll levels. The AOCS methods used for this analysis are summarized in Table S3.

RESULTS AND DISCUSSION

The results are presented and discussed in three sections. The first section reviews the quality of SBM imported from major producing countries, including discussion of the results of various SBM quality studies (including those used in the meta-analysis). The second section is the comparative results generated from the meta-analysis of US and Brazil SBM chemical composition, nutritional value, minerals and limiting amino acid composition. The last section summarizes the results of the soybean oil quality survey.

Quality of SBM imported from major producing countries

García-Rebollar et al. (2016) investigated the nutritional value of SBM from Argentina, Brazil and the US. They analyzed at least 165 meal samples per country of origin for a total of 515 samples each year from 2007 to 2015. Meals from Brazil and the US averaged significantly ($P < 0.001$) higher CP (532 g/kg) than meals from Argentina (517 g/kg). The Lys content of meal from the US soybeans averaged significantly ($P < 0.001$) higher at 62 g/kg of CP than Lys content of meal from Brazil (61 g/kg) with the Lys content of meal from Argentina being intermediate (6.11%). Meal from the US had more sucrose (84, 64 and 78 g/kg) and stachyose (64, 53 and 57 g/kg) than meal from Brazil and Argentina ($P < 0.001$). In contrast, the US meal had less neutral detergent fiber (90, 118 and 102 g/kg) and raffinose (11, 16 and 14 g/kg) than meal from Brazil and Argentina ($P < 0.001$). The total residual neutral lipid content was highest ($P < 0.05$) in the meal from Brazil indicating less thorough defatting of the meal than meal from Argentina and the US (Guzmán et al., 2016). The mineral content of SBM also depended on origin, with meal from Brazil having more iron (Fe) but less calcium (Ca), phosphorus (P) and potassium (K) than meal from the US and Argentina ($P < 0.001$). The apparent metabolizable energy corrected for nitrogen (N) in poultry and net energy for pig feed estimated from published equations were higher ($P < 0.001$) for meal from the US than those from South American. Meal from the US had less heat damage. Fiber levels on a CP basis were lower in US meal than those prepared from South American soybeans.

The influence of soybean protein source on piglets growth performance and nutrient digestibility was investigated by Guzmán et al. (2016). They observed higher ($P < 0.01$) average daily gain in piglets fed meal from US soybeans than meal from Brazil or Argentina. Post-weaning diarrhea was higher in piglets fed meal from Argentina than meal from Brazil or the US. Nutrient digestibility tended to be higher ($P < 0.1$) from the US sourced meal versus meal from Argentina or Brazil. Li et al. (2015) reported on the digestible and metabolizable energy in 22 sources of SBM produced from soybeans of different origins in crushers in China fed to growing pigs. The shipments of soybeans processed included six processed in China, six from the US, seven from Brazil and three from Argentina. Li et al. (2015) reported the average digestible and metabolizable energy in meal from China, the US, Brazil and Argentina were 15.7, 15.9, 15.6 and 15.9 MJ/kg and 15.1, 15.3, 15.0 and 15.4 MJ/kg with none of these levels showing any significant difference.

Lagos and Stein (2017) at the University of Illinois also investigated the chemical composition and AA digestibility in swine of SBM produced in the US, China, Argentina, Brazil and India. This study was based on five sources of meal from Argentina, Brazil, China and the US and four from India. The five US sources were from crushing plants in Iowa, Illinois, Indiana, Ohio and South Dakota. The meals from China and India were collected from feed mills or crushing plants located in those countries, but meal from Argentina and Brazil were collected from feed mills in Denmark, the Philippines, South Korea and Spain. They found that the concentration of CP per DW was greater ($P < 0.05$) in meal from Brazil and India (49.3% and 49.5%) than in meal from China (45.1%), Argentina (46.7%) or the US (47.3%). The concentration of most essential AA followed the same pattern as CP with the exception that meal from the US contained more ($P < 0.05$) indispensable AA than meal from China or Argentina. Of the 10 indispensable AA, significant differences were seen in meal from all five countries of origin ($P < 0.05$), although the differences for methionine and valine were very small. In most cases, levels of indispensable AA were higher in meal from Brazil, India and the US than from Argentina and China. The only exception was isoleucine that averaged 2.3% in meal from Brazil and India, 2.2% in meal from the US and Argentina and 2.1% from China. However, meal from India contained more ($P < 0.05$) trypsin inhibitor activities than meal from the other countries. A greater ($P < 0.05$) apparent- and standard-ileal digestibility of CP and most AA was observed in meal from the US compared with meal from Brazil, Argentina, and India. Because of the lower concentration of AA in meals from China, the concentration of standardized ileal digestible AA in meal from China was less ($P < 0.05$) than that in meal from the US soybean. Meal prepared from the US or Brazil had less ($P < 0.05$) variability in standardized ileal digestibility values than meal from Argentina, China, or India.

Lopez et al. (2020) conducted experiments to compare the nutritional composition and the concentration

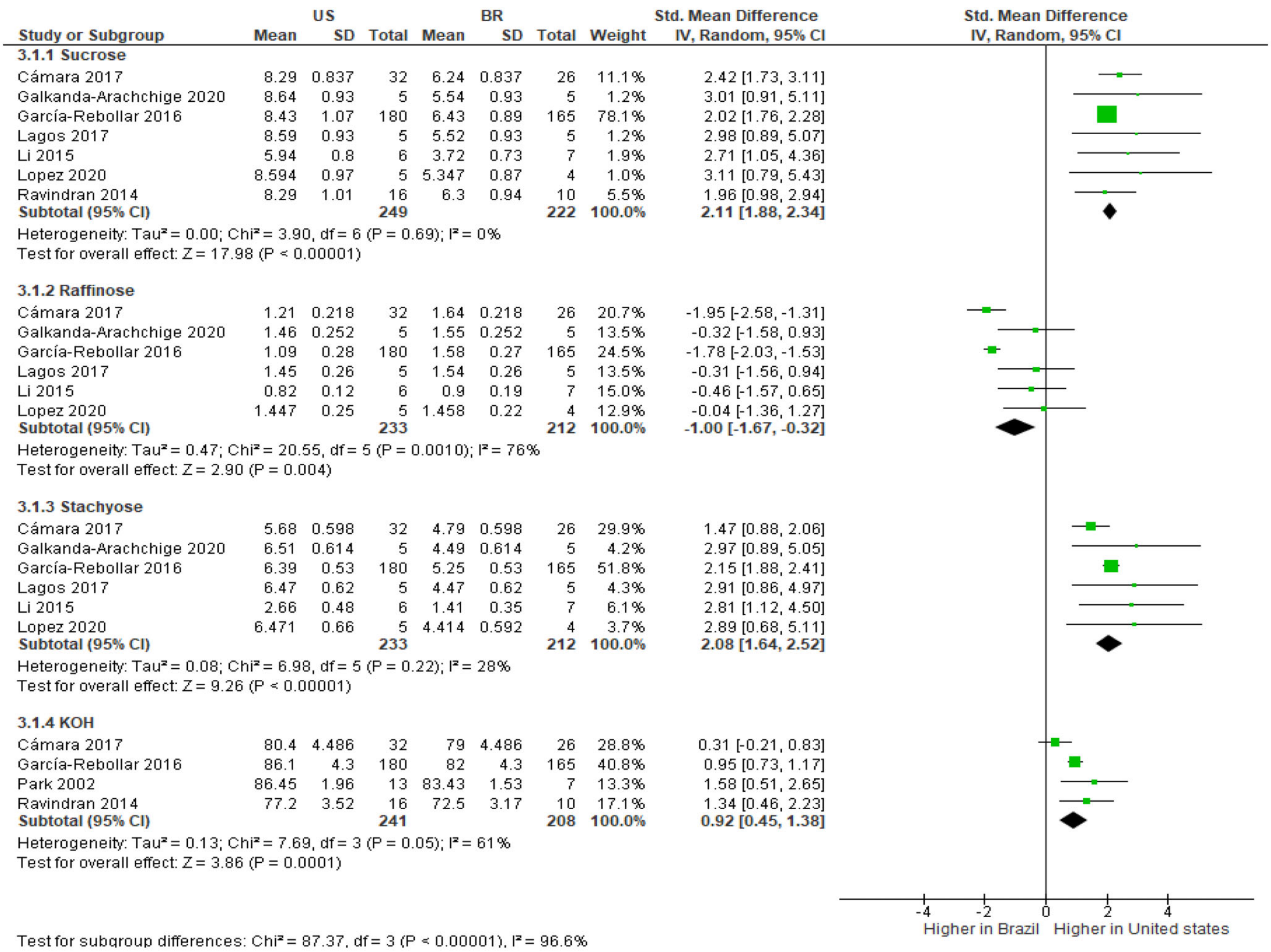

FIGURE 1 Chemical's composition plot of soy meal based on studies carried out for US and Brazil soybeans. KOH – KOH soluble protein (SP).

of digestible and metabolizable-energy of SBM from the leading soybean producing countries in the world when fed to growing pigs. Five sources of SBMs from Argentina, China, and the US, and four sources from Brazil and India were used. The coefficient of apparent total tract digestibility of gross energy and concentrations of digestible- and metabolizable-energy in each diet were calculated using the direct procedure and the digestible- and metabolizable energy in each source of meal were then calculated by difference. The results indicated ($P < 0.10$) for Brazilian meal (17.6 MJ/kg) to have greater concentration of gross energy than meal from China and the US (17.3 MJ/kg). The coefficient of apparent total tract digestibility of gross energy in meal from the US (0.85), China (0.86), and Argentina (0.86) was greater ($P < 0.05$) than in meal from India (0.83). Concentrations of digestible- and metabolizable-energy on a DW basis in Indian meal were the least ($P < 0.05$) among these countries, and Argentinian meal had a greater concentration of digestible- and metabolizable-energy than meal from the US. There were no differences in the coefficient of apparent total tract digestibility of gross energy among sources of SBM within each country and no differences in the concentration of gross- or metabolizable-energy were observed among sources of meal within Argentina or the US. However, there were differences in the concentration of digestible and metabolizable energy among sources of meal collected in India and China, and a tendency ($P < 0.10$) for differences in the concentration of metabolizable energy among sources of meal collected in Brazil. Lopez et al. (2020) concluded that SBM from Argentina and the US

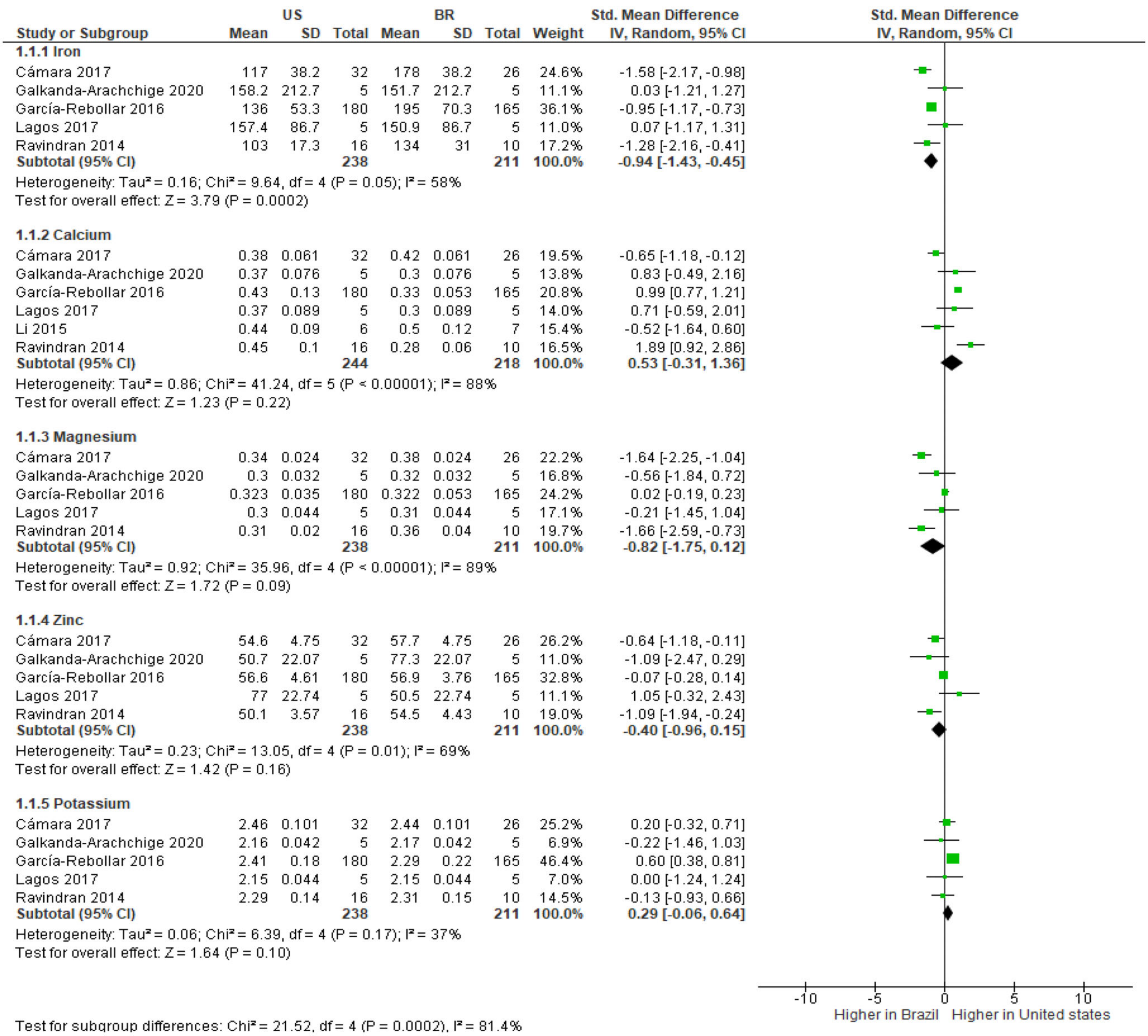

FIGURE 2 Minerals plot of soy meal based on studies carried out for US and Brazil soybeans.

were more consistent than those from the other countries. High variability of composition of soybeans from different regions in China also have been reported by Yang et al. (2021).

Ibáñez et al. (2020) conducted a meta-analysis to quantify the relation between the country of origin of the soybeans and the chemical composition, protein quality and nutritive value of the SBM. The data was based on 18 publications from 2002 to 2018 with a total of 1944 samples of SBM from Argentina, Brazil, India and the US. The origin of the soybeans had consistent and significant effects on most of the chemical variables of the corresponding SBM. The meal from Brazil had more CP, neutral detergent fiber, raffinose and iron but less sucrose, stachyose and K contents than meal from the US or Argentina ($P < 0.05$). The percentage of AA Lys, methionine, threonine and cysteine were greater for the meal from the US and Argentina than for the meal from Brazil and India ($P < 0.05$). Protein dispersibility index, KOH soluble protein (SP) and trypsin inhibitor activity were lower for the meal from Argentina and Brazil than for those from the US and India ($P < 0.05$). A significant relation was observed between the protein dispersibility index and SP ($r = 0.614$; $P = 0.001$).

Soybean meal from Argentina, Brazil, China, India and the US were also evaluated for their performances in the diet of Pacific white shrimp (Galkanda-Arachchige et al., 2021). These meal samples were analyzed for proximate composition, AA profiles, sugars, fiber, macro- and micro-minerals. A growth trial was conducted using SBM-based test diets (350 g/kg protein and 80 g/kg lipid), and a digestibility trial was conducted from diets formulated by mixing the basal diet and test ingredients (70:30) on a DW basis. Significantly higher growth (as standardized thermal growth coefficient) was observed in shrimp fed meal from China over Brazilian meal. However, growth performances of shrimp fed SBM sourced from, Argentina, India and the US were not different from meal from Brazil and China. No significant differences were observed for apparent DW, energy and protein digestibility coefficients ($P < 0.05$) of meal from the countries. The differences observed in the ingredient chemical profile of SBM among the countries were not reflected in the growth and digestibility data of shrimp. These results highlight the importance of multiple variables influencing the biological value of SBM and that simplified generalizations, such as country of origin, do not define the quality of ingredients very well. Sucrose is also of interest in pig and poultry feed but not as much for seafood.

Zhang (2021) compared the nutritive value of SBM from Brazilian and US soybeans exported to China. 23 Brazil and 27 US SBM samples were analyzed and the nutrient values compared. Lys levels of the US

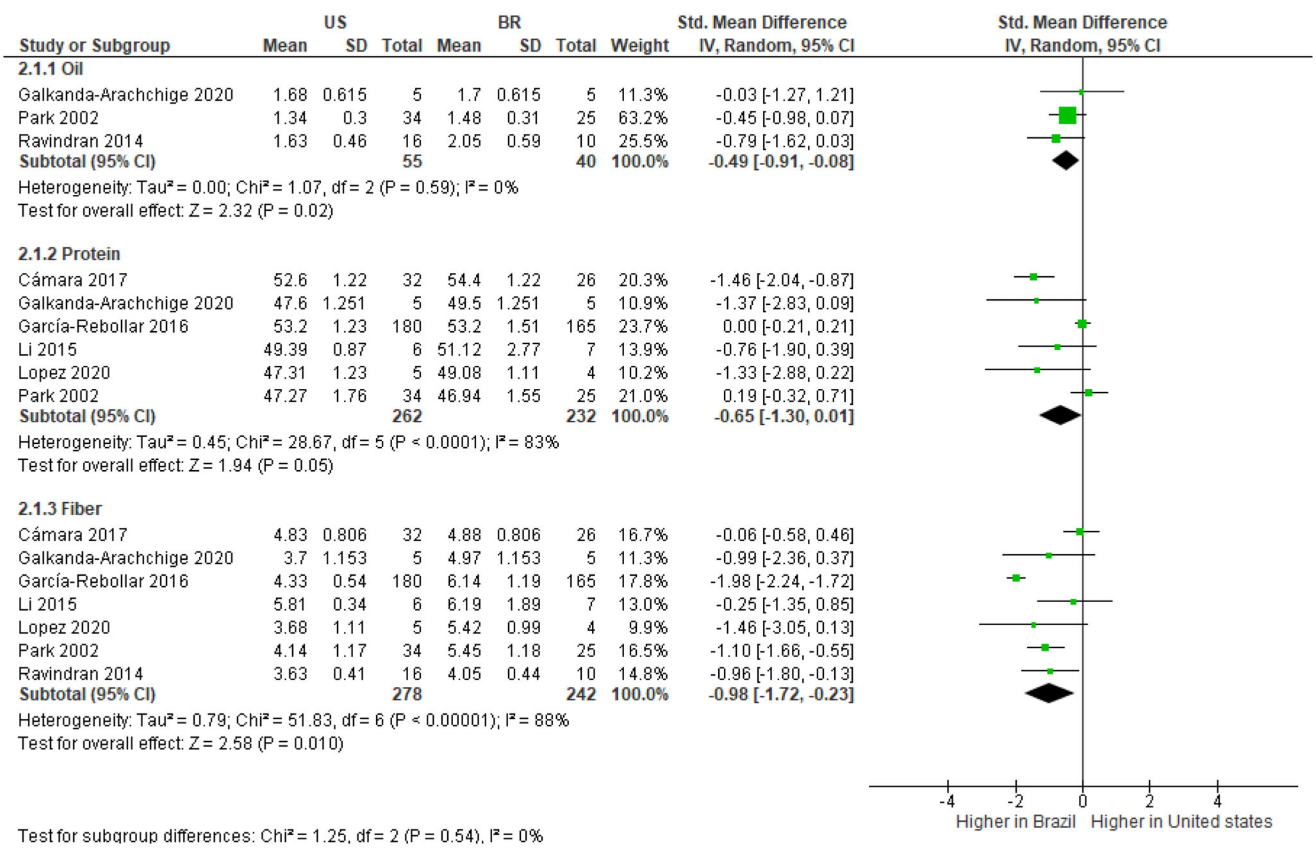

FIGURE 3 Oil, protein and fiber plot of soy meal based on studies carried out for US and Brazil soybeans.

meal were significantly ($P < 0.001$) higher than meal from the other four sources. The methionine plus cysteine concentrations were also greater in meal from the US and Argentina than meals from other countries (Zhang, 2021). The sucrose and stachyose levels in meal from the US soybeans were statistically greater than meal from Brazil. Zhang (2021) concluded that the quality of US originated SBM in the Chinese market is greater than meal from Brazil.

Meta-analysis of US and Brazil SBM chemical composition, nutritional value, minerals and limiting amino acid composition

Chemical composition

Based on the publication record, seven articles for sucrose, six articles for raffinose and stachyose and four articles for SP, were included and the results are shown in Figure 1. A total of 233–249 samples were included in this assessment. The meta-analysis suggested a significant difference and large heterogeneity for SP and raffinose and small heterogeneity for stachyose and sucrose. Overall, the meta-analysis showed that the SP, sucrose and stachyose levels were higher in the US soybean samples than soybean from Brazil. On the other hand, raffinose was lower in the soybean samples from the US. Ibáñez et al. (2020) confirmed that the raffinose levels were higher in SBM from Brazil and India compared to those from Argentina and the US. A Funnel plot indicating chemical composition reported in different studies conducted for the US and Brazil soy meal is shown in Figure S1.

Minerals

Based on available studies, five articles for Fe, Mg, K and Zn and six articles for Ca were included. The results are shown in Figure 2. A total of 238–244

Study or Subgroup	US Mean	US SD	US Total	BR Mean	BR SD	BR Total	Weight	Std. Mean Difference IV, Random, 95% CI
13.1.1 Lysine								
Cámara 2017	6.127	0.044	32	6.079	0.044	26	10.7%	1.08 [0.52, 1.63]
Galkanda-Arachchige 2020	3.09	0.086	5	3.06	0.086	5	2.1%	0.32 [-0.94, 1.57]
García-Rebollar 2016	3.28	0.067	180	3.23	0.11	165	71.5%	0.55 [0.34, 0.77]
Lagos 2017	3.07	0.089	5	3.05	0.089	5	2.1%	0.20 [-1.04, 1.45]
Li 2015	3.26	0.1	6	3.22	0.13	7	2.7%	0.32 [-0.78, 1.42]
Lopez 2020	3.068	0.088	5	3.025	0.0798	4	1.8%	0.45 [-0.89, 1.80]
Park 2002	3.03	0.13	13	2.94	0.13	7	3.7%	0.66 [-0.28, 1.61]
Ravindran 2014	2.88	0.2	16	2.79	0.25	10	5.2%	0.40 [-0.40, 1.19]
Subtotal (95% CI)			**262**			**229**	**100.0%**	**0.58 [0.40, 0.77]**
Heterogeneity: Tau² = 0.00; Chi² = 4.13, df = 7 (P = 0.76); I² = 0%								
Test for overall effect: Z = 6.29 (P < 0.00001)								
13.1.2 Cysteine								
Cámara 2017	1.462	0.021	32	1.43	0.021	26	25.4%	1.50 [0.91, 2.09]
Galkanda-Arachchige 2020	0.63	0.019	5	0.63	0.019	5	12.2%	0.00 [-1.24, 1.24]
Lagos 2017	0.63	0.022	5	0.62	0.022	5	11.9%	0.41 [-0.85, 1.67]
Li 2015	0.7	0.033	6	0.68	0.293	7	14.4%	0.09 [-1.01, 1.18]
Park 2002	0.58	0.08	13	0.5	0.08	7	16.3%	0.96 [-0.02, 1.93]
Ravindran 2014	0.75	0.03	16	0.73	0.04	10	19.9%	0.57 [-0.24, 1.38]
Subtotal (95% CI)			**77**			**60**	**100.0%**	**0.71 [0.18, 1.24]**
Heterogeneity: Tau² = 0.20; Chi² = 9.38, df = 5 (P = 0.09); I² = 47%								
Test for overall effect: Z = 2.64 (P = 0.008)								
13.1.3 Methionine								
Cámara 2017	1.351	0.016	32	1.318	0.016	26	18.5%	2.03 [1.39, 2.68]
Galkanda-Arachchige 2020	0.66	0.022	5	0.65	0.022	5	8.5%	0.41 [-0.85, 1.67]
García-Rebollar 2016	0.73	0.014	180	0.71	0.021	165	28.9%	1.13 [0.90, 1.36]
Lagos 2017	0.65	0.022	5	0.64	0.022	5	8.5%	0.41 [-0.85, 1.67]
Li 2015	0.67	0.022	6	0.65	0.032	7	9.9%	0.67 [-0.47, 1.80]
Park 2002	0.63	0.03	13	0.58	0.03	7	10.7%	1.60 [0.52, 2.67]
Ravindran 2014	0.72	0.02	16	0.69	0.07	10	14.9%	0.64 [-0.18, 1.45]
Subtotal (95% CI)			**257**			**225**	**100.0%**	**1.10 [0.67, 1.54]**
Heterogeneity: Tau² = 0.15; Chi² = 12.83, df = 6 (P = 0.05); I² = 53%								
Test for overall effect: Z = 5.01 (P < 0.00001)								
13.1.4 Tryptophan								
Cámara 2017	1.368	0.011	32	1.356	0.011	26	22.9%	1.08 [0.52, 1.63]
Galkanda-Arachchige 2020	0.71	0.024	5	0.7	0.024	5	7.2%	0.38 [-0.88, 1.63]
García-Rebollar 2016	0.73	0.0154	180	0.72	0.0234	165	41.6%	0.51 [0.29, 0.72]
Lagos 2017	0.7	0.022	5	0.69	0.022	5	7.2%	0.41 [-0.85, 1.67]
Li 2015	0.62	0.026	6	0.62	0.038	7	9.2%	0.00 [-1.09, 1.09]
Park 2002	0.61	0.1	13	0.64	0.05	7	11.9%	-0.33 [-1.26, 0.59]
Subtotal (95% CI)			**241**			**215**	**100.0%**	**0.48 [0.11, 0.84]**
Heterogeneity: Tau² = 0.07; Chi² = 8.06, df = 5 (P = 0.15); I² = 38%								
Test for overall effect: Z = 2.54 (P = 0.01)								

Test for subgroup differences: Chi² = 5.63, df = 3 (P = 0.13), I² = 46.7%

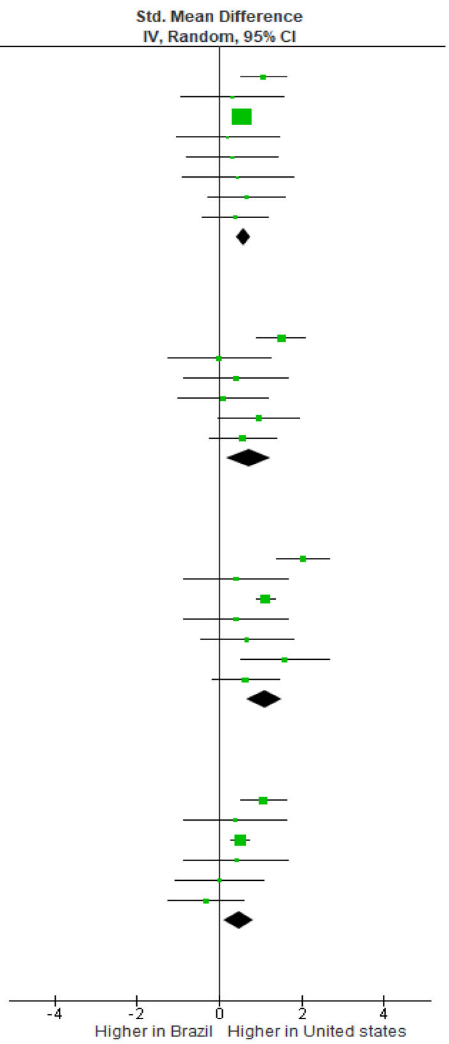

FIGURE 4 Amino acid plot of soy meal based on studies carried out for US and Brazil soybeans.

samples are included in this assessment. These results show that the difference is significant for all minerals except for K although there is a small heterogeneity observed for K. Overall, the meta-analysis shows higher levels Fe, Zn and Mg and lower levels of Ca and K in soybeans from Brazil than soybeans from the US. These results are consistent with an earlier report (Ibáñez et al., 2020). A Funnel plot representing publication bias for these minerals is shown in Figure S2.

Selected nutritional values

Based on the available studies, three articles for oil, six articles for protein and seven for fiber were included. The results are shown in Figure 3. A total of 55–278 samples are included in this assessment. The results show that the differences are significant for protein and fiber although there is a small heterogeneity observed for oil. Overall, the meta-analysis shows that the fiber and protein levels were higher in soybeans from Brazil and these results are consistent an earlier report (Ibáñez et al., 2020). A Funnel plot representing publication bias for nutrition is shown in Figure S3.

Selected amino acids

Selected AA, including Lys, cysteine, methionine and tryptophan, were used for meta-analysis. Based on the available information, eight articles for Lys, six articles for cysteine and tryptophan and seven for methionine, were included and the results are shown in Figure 4. A total of 77–262 samples are included in this assessment. The results show that the difference is significant for methionine although a small heterogeneity was observed for other AA. Overall, the meta-analysis showed that the levels of methionine was higher in the soybeans from the US compared to Brazil and these results are consistent with an earlier report (Ibáñez et al., 2020). A Funnel plot representing publication bias for AA is shown in Figure S4.

Soybean oil quality by origin

Table 2 summarizes the mean results of the crude degummed soybean oil attribute analysis by year and origin. Little difference was seen in Lovibond red color among the 557 oil samples with larger differences between shipment years than among the origin of the soybeans (Figure S5). The FFA levels were consistently higher in oil derived from Brazilian soybeans and significantly lower in the US produced soybeans, with levels from Argentine soybeans intermediate and most variable (Figure S6). NOL was also consistently higher in oil derived from Brazilian soybeans and significantly lower in the US produced soybeans, with levels from Argentine soybeans at an intermediate level

TABLE 2 Quality of oil shipped or produced from seeds shipped at destination crushers from 2020 to 2021.

Origin	Color[1]	FFA[2] (%)	NOL[3] (%)	Iodine[4]	Unsapon[5] (%)	Sapon[6]	Ca[7] (ppm)[11]	Mg[8] (ppm)	Fe[9] (ppm)	P[10] (ppm)	Chlorophyll, (ppm)[12]
2020–21 shipments											
Argentina India Vessel	11.7^{a}	0.57^{b}	1.6^{a}	128.3^{b}	0.8^{bc}	191.3^{c}	34.2^{c}	12.3^{b}	21.4^{b}	85.2^{bc}	
USA South Korea crusher	11.6^{ab}	0.36^{c}	0.87^{c}	129.8^{a}	0.84^{b}	193.0^{bc}	47.1^{b}	16.0^{b}	16.9^{c}	79.1^{c}	-
Brazil South Korea crusher	11.3^{bc}	1.2^{a}	1.6^{a}	126.1^{c}	0.73^{c}	194.2^{ab}	72.7^{a}	40.2^{a}	24.6^{a}	144.5^{a}	-
USA South Korea Vessel	11.1^{cd}	0.51^{b}	0.96^{bc}	129.2^{a}	0.75^{c}	192.2^{bc}	42.1^{bc}	15.1^{b}	20.4^{b}	82.2^{c}	-
USA India Vessel	10.5^{d}	0.6^{b}	0.83^{bc}	129.2^{ab}	1.0^{a}	197.2^{a}	36.3^{bc}	19.3^{b}	22.8^{ab}	110.6^{b}	-
2021–22 shipments											
Argentina India Vessel	10.6^{ab}	0.54^{c}	0.98^{b}	128.7^{a}	0.98^{a}	192.2^{bc}	44.5^{b}	25.8^{c}	6.4^{b}	91.5^{b}	4.3^{b}
USA South Korea crusher	10.4^{b}	0.49^{c}	0.99^{b}	127.7^{a}	0.88^{bc}	191.6^{c}	91.9^{a}	43.7^{b}	10.4^{a}	137.4^{a}	3.9^{b}
Brazil South Korea crusher	10.6^{ab}	1.25^{a}	1.7^{a}	126.0^{a}	0.83^{c}	193.7^{ab}	91.0^{a}	51.5^{a}	8.7^{ab}	144.0^{a}	6.4^{a}
USA India Vessel	10.9^{a}	0.70^{b}	0.90^{b}	130.4^{a}	0.98^{a}	195.6^{a}	30.0^{b}	17.6^{c}	5.5^{b}	70.8^{b}	1.9^{c}

Note: Means followed by different letters are significantly different ($P < 0.05$) by Tukey's test.
[1]Lovibond red color.
[2]FFA-free fatty acids.
[3]NOL, neutral oil loss.
[4]Iodine value.
[5]Unsaponifiable (mg KOH/g).
[6]Saponification (mg KOH/g).
[7]Calcium.
[8]Magnesium.
[9]Iron.
[10]Phosphorus.
[11]Part per million.
[12]Not assayed.

(Figure S7). Iodine values were highest in the oil from the US derived soybeans and lowest for Brazilian derived soybeans, although the differences were not always significant due to high variability of the iodine values among the samples (Figure S8). This would be expected due to the inverse relationship of fatty acid unsaturation and seed maturation temperature (Carrera & Dardanelli, 2017; Dornbos & Mullen, 1992; Medic et al., 2014; Oliva et al., 2006).

Small but significant differences were seen for the percentage unsaponifiable material and saponification values among the samples but there was no clear association to the source of the soybean seeds (Table 2, Figures S9 and S10). Ca and Mg also showed moderate and variable differences ranging from 30 to 91.9 ppm for Ca and 12.3 to 51.5 ppm for Mg (Table 2, Figures S11 and S12). The oil from Argentina showed lowest levels of Ca and Mg (Table 2, Figures S11 and S12). The levels of iron, Fe, was highly variable ranging from 5.5 to 24.6 ppm. Fe levels depend on soil Fe soybeans were produced in and storage and handling conditions. Seed damage is also reported to greatly increase Fe levels (Evans et al., 1974). The *P* levels of the oil samples were highest in oil from soybeans shipped from Brazil and lowest in oil from soybeans shipped from Argentina, with variable levels seen in oil from the US soybeans (Figure S13). Chlorophyll levels were highest in oil from Brazil with oil from Argentina averaging a little higher chlorophyll levels than oil from the US (Figure S14).

Quantifying soybean oil quality differences by origin has important implications for refiners. If a refiner purchases crude oil from different origins (or whole soybeans to crush), these quality differences will have economic implications during the refining process. Differences in NOL will have a direct impact on revenue as higher neutral oil loss results in lower refining yields and lower volumes available to sell. Higher FFA content will increase input costs as more caustic solution will be required to neutralize the oil. Based on this analysis, end users should be aware that soybean oil composition is different by origin. This also suggests that there is a need to quantify these economic differences to better inform end users.

CONCLUSIONS

The US-derived soybean meal was found to have less fiber, more sucrose and Lys and better protein quality than meal from soybeans grown in South America and China. Meta-analysis highlighted the relation between Brazil and the US as the top soybean exporters to China, and the SBM chemical composition, nutritional value, minerals and AA composition. Soybeans from Brazil had higher levels of protein and fiber than the US soybeans but the later had higher SP and methionine content. Furthermore, the composition of the US soybean oil was superior in NOL, FAA, and to a lesser extent Color. Conducting a multi-year sample survey to capture variation in crop years will be critical for understanding compositional differences and refining cost implications.

AUTHOR CONTRIBUTIONS

Huazhen Liu did much of the writing, prepared many of the figures and did the statistical analyses, Mohammad Fazel Soltani Gishini did the meta-analyses, some of the writing, prepared some of the figures, Micah Pope did some of the writing, prepared some of the figures and provided editing, Todd Doehring did some of the writing, prepared some of the figures and provided editing, Pradeep Kachroo did some of the writing and provided editing, David Hildebrand did much of the writing, extensive editing and made the submission.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

ETHICS STATEMENT

No humans or animals were used in this research.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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