Assessment of the main sources of variability of soybean (*Glycine max*) expeller composition and quality: a field study

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Abstract: Pairs of soybean seeds and their correspondent expeller samples were collected from ten extrusion-expelling processing plants in Argentina. Seeds were analyzed for proximal composition, bulk moisture content (MC) and individual seed MC. Soybean expeller (SBE) samples were analyzed for proximal composition, bulk MC, protein solubility in KOH, expeller urease activity and free fatty acid content. Results indicated that average soybean composition was 136 g kg^{-1} MC, 207 g kg^{-1} oil and 391 g kg^{-1} crude protein (CP), while the oil extraction efficiency (OEE) of the process was 60.7%. The expeller composition was 928 g kg^{-1} dry matter (DM), 81 g kg^{-1} oil and 442 g kg^{-1} CP. In soybean seeds, coefficient of variation (CV) of MC was 17.2%, 3.0% for CP and 5.1% for oil, while in SBE, CV for DM was 2.9%, 3.9% for CP and 19.7% for oil. A relationship among soybean seed MC, OEE and expeller composition was found. The findings indicate that conditioning the soybean MC prior to processing is important not only to maximize OEE, but also to achieve uniform expeller composition and to assure deactivation of anti-nutritional factors.

Keywords: soybean processing, extrusion-expelling, oil extraction efficiency, chemical composition, individual seed moisture

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1 Introduction

In the 2015-2016 period, soybean (*Glycine max*) production in Argentina was 58.8 million tons, of which 70% were processed into soybean meal (SBM) in large crushing plants with the solvent extraction method, 7%-8% were processed into soybean expeller (SBE) in small and medium enterprises (SMEs) with the extruding-expelling method (E-E), and the rest was exported as seeds (Bragachini et al., 2017; MinAgro, 2017).

The E-E process typically yields 12%-14% of oil and 86%-88% of SBE, with an average residual oil content of 50 to 110 g kg^{-1} in the expelled product (Lusas and Rhee,

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1995; Woerfel, 1995). SMEs located in the argentine Pampa´s region produce SBE, which is used as feed for different local animal production industries (beef, dairy, hogs and poultry), and oil for biodiesel transformation (used as fuel for farming labors, grain dryers, boilers for industrial processes, etc.), being these two by-product key components in the economic development of small cities (Bragachini et al., 2017). Variability in the composition and quality of the SBE was documented by Juan et al. (2015). This variability could be induced by intrinsic characteristics of the different processing equipment, processing temperature and pressure conditions (Bargale et al., 1999), the raw material composition (Grieshop et al., 2003; García-Rebollar et al., 2016), and raw material moisture content (MC) (Zhu et al., 1996).

The effect of MC in the E-E process and, hence, in the SBE composition and oil extraction efficiency (OEE) is of special concern, since many SMEs do not have drying capacity to condition the soybean to a specific MC before processing. The manufacturers of E-E equipment recommends processing soybean between 100 to 110 g kg^{-1} MC to maximize OEE (Bragachini et al., 2017), which is 25 to 35 g kg^{-1} lower than the typical trade MC for soybean in Argentina (135 g kg^{-1}). The economics performance of the E-E processing plants is strictly related to the OEE, which in Argentina was estimated to be lower than 70% (Juan et al., 2015; Bragachini et al., 2017). Bargale et al. (1999) evaluated the E-E process under different combinations of temperature and pressure and stated that the maximum OEE could be as high as 90.6%, implying that there is an important gap between the average OEE observed in Argentina and the potential of the technology.

In terms of feed diet conformation, SBE could have advantages over SBM. Zhang and Parsons (1993) reported higher digestible energy and amino acid availability in SBE compared to SBM. However, they remark that feeds with large variations in their composition are problematic, affecting negatively the weight gain in the beef, poultry and hogs industries and reducing milk production in the dairy industry. This is an important concern due to the high variability reported in SBE composition. It could be speculated that processing soybean without controlling MC could lead to changes in the OEE and, hence, contribute to increase the variability in the SBE composition and quality. Thus, the objectives of this study were to characterize quality and composition of soybean seeds and expellers in extrusion-expelling plants in Argentina and to determine the main source of variability in the expeller quality and composition.

2 Materials and methods

2.1 Soybean seeds and expeller samples

This study was conducted during 2015 and 2016. The experimental materials were obtained from 10 different E-E plants located in the provinces of Buenos Aires (five plants), Santa Fe (two plants), Córdoba (two plants) and Entre Ríos (one plant). The geographical distribution and number of sampling locations represent the importance of each province in the total production of SBE in the country. At each processing plant, pairs of soybean seeds (1 kg) and SBE (5 kg) were collected by triplicate during three consecutive days to capture the variability of the raw material and the processing conditions. The soybean samples were collected directly from the conveyor that was feeding the E-E process, while the SBE samples were collected at the exit of the screw press. The collected samples were immediately sent to the Grain Quality Lab of INTA Balcarce, and stored in a chamber at 4°C in a double hermetic bag until they were analyzed (Castellari et al., 2015; Capitani et al., 2018).

2.2 Soybean characterization

Chemical composition of bulk whole seed soybean samples was determined using near infrared spectroscopy (NIRS) (NIR Systems 6500, FOSS, USA), using the calibrations developed by the Food and Feed Laboratory, INTA Anguil Experimental Station, La Pampa province, Argentina. The NIR standard error of cross-validation (SECV) and coefficient of determination (R^2) were 0.31% (wb) and 0.97 for MC, 0.61% (wb) and 0.93 for crude protein (CP), and 0.33% (wb) and 0.96 for oil content, respectively.

Individual soybean seeds MC was determined by weighing and drying 20 individual seeds (three replicates) in air-forced oven at 102°C for 72 hours, according to the method described by Azcona et al. (2009). The individual seed MC was determined only in samples collected from the three E-E plants located near INTA Balcarce Experimental Station, because in those facilities soybean was artificially dried before processing (and presumably samples had high individual seed variability), and because they were close enough to the lab for processing before moisture variability disappears.

2.3 Expeller characterization

SBE samples were ground to 1 mm (Knifetec mill, FOSS, USA), and chemical composition of the SBE samples was determined using NIRS. Statistical parameters (SECV and R^2) of NIRS calibrations were 0.51% (wb) and 0.96 for CP, 0.31% (wb) and 0.99 for residual oil, and 0.31% (wb) and 0.97 for MC, respectively. The MC of ground SBE was also determined with a modified standard method (AOCS, 2009), drying samples in a stove with forced air circulation at 103°C during 2 hours. In this study, MC, oil and CP of soybean and SBE were expressed in g kg^{-1} of dry matter. The OEE was calculated from the soybean and SBE oil contents as follows:

$$OEE = (Oil_{SB} - Oil_{SBE}) / Oil_{SB} * 100 \quad (1)$$

Where:

OEE is oil extraction efficiency (%)

Oil_{SB} is soybean oil content (g kg^{-1})

Oil_{SBE} is oil content in the soybean expeller (g kg^{-1})

Additionally, the following quality parameters of SBE were determined: protein KOH solubility expressed as percentage of total protein (by NIRS, SECV= 2.79% and R^2= 0.870), urease activity expressed as pH units (SAGPyA, 1999) and free fatty acid in crude oil after Soxhlet extraction (AOCS, 1997), expressed as percentage in dry matter basis.

2.4 Statistical analyses

Descriptive statistics (means, standard deviation (SD) and coefficient of variation (CV)) were used to characterize the composition and quality of soybean and SBE. Multiple or simple linear regression models were adjusted to characterize the relationship between compositional and quality parameters of SBE and soybean seeds. In order to compare all possible subsets of models with three predictors (MC_{SB}, Oil_{SB} and CP_{SB}), adjusted R^2, Mallow´s Cp, and Akaike (AIC) and Bayesian (BIC) Information Criteria were considered (mainly the last one). The assumptions were checked for all selected models and significance of predictors was determined. All analysis were done using the "R" program (R version 3.5.1) (R-Core Team, 2017).

3 Results

3.1 Soybean seed and expeller chemical composition and protein quality indicators

Across all processing plants, the average MC of the soybean seed was 136 g kg^{-1}, the CP was 391 g kg^{-1}, and the oil content 207 g kg^{-1} (Table 1). On the other hand, the SBE had an average dry matter (DM) of 928 g kg^{-1}, the CP was 442 g kg^{-1}, and the oil content was 81 g kg^{-1}.

An important variability was observed in the MC of the raw material (CV of 17.2%), while the variability in oil and CP of the soybean seeds was lower (CV of 5.1% and 3.0% for oil and CP, respectively). The SBE resulted with a larger variability in oil compared to that of the raw material (CV of 2.9%, 3.9% and 19.7% for DM, CP and oil, respectively). The analysis intra processing plants indicated that in some of them there was a large variability in the soybean MC (CV above 15% in plants 3, 8 and 10), but relatively low variability in oil and CP. However, the SBE had larger variability in oil, especially in plants 3 and 8 (CV above 25%).

The average OEE across all plants was 60.7% and with a large variability (CV of 13.8%). The analysis intra plants indicated that there was also a large variability in this parameter in plants 3 and 8 (CV above 20%).

The average quality parameters of the SBE across all plants indicated that the KOH solubility was 79.1%, the urease activity was 0.07 pH units, and the free fatty acid concentration in oil was of 2.6 mg KOH g^{-1}. The variability was relatively low for KOH solubility (CV of 5.2%), and high for urease activity and acidity (CV of 179% and 20.7%, respectively).

Table 1 Soybean seed and expeller composition (g kg^{-1}) and quality parameters. SD between brackets

Plant	Parameter	Soybean seed			Expeller						
		MC_{SB}	CP_{SB}	Oil_{SB}	DM_{SBE}	CP_{SBE}	Oil_{SBE}	OEE (%)	KOH (%)	UA (pH units)	Acidity (mg g^{-1})
1	Avg.	143 (9.6)	385 (5.5)	201 (2.0)	938 (4.8)	425 (10.1)	89 (8.6)	55.7 (4.41)	82.7 (1.74)	0.02 (0.02)	3.0 (0.29)
(n:7)	CV(%)	6.7	1.4	1.0	0.51	2.4	9.6	7.9	2.1	68.8	9.6
2	Avg.	162 (13.2)	380 (8.0)	216 (9.2)	880 (21.7)	436 (5.0)	93 (6.5)	56.9 (4.63)	78.7 (3.38)	0.21 (0.11)	3.0 (0.97)
(n:5)	CV(%)	8.2	2.1	4.3	2.47	1.2	7.0	8.1	4.3	52.0	32.7
3	Avg.	153 (31.6)	390 (13.4)	204 (1.7)	925 (18.2)	428 (18.8)	106 (31.4)	48.1 (15.76)	76.7 (1.38)	0.04 (0.01)	2.5 (0.58)
(n:2)	CV(%)	20.7	3.4	0.8	1.97	4.4	29.6	32.8	1.8	35.4	22.7
4	Avg.	135 (10.2)	407 (1.9)	193 (2.0)	893 (17.7)	453 (1.6)	89 (7.6)	54.1 (4.18)	80.1 (2.92)	0.01 (0.01)	2.6 (0.35)
(n:3)	CV(%)	7.5	0.5	1.1	1.98	0.3	8.6	7.7	3.6	100.0	13.5
5	Avg.	118 (12.7)	388 (8.5)	218 (10.3)	947 (5.9)	438 (13.3)	72 (9.1)	67.1 (2.66)	76.5 (1.13)	0.01 (0.01)	2.4 (0.46)
(n:3)	CV(%)	10.8	2.2	4.7	0.62	3.0	12.7	4.0	1.5	173.2	19.0
6	Avg.	93 (7.5)	410 (3.6)	203 (3.7)	951 (3.0)	478 (2.7)	62 (2.3)	69.7 (0.83)	78.0 (2.95)	0.27 (0.32)	2.1 (0.21)
(n:3)	CV(%)	8.0	0.9	1.8	0.31	0.6	3.7	1.2	3.8	119.6	9.7
7	Avg.	130 (2.2)	384 (5.2)	216 (2.8)	933 (2.0)	447 (11.2)	58 (4.7)	73.2 (2.54)	77.1 (0.93)	0.03 (<0.01)	-
(n:3)	CV(%)	1.7	1.4	1.3	0.22	2.5	8.2	3.5	1.2	10.8	-
8	Avg.	150 (33.6)	392 (16.4)	214 (17.4)	939 (20.4)	447 (13.0)	83 (23.1)	60.5 (13.01)	79.1 (2.24)	0.03 (0.02)	2.6 (0.28)
(n:3)	CV(%)	22.4	4.2	8.1	2.18	2.9	27.6	21.5	2.8	62.4	11.1
9	Avg.	130 (1.8)	399 (2.3)	211 (0.9)	931 (0.7)	457 (1.6)	73 (0.8)	65.6 (0.33)	83.3 (1.64)	<0.01 (0.01)	2.0 (0.11)
(n:3)	CV(%)	1.4	0.6	0.4	0.07	0.4	1.1	0.5	2.0	173.2	5.4
10	Avg.	123 (20.6)	386 (7.9)	201 (12.4)	956 (4.8)	437 (14.8)	78 (5.8)	61.2 (1.55)	74.5 (7.87)	0.06 (0.08)	2.8 (0.38)
(n:4)	CV(%)	16.8	2.0	6.2	0.50	3.4	7.4	2.5	10.6	152.5	13.8
All	Avg.	136 (23.3)	391 (11.6)	207 (10.7)	928 (27.2)	442 (17.4)	81 (16.0)	60.7 (8.40)	79.1 (4.09)	0.07 (0.13)	2.6 (0.55)
(n:36)	CV(%)	17.2	3.0	5.1	2.9	3.9	19.7	13.8	5.2	179.6	20.7

3.2 Correlations among composition and quality variables of soybean seeds and expeller

Several relationships among compositional and quality parameters of soybean and SBE were investigated and reported in Table 2.

Table 2 Pearson coefficient of correlation "r" among chemical and quality parameters of soybean seeds (SB) and expeller (SBE) and significance level of the correlation

	MC_{SB}	Oil_{SB}	CP_{SB}	DM_{SBE}	CP_{SBE}	Oil_{SBE}	EE	KOH	UA	Acidity
MC_{SB}	1									
Oil_{SB}	0.021^{NS}	1								
CP_{SB}	-0.359^{*}	-0.540^{***}	1							
DM_{SBE}	-0.507^{*}	-0.080^{NS}	-0.004^{NS}	1						
CP_{SBE}	-0.609^{***}	0.021^{NS}	0.655^{***}	0.194^{NS}	1					
Oil_{SBE}	0.752^{***}	-0.228^{NS}	-0.233^{NS}	-0.585^{***}	-0.620^{***}	1				
EE	-0.685^{***}	0.441^{**}	0.096^{NS}	0.509^{**}	0.580^{***}	-0.974^{***}	1			
KOH	0.317^{+}	0.086^{NS}	-0.044^{NS}	0.020^{NS}	-0.186^{NS}	0.188^{NS}	-0.154^{NS}	1		
UA	0.045^{NS}	0.111^{NS}	0.065^{NS}	-0.307^{*}	0.219^{NS}	0.047^{NS}	-0.005^{NS}	-0.056^{NS}	1	
Acidity	0.285^{NS}	-0.297^{NS}	-0.192^{NS}	-0.287^{NS}	-0.411^{*}	-0.271^{NS}	-0.325^{*}	-0.247^{NS}	0.073^{NS}	1

Significance level: NS: no significant; +: $p<0.1$; *: $p<0.01$; **: $p<0.001$; ***: $p<0.0001$

3.3 Moisture content of individual soybean seed

Table 3 shows the average and variability (SD and CV) of the individual seed MC, and it was observed that all samples have dispersion in MC with SD ranging from 3.3 to 14.9 (CV from 2.8% to 12.7%).

Table 3 Average values, standard deviation and coefficient of variation of individual seed moisture contents of soybean samples collected from different processing plants

Sample	Average individual seed MC (g kg^{-1})	SD	CV (%)
1	149	8.4	5.63
2	127	8.4	6.62
3	124	7.7	6.26
4	121	8.1	6.68

5	118	9.4	7.98
6	117	14.9	12.73
7	115	7.0	6.11
8	114	3.3	2.85
9	113	6.3	5.56
10	105	5.6	5.36

Note: MC is moisture content, SD is standard deviation and CV is coefficient of variation

4 Discussion

4.1 Composition and variability of soybean seed and expeller

In general, the soybean composition obtained in this study (391 g kg^{-1} CP and 207 k kg^{-1} oil) was similar to that reported by Juan et al. (2015) and Cuniberti and Herrero (2018) for argentine soybeans. In particular, the last authors indicated that the average composition for the last 21 years was 382 g kg^{-1} and 229 g kg^{-1} for CP and oil content, respectively, and that there was a constant decrease in CP over the years (at a rate of 5 g kg^{-1} per year). The variability in the composition of soybean of this study (CV of 3% and 5.1% for CP and oil, respectively) was slightly lower than in the report of Juan et al. (2015) (CV of 3.6% and 7.6% for CP and oil, respectively). Grieshop et al. (2003) reported compositional values of soybean collected from US processing plants. In the comparison, US soybean has 21 g kg^{-1} higher CP (412 g kg^{-1}) and 21 g kg^{-1} lower oil concentration (186 g kg^{-1}). In terms of variability, US soybeans had a similar CV for oil (5.6%) but lower for CP (0.8%). The difference in the average composition and variability between the soybean produced in Argentina and in the USA could be due to differences in the genotype used, the climatic conditions, soil type and agricultural practices (Singh, 2010).

The SBE composition reported in this study (928 g kg^{-1} DM, 442 g kg^{-1} CP and 81 g kg^{-1} oil) was also similar to the report of Juan et al. (2015) (932, 135 and 85 g kg^{-1} for DM, CP and oil, respectively). Karr-Lilienthal et al. (2006) reported higher CP in soybean meals prepared by E-E processing in US (from 451 to 526 g kg^{-1}), but with dehulled soybean seeds. One alternative to SBE in diets conformation is the SBM. In comparison with SBE, SBM has higher CP (510-540 g kg^{-1}), lower oil (19-40 g kg^{-1}) and lower DM (880-890 g kg^{-1}) (Lusas and Rhee, 1995; Woerfel, 1995). Garcia-Rebollar et al. (2016) reported that SBM from Argentina has lower CP than SBM from the US, Brazil, China and India. The main reason for the lower CP of the argentine SBM can be explained mainly due to the lower CP of the Argentine soybean seeds. Along the same line, it could be speculated that SBE produced in the US, Brazil or other country would also yield SBE with higher CP than that reported in this paper.

Large variability in SBE composition could lead to problems for trading (loads of SBE with different DM) and for calculation of animal diets. In this study, DM, CP and oil of the SBE had a CV of 2.9%, 3.9% and 19.7%, respectively. Contrastingly, Karr-Lilienthal et al. (2006) reported lower variability in SBE composition in the US (0.4%, 1.8% and 6.6% for DM, CP and oil, respectively), and García-Rebollar et al. (2016) and Grieshop et al. (2003) reported substantially lower variability in SBM composition of different origins (CV of 0.2%-0.7%, 0.5%-1.3% and 2.6%-19.3% for DM, CP and oil, respectively). This would imply that diet conformation with SBM would be less problematic than with SBE due to the lower variability of the first product.

4.2 Oil extraction efficiency and soybean expeller composition

As shown in Table 1, the OEE was on the average of 60.7% (range of 48.1%-73.2%), lower than expected according to the literature (around 70% for standard E-E process operations) (Nelson et al., 1987; Bargale et al., 1999), implying that some factors are limiting the process. The most critical independent variables of the extrusion process are temperature, MC and screw speed (Aguilera and Kosikowski, 1976). Floyd et al. (2013) stated that soybean viscoelastic properties were affected in a lesser extent by temperature and, in a larger extent, by MC. Along the same line, Chen et al. (2010) concluded that higher MC of feed resulted in lower viscosity and lower conversion ratio of mechanical energy into heat energy during the extrusion process. On the other hand, Nelson et al. (1987)

indicated that at a temperature above 135°C, the SBE assumes a fluid state that facilitates the oil recovery during the extrusion process. Thus, it could be hypothesized that as soybean moisture increases, changes in the viscoelastic properties of soybeans prevents reaching high temperatures during the extrusion process and, consequently, less oil is extracted. Equation 2 shows the prediction model for OEE, based on soybean moisture and oil contents. Furthermore, since soybean MC affected the OEE, it also affected the SBE composition. Also, higher CP in the soybean seed results in higher CP in the SBE (Table 2). Equations 3 and 4 show the prediction models obtained for oil and CP of the SBE.

$$OEE = (245.884 - 3.2169 \times MC_{SB} + 3.5871 \times Oil_{SB}) \quad (2)$$

($R^2 = 0.6765$, $p = 8.202\text{x}10^{-9}$)

$$Oil_{SBE} = (77.535 + 0.6693 \times MC_{SB} - 0.3670 \times Oil_{SB}) \quad (3)$$

($R^2 = 0.6257$, $p = 9.101\text{x}10^{-8}$)

$$CP_{SBE} = (-121.811 - 0.3261 \times MC_{SB} + 1.1581 \times CP_S) \quad (4)$$

($R^2 = 0.7229$, $p = 4.784\text{x}10^{-7}$)

Where: Oil_{SBE} is the soybean expeller oil content (g kg^{-1}, db); CP_{SBE} is the soybean expeller crude protein content (g kg^{-1}, db); OEE is the oil extraction efficiency (%);MC_{SB} is the soybean moisture content (g kg^{-1}, db); Oil_{SB} is the soybean oil content (g kg^{-1}, db) and CP_{SB} is the soybean crude protein content (g kg^{-1}, db).

Figure 1 shows the OEE, CP and oil content of the expeller as function of MC according to Equations 2 to 4. As the processing MC of the soybean decreases, the OEE increases, the residual oil content decreases and the CP increases. For example, processing soybean seeds (207 g kg^{-1} oil and 391 g kg^{-1} CP) at the market MC (135 g kg^{-1}) gave an OEE of about 55%. If the soybean seeds were dryer (eg. 110 g kg^{-1}), the OEE would increase to 63.5% and the SBE would result with lower oil content (17 g kg^{-1} less), and higher CP (8.5 g kg^{-1} more). This is because processing seeds with lower MC increases the viscosity of the extruded product, which increases the conversion ratio of mechanical energy into heat energy, which leads to an increase in the temperature of the SBE, allowing the SBE to reach a fluid condition.

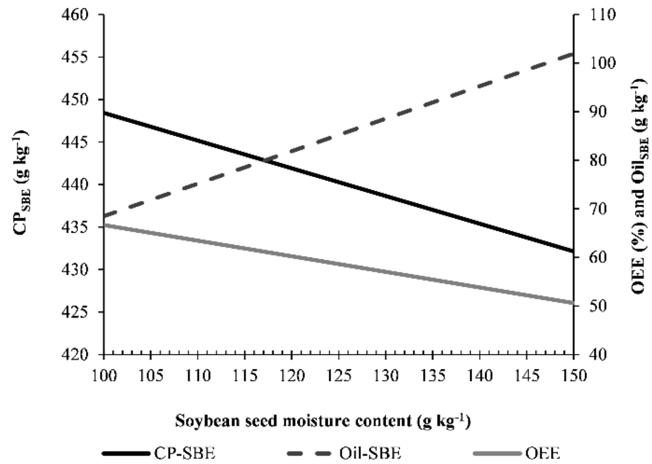

Figure 1 Effect of soybean seeds moisture content on oil extraction efficiency (OEE), protein (CP-SBE) and oil (Oil-SBE) contents of the expeller

The higher temperature and the fluidized condition of the SBE facilitate the oil extraction during the E-E process (Chen et al., 2010; Floyd et al., 2013; Nelson et al., 1987). Aremu and Ogunlade (2016b) found a similar behavior in the oil extraction efficiency of African oil bean (leguminous with >52% oil content). They observed that oil yield and expression efficiency decreased with an increase in MC. In addition to soybean MC, feed material, extruder configuration and processing condition can also affect the SBE composition and quality (eg. protein dispersibility index) (Crowe et al., 2001). However, most of the soybean seeds that the E-E plants can buy in the market for processing into SBE have a MC of 135 g kg^{-1} or higher. Thus, having the capability of drying the soybean seeds before processing is of great importance for these plants since it allows increasing the OEE of the process and the amount of CP in the SBE, helping to increase the economic performance of the operation and to produce SBE with higher nutritional value.

4.3 Soybean oil and protein quality indicators

Presence of free fatty acid in crude oil is an indicator of fat rancidity. Oil acidity is usually determined in the extracted oil, and the referential value is 4.0 mg KOH g^{-1} of cold pressed and virgin oil (FAO, 1999), implying that the oil samples from this study did not present rancidity problems since all samples resulted with acidity values below the suggested limit (Table 1).

The most important anti-nutritional factors in soybean are trypsin inhibitors, which can be almost completely eliminated by heat treatment during the E-E processes (Smit et al., 2018). Urease activity is extensively used as an indirect indicator of the deactivation of anti-nutritional factors by temperature treatment. Insufficient heat treatment is a concern for poultry and pig feed, since poorly inactivated SBE causes nutritional problems in production of pigs and poultry (Zhang and Parsons, 1993), indicating that the heat treatment during the E-E process becomes critical. Urease activity across all samples was in average 0.08 pH units, below the maximum permissible value of 0.20 pH units (SAGPyA, 1999) (Table 2). However, in 4 of 36 samples (11%) the urease activity was above the critical limit, implying that under some E-E processing conditions, the inactivation of anti-nutritional factors was not achieved. García-Rebollar et al. (2016) reported SD values of urease activity in SBM samples of 0.002, substantially lower than in this study for SBE (0.13), implying that overall the thermal treatment in the SBM process was more appropriated (reached higher temperature) to inactivate trypsin inhibitors than the thermal treatment of the SBE process. The only significant correlation of urease activity, although weak (r = -0.307 and p < 0.01) was with the DM of the expeller. This would imply that the higher the MC of the soybean, the more difficult it is to reach the inactivation temperature in the expeller. Evidence of the effect of seed MC on the temperature reached during the E-E process could be found in Aremu and Ogundale (2016a, 2016b).

On the other hand, excessive temperature during the E-E process can produce protein denaturation/aggregation and, in extreme conditions, alteration of amino acids. When this occurs, protein functionality (determined as protein dispersibility index, protein KOH solubility, water holding capacity, emulsification capacity, etc.) is affected and, under more extreme conditions, even protein digestibility can be affected (Papadopoulos, 1989). The thermal treatments carried out during the E-E process produce a loss of protein solubility in KOH below the reasonable values, which can be due to the formation of aggregates with covalent bonds as demonstrated by Sobral et al. (2012) in roasted flours. In this context, Ingrassia et al. (2017) showed that the protein aggregation mediated by covalent interactions as a result of Maillard type reactions induces a loss of KOH solubility. Consequently, protein solubility in KOH is used as an indicator of under and over-heating for SBM and SBE (Wang and Johnson, 2001). In addition, Araba and Dale (1990a, 1990b) proposed to use protein solubility as an indicator of under and over-processing of SBMs, establishing that values higher than 85% and lower than 70% indicate under or over-processing, respectively. In this study, KOH solubility was 79.1, suggesting appropriated processing, slightly lower than that reported for SBM (81.2-86.1) by García-Rebollar et al. (2016). The only significant relationship of KOH, although weak (r = 0.317 and p < 0.1), was with soybean MC, implying that as the MC of the soybean increases, the KOH solubility of the expeller also increases, as result of the lower temperature reached during the processing of wet soybean seed.

4.4 Individual kernel moisture content

Individual kernel MC distribution was identified as single mode distribution, with a CV from 2.8% to 12.7%, in the range of that reported by Cardoso et al. (2007) (CV of 10%). Figure 2 shows the relationship of individual seed MC and OEE of three samples with similar average MC (105-110 g kg^{-1}) but different variability in individual seed MC, and it can be appreciated that as variability increased OEE decreased. This effect could be explained because MC affects the viscoelastic properties of the individual seeds, the energy required and the overall performance of the extrusion process (Floyd et al., 2013). However, it is important to remark that a more comprehensive study should be implemented to obtain a statistically significant correlation between individual seed MC and OEE of the extrusion process.

Measuring the average MC of a bulk sample with electronic moisture meters is a common practice among E-

E processing plants. However, measuring the individual seed MC is not usual, since it requires specific equipment, training and time. Thus, knowing the main sources of individual seed MC variability and how it can be prevented could help to improve the process performance. Artificial drying is a major source of individual seed MC variability, especially high temperature drying (Liu et al., 1997), thus, reducing drying temperature could help to reduce moisture variability. Additional recommendations for reducing individual seed MC variability are storing the recently dried soybean for some days before processing (Cardoso et al., 2007), implementing natural air/low temperature in-bin drying and avoiding blending loads of soybean with different MC (i.e., 80 and 130 g kg^{-1}) to conform a processing load around 110 g kg^{-1} MC.

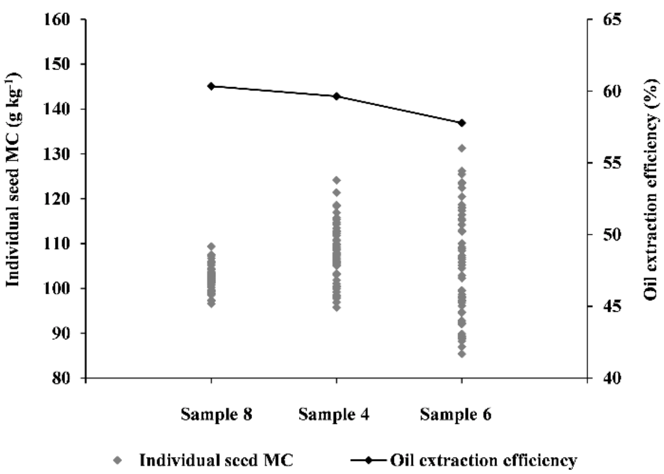

Figure 2 Variability of individual seed moisture content of three soybean samples and oil extraction efficiency

4.5 Compositional variability in expeller samples from the same processing plant

Figure 3 shows the average and SD of soybean MC and residual oil percentage in the SBE of samples collected during three different days in ten processing plants, indicating that when the variability of the soybean MC of a particular processing plant was high, the variability in the composition of the SBE was also high (eg. plants 3 and 8). This points out that feed manufacturers could have difficulties to conform uniform diets even using SBE from the same processing plant, especially if that plant does not have a reliable procedure for controlling the soybean MC prior to processing.

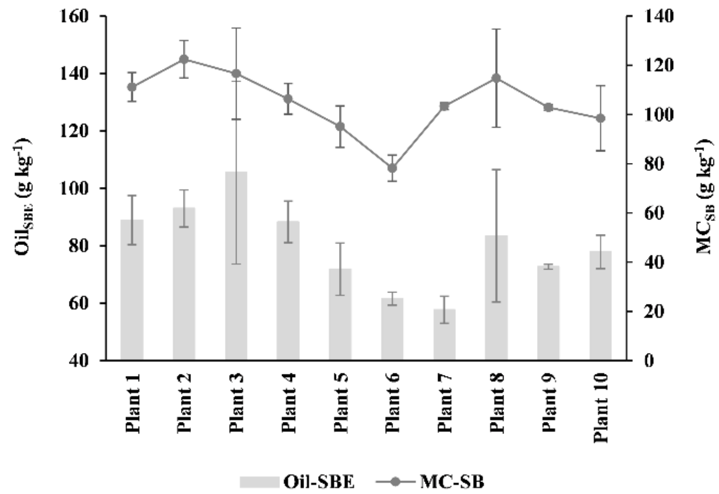

Figure 3 Expeller residual oil content (Oil-SBE) and soybean moisture contents (MC-SB) of samples collected from different processing plants (error bar denotes the standard deviation)

5 Conclusion

Variations in soybean MC result in variations in SBE composition and quality. Precise control of soybean seeds MC is of capital importance, not only to maximize oil extraction and achieve uniform expeller composition, but also to assure anti-nutritional factors deactivation. These conclusions were drawn from data collected from ten commercially operated extrusion-expelling plants under no-controlled conditions. Pilot lab scale experiments, under controlled conditions, would be required to better quantify the effect of soybean seeds MC on composition and quality of SBE.

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References

Aguilera, J. M., and F. V. Kosikowski. 1976. Soybean extruded product: a response surface analysis. *Journal of Food Science*, 41(3), 647–651.

AOCS. 1997. *Official Method Ca 5a-40-Free Fatty Acids.* American: American Oil of Chemists Society.

AOCS. 2009. *Official Method Ba 2a-38-Moisture and Volatile Matter Forced Draft Oven Method*. American: American Oil of Chemists Society.

Araba, M., and N. M. Dale. 1990a. Evaluation of protein solubility as an indicator of overprocessing soybean meal. *Poultry Science*, 69(1): 76–83.

Araba, M., and N. M. Dale. 1990b. Evaluation of protein solubility as an indicator of underprocessing soybean meal. *Poultry Science*, 69(10): 1749–1752.

Aremu, A. K., and C. A. Ogunlade. 2016a. Effect of operating parameters on mechanical oil expression from African oil bean seeds. *Global Journal of Science Frontier Research: D, Agriculture and Veterinary*, 16(1): 19-26.

Aremu, A. K., and C. A. Ogunlade. 2016b. Influence of moisture content and seed dimension on mechanical oil expression from African oil bean (*Pentaclethra macrophylla*) seeds. *Journal of Biosystems Engineering*, 41(3): 190-200.

Azcona, J., R. Bartosik, L. Cardoso, C. Casini, A. Curetot, M. Desimone, and H. Ferrari. 2009. *Grain Storage in Plastic Bags*. Manfredi, Córdoba, Argentina: INTA.

Bargale, P. C., R. J. Ford, F. W. Sosulski, D. Wulfsohn, and J. Irudayaraj. 1999. Mechanical oil expression from extruded soybean samples. *Journal of the American Oil Chemists' Society*, 76(2): 223–229.

Bragachini, M., F. Ustarroz, A. E. Saavedra, J. M. Méndez, D. Mathier, M. Bragachini, N. Sosa, R. M. Alladio, C. Accoroni, and H. Hennung. 2017. *Evolution of the Argentine Agricultural Sector*. Manfredi, Córdoba, Argentina: INTA.

Capitani, M. I., M. Sandoval-Peraza, L. A. Chel-Guerrero, D. A. Betancur-Ancona, S. M. Nolasco, and M. C. Tomás. 2018. Functional chia oil-in-water emulsions stabilized with chia mucilage and sodium caseinate. *Journal of the American Oil Chemists' Society*, 95(9): 1213-1221.

Cardoso, M. L., R. E. Bartosik, and J. C. Rodríguez. 2007. Study of the evolution of individual seed moisture content in corn and soybean silo bags. In *Proceedings of the X Congreso Argentino de Ingeniería Rural Y II Del MERCOSUR*, 1-22. Córdoba, Argentina, September 19-22.

Castellari, C. C., M. G. Cendoya, F. J. Marcos Valle, V. Barrera, and A. M. Pacin. 2015. Extrinsic and intrinsic factors associated with mycotoxic fungal populations of corn grains (Zea mays L.) stored in bag silos in Argentina. *Argentine Journal of Microbiology*, 47(4): 350–359.

Chen, L., Y. Wei, B. Zhang, and A. O. Ojokoh. 2010. System parameters and product properties response of soybean protein extruded at wide moisture range. *Journal of Food Engineering*, 96(2): 208-213.

Crowe, T. W., L. A. Johnson, and T. Wang. 2001. Characterization of extruded-expelled soybean flours. *Journal of the American Oil Chemists' Society*, 78(8): 775–779.

Cuniberti, M., and R. Herrero. 2018. *Problematic of Low Protein in Soybean*. Marcos Juárez, Córdoba, Argentina: INTA.

FAO. 1999. Codex Standard for Named Vegetable Oils (CODEX-STAN 210). Available at: http://www.fao.org/docrep/004/y2774e/y2774e04.htm#bm4.1. Accessed July 2018.

Floyd, L. H., J. K. Mensah, H. J. Barre, and K. Majidzadeh. 2013. Viscoelastic behavior of soybeans due to temperature and moisture content. *Transactions of the ASAE*, 22(5): 1219-1224.

García-Rebollar, P., L. Cámara, R. P. Lázaro, C. Dapoza, R. Pérez-Maldonado, and G. G. Mateos. 2016. Influence of the origin of the beans on the chemical composition and nutritive value of commercial soybean meals. *Animal Feed Science and Technology*, 221: 245–261.

Grieshop, C. M., C. T. Kadzere, G. M. Clapper, E. A. Flickinger, L. L. Bauer, R. L. Frazier, and G. C. Fahey. 2003. Chemical and nutritional characteristics of United States soybeans and soybean meals. *Journal of Agricultural and Food Chemistry*, 51(26): 7684-7691.

Ingrassia, R., G. G. Palazolo, P. H. Risso, and J. R. Wagner. 2017. Glycosylation, denaturation, and aggregation of soy proteins in defatted soy flakes flour: influence of thermal and homogenization treatments. *International Journal of Food Properties*, 20(10): 2358–2372.

Juan, N. A., J. I. Massigogue, L. Errasquin, J. M. Méndez, D. C. Ochandio, A. E. Saavedra, M. C. Paolilli, R. M. Alladio, C. Accoroni, and E. F. Behr. 2015. *Quality of Soybean and Expeller Processed by The Extruding/Expelling Industry in Argentina*. Manfredi, Córdoba, Argentina: INTA.

Karr-Lilienthal, L. K., L. L. Bauer, P. L. Utterback, K. E. Zinn, R. L. Frazier, C. M. Parsons, and G. C. Fahey. 2006. Chemical composition and nutritional quality of soybean meals prepared by extruder/expeller processing for use in poultry diets. J*ournal of Agricultural and Food Chemistry*, 54(21): 8108–8114.

Liu, Q., C. Cao, and F. W. Bakker-Arkema. 1997. Modeling and analysis of mixed-flow grain dryer. *Transactions of the ASAE*, 40(4): 1099–1106.

Lusas, E. W., and K. C. Rhee. 1995. Soy protein processing and utilization. In *Practical Handbook of Soybean Processing and Utilization*, 117–160. Erickson R.D., 117-160. St. Louis, Missouri: Elsevier.

MinAgro. 2017. Agricultural Statistics: Argentine Soybean Production. Available at: https://datos.agroindustria.gob.ar/dataset/estimaciones-agricolas/archivo/95d066e6-8a0f-4a80-b59d-6f28f88eacd5. Accessed March 2019.

Nelson, A. I., W. B. Wijeratne, S. W. Yeh, T. M. Wei, and L. S. Wei. 1987. Dry extrusion as an aid to mechanical expelling of oil from soybeans. *Journal of the American Oil Chemists' Society*, 64(9): 1341–1347.

Papadopoulos, M. C. 1989. Effect of processing on high-protein feedstuffs: a review. *Biological Wastes*, 29(2): 123–138.

R-Core Team. 2017. R: A language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. Available at: URL http://www.R-project.org/. Version 3.4.3

SAGPyA. 1999. Resolution N°317/99. Norm XIX: Oilseed Byproducts. Available at: http://www.minagri.gob.ar/sitio/areas/d_recursos_humanos/concurso/normativa/_archivos//000001_Resoluciones/000000_RESOLUCI%C3%93N%20317-1999%20Subproductos%20de% 20Oleaginosos.pdf. Accessed March 2019.

Singh, G. 2010. *The Soybean: Botany, Production and Uses*. 1st ed. Oxfordshire, UK: CAB International.

Smit, M. N., J. L. Landero, M. G. Young, and E. Beltranena. 2018. Effects of feeding canola meal or soy expeller at two dietary net energy levels on growth performance, dressing and carcass characteristics of barrows and gilts. *Animal Feed Science and Technology*, 235: 166–176.

Sobral, P. A., G. G. Palazolo, and J. R. Wagner. 2012. Evaluation of structural changes in soybean proteins during the process for making defatted soybean meal. *Aceites & Grasas 87*, XXII(2): 82-90.

Wang, T., and L. A. Johnson. 2001. Survey of soybean oil and meal qualities produced by different processes. *Journal of the American Oil Chemists' Society*, 78(3): 311–318.

Woerfel, J. B. 1995. Extraction. In *Practical Handbook of Soybean Processing and Utilization*, 65–92, Erickson D.R, 65-92. Location: St. Louis, Missouri. Elsevier.

Zhang, Y., and M. C. Parsons. 1993. Effects of extrusion and expelling on the nutritional quality of conventional and Kunitz trypsin inhibitor-free soybeans. *Poultry Science*, 72(12): 2299–2308.

Zhu, S., M. N. Riaz, and E. W. Lusas. 1996. Effect of different extrusion temperatures and moisture content on lipoxygenase inactivation and protein solubility in soybeans. *Journal of Agricultural and Food Chemistry*, 44(10): 3315–3318.