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Research article

Drying of soybean seeds and effect on protein quality and oil extraction efficiency by extruding-expelling process

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ABSTRACT: Soybean seeds (*Glycine max*) were dried under real scale conditions to different final moisture content (m.c.) (9.1, 9.7, 10.9 %, and control with 16.2 %) and processed through extruding-expelling. Results indicated that soybean seed m.c. affected the composition of the soybean expeller and, thus, the oil extraction efficiency (OEE), which increased as the seed m.c. decreased. A polynomic model was proposed for predicting OEE as a function of soybean m.c., indicating that drying soybean to 10 % resulted in an OEE of approximately 65 %. A thin layer drying experiment of soybean seeds indicated that the protein dispersibility index (PDI) was not affected as regards drying air temperatures up to approximately 69 °C, and a bi-linear model with a non-pre-established break point was fitted. The real scale drying treatment in a rack type dryer (mixed flow) did not show any effect ($p > 0.05$) on the PDI at 80 °C, while at 115 °C a reduction ($p < 0.05$) was observed (PDI reduction was 0.8 and 2.1 percentage points, respectively).

Keywords: soybean expeller, protein dispersibility index, thermal treatment, thin layer drying, individual seed moisture content

Introduction

The optimized oil extraction efficiency (OEE) by extruding-expelling of soybeans seeds (*Glycine max*) is slightly higher than 70 % (Bargale et al., 1999; Nelson et al., 1987). However, in a survey on different processing plants in Argentina Maciel et al. (2020) found that the average OEE was substantially lower, approximately 60 %, hypothesizing that the leading cause of low efficiency was the lack of control of moisture content (m.c.) of the processed seed (9.3 %-16.2 % d.b.). Manufacturers of extruding-expelling equipment recommend processing soybean with m.c. between 11 and 12 % on a dry basis (d.b.) (Juan et al., 2015), but this is an empirical recommendation (there is no published data). Additionally, the typical harvest and marketing m.c. of soybean in Argentina is 15.6 % (d.b.) (Bragachini et al., 2017); therefore, soybean must be artificially dried to optimize the OEE. However, information to determine the optimized processing seed m.c. is needed.

On the other hand, an increasing amount of soy protein is used in food content due to its high nutritional value and functional properties (Kang et al., 1991; Nishinari et al., 2014; Sui et al., 2021). Heat treatments, including drying, can produce denaturation and other structural modifications in soybean proteins (Fennema, 1996). Changes in the structure and functional properties due to heat treatment can be evaluated through the protein dispersibility index (PDI) (Kinsella, 1979), and the effect of heat treatment on deactivation of anti-nutritional factor was extensively considered (Liu and Ruiz, 2021; Vagadia et al., 2017; Žilić et al., 2012). Soybean drying has been comprehensively studied in the past in terms of its effect on seed germination (Anand et al., 2021; Barrozo et al., 2006; Brito et al., 2021; Hartmann Filho et al., 2016a; Jaques et al., 2022; Pfeifer et al., 2010; Souza et al., 2021). However, to our knowledge, there is only one study on the effect of seed drying on PDI (Santos et al., 2015). In addition to the potential effect on protein quality, the drying temperature also affects the energy efficiency of the drying process. In general, the higher the drying air temperature, the higher the efficiency and capacity of the dryer (Morey et al., 1976). Thus, a compromise must be sought between the temperature at which a dryer can be operated to maximize its efficiency and capacity, and still not affect the soy protein quality. Therefore, the objectives of this work were: 1) to study the effect of the soy seed m.c. on the OEE through the extruding-expelling method real scale conditions; and 2) to evaluate the effect of the drying treatment of the soy seed on the quality of the protein quantified as PDI.

Materials and Methods

Different drying treatments were carried out under controlled conditions at laboratory scale (thin layer drying) and at real scale in an extrusion-expelling plant as described in Figure 1.

Drying treatments and oil extraction efficiency

The real scale drying test was conducted in an extruding-expelling plant in Balcarce, Buenos Aires, Argentina (37°48′41″ S, 58°13′19″ W, altitude 106 m). The dryer in the experiment was a rack type of dryer with a holding capacity of 22 m^3 (or 17 t of soybean) (Avello, 15T), an airflow rate of 40 m^3 min^{-1} t^{-1} and a biodiesel burner as a heat source (Figure 2). The weather conditions during these experiments were typical for the soybean drying season in the location (May to July). The ambient temperature

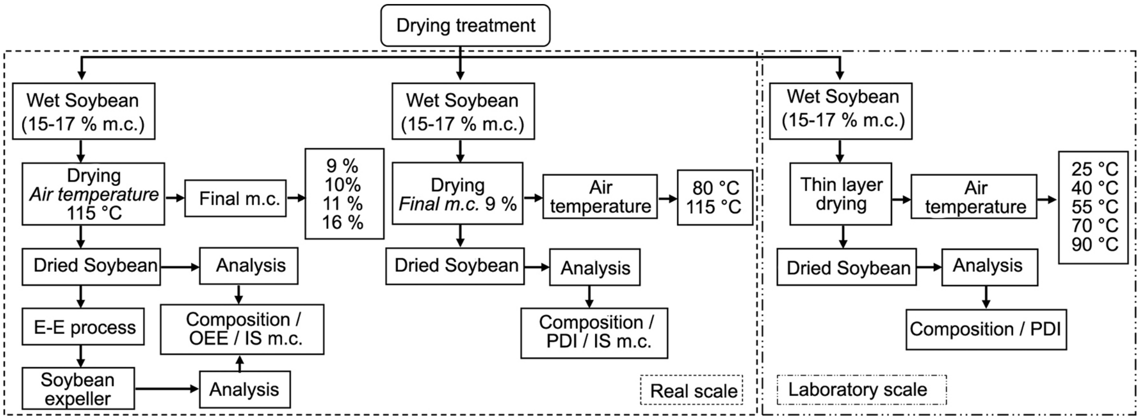

Figure 1 – Conceptual diagram of soybean drying treatments evaluated under laboratory (controlled) and field (real scale) conditions (m.c. = moisture content; E-E process = extruding-expelling process; OEE = oil extraction efficiency; IS m.c. = individual seed moisture content; PDI = protein dispersibility index).

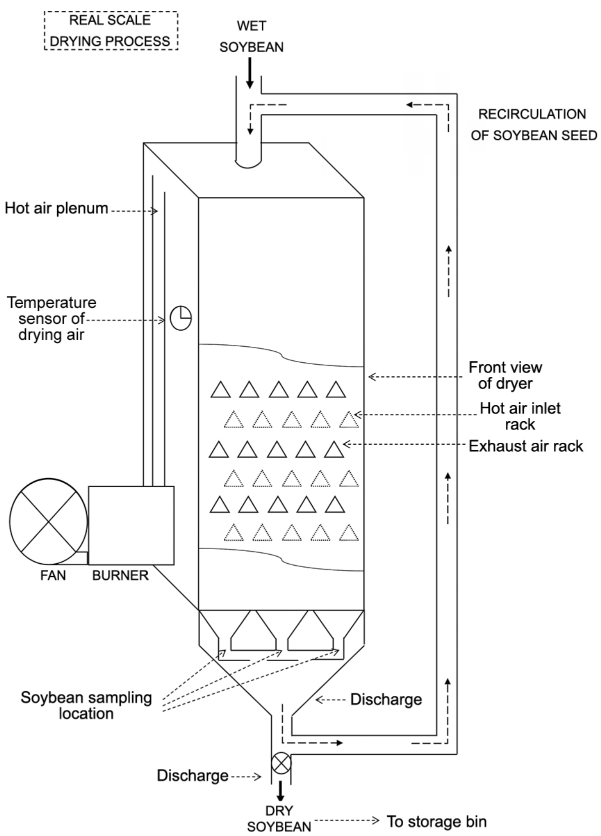

Figure 2 – Conceptual diagram of rack dryer used to evaluate the drying treatments under real scale conditions.

ranged between 3.1 and 16.1 °C (9.9 °C on average) and the relative humidity between 68 and 100 % (90 % on average). Three batches of soybean (17 t each) with an initial m.c. in the range of 15-17 % d.b. were used for three drying treatments at 115 °C until reaching 9, 10 and 11 % final m.c. [Hereinafter, all references to m.c. are expressed on a dry basis, unless otherwise indicated as a wet basis (w.b.)].

A fourth treatment was considered in which soybean was processed "as is" (16 % m.c.). The drying procedure consisted of filling the dryer with approximately 17 t of wet soybean, turning on the fan and the burner, setting the temperature of the drying air to 115 °C by regulating the burner intensity (the dryer has a temperature sensor in the hot air plenum), and recirculating the soybean in the dryer until the desired final m.c. was achieved. The drying times were 04h15, 04h00 and 02h30 for drying treatments of 9, 10 and 11 % of final m.c., respectively. The m.c. of soybean seeds during the drying treatment was controlled every 10 min by collecting 1 kg of sample at the outlet of the running dryer (Figure 2). The m.c. was measured with a portable moisture meter (Tesma, Plus 2). After achieving the final m.c. the dryer was turned off and the seed batch remained in the dryer until the next day, when it was transferred to a metal bin for 24-48 h of stabilization prior to processing it in an expeller.

Extruding-expelling process

The dried and stabilized soybean seed underwent an extruding-expelling process at the same facility. The extruder (YPHS138 Extruder, Anyang General International) had a capacity of 0.8 t h^{-1} and the two presses (OIL PRES ZX-130H, Anyang General International) had a capacity of 0.4 t h^{-1} each (Figure 3). Each batch of dried soybean was processed over three consecutive days.

Soybean and soybean expeller sampling and conditioning

Pairs of soybean seed and expeller samples were collected during each day of processing. Approximately 1 kg of seeds was collected at the inlet of the extruder with a plastic container and placed in a double hermetic bag to avoid changes in m.c. (Figure 3). Next, 60 soybean seeds (without visible damage) were individually placed in Eppendorf tubes and hermetically sealed to determine

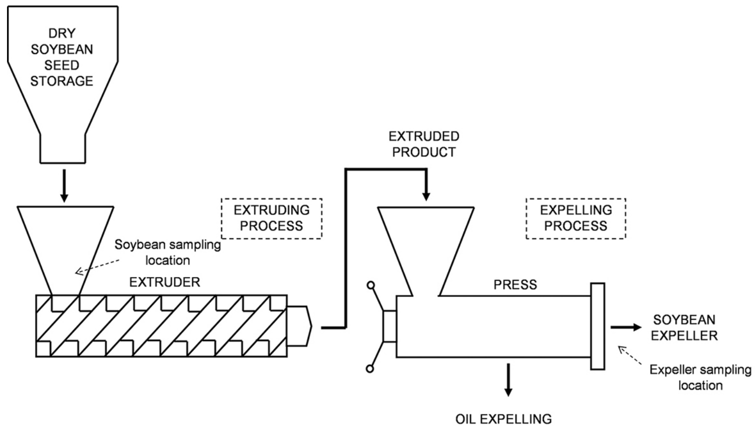

Figure 3 – Conceptual diagram of extruding-expelling process.

individual seed m.c. The expeller samples (5 kg) were collected at the press outlet with a plastic container and immediately transferred to a double hermetic plastic bag. This procedure was repeated four times at each sampling date at intervals of 15-20 min to make a composite sample of seed and expeller and capture the variability of the process. The pairs of composite samples were immediately taken to the laboratory (37°45′42″ S, 58°18′5″ W, altitude 127 m) for processing. The soybean samples were first evaluated through visual inspection (absence of insects and mold damage), cleaned, ground and sifted following the procedure described in the Argentinian standard for oleaginous by-products (SAGPyA, 1999).

Drying treatment and protein quality

Thin layer drying (laboratory scale)

Soybean sample selection and preparation

The drying treatments were carried out on soybeans provided by the National Network of Soybean Cultivars (RECSO) (INTA-Argentine Seed Growers Association). Soybean was harvested in 2017 at the experimental field (37°46′7″ S, 58°18′17″ W, altitude 117 m) with an average m.c. of 18.7 % and cleaned using a standard sieve for separation of broken grains (holes of 4.76 mm in diameter). In addition, a visual inspection was carried out to remove any additional broken or damaged grain.

Drying kinetic curves

The drying kinetic curves for 25, 40, 55, 70 and 90 °C were determined in triplicate in an electric oven with forced air circulation (ORL, P36-J-X) and temperature control system (± 1 °C). For each determination, 82 g of soybean seeds (18.7 % m.c.) were placed in a metal mesh tray (100 mm × 100 mm) as a thin layer (2-grain layers depth with a surface charge density of 0.82 g cm^{-2}). The approaching air velocity was regulated to 0.3 m s^{-1} (measured using a hot wire anemometer Lutrom, AM-4204). For each determination, the weight loss of the soybean sample was measured at defined time intervals (according to the drying air temperature) on a scale with a resolution of 0.01 g (Sartorius, M-Power AZ601), until reaching a moisture ratio (MR) lower than 0.6276 (obtained from Eq. (1)), corresponding to a final m.c. of 11.7 % (Rafiee et al., 2009).

$$MR = X/X_0 \qquad (1)$$

where: X is the m.c. of the sample after a predetermined drying time and X_0 the initial m.c. of the sample, both expressed as kg of water kg^{-1} of dry matter.

Additionally, the Page model Eq. (2) (Rafiee et al., 2009) was fitted and the specific parameters were obtained for each temperature treatment. Next, the calibrated Page model was used to estimate the drying time necessary to carry out the subsequent drying treatments on a laboratory scale.

$$MR = \exp^{(-1kt^{n})} \qquad (2)$$

where: k is a model coefficient (min^{-1}), t, time (min), and n, a model constant.

Thin layer drying procedure for protein quality effect determination

Approximately 12 kg of soybean with 18.7 % m.c. were divided into 15 sub-samples of 750 g each with a Boerner grain divider and assigned to a drying treatment (25, 40, 55, 70 and 90 °C) following a completely randomized design in triplicate. The drying treatments at 40, 55, 70 and 90 °C were carried out in an electric oven with forced air circulation (ORL, P36-J-X) plus temperature control system (± 1 °C), and the control treatment was carried out under laboratory air conditions (approximately 25 °C and 50 % of relative humidity). The approaching air velocity was regulated to 0.3 m s^{-1} (measured using a hot wire anemometer Lutrom, AM-4204). The drying procedure consisted of placing the seed sub-sample in a metal mesh tray (300 mm × 300 mm) as a thin layer (2 grain layers depth) with a surface charge density of 0.83 g cm^{-2}. The procedure consisted of drying each sample to a final m.c. of 11.7 %, corresponding to a moisture ratio of 0.6276 (Rafiee et al., 2009). The prescribed drying time (44h39, 04h41, 02h20, 01h17 and 00h46 for 25, 40, 55, 70 and 90 °C, respectively) was determined in the previous section.

After drying, the sample was placed in a double hermetic bag and stabilized at 4 °C in a cooling chamber for two weeks. Next, the sub-samples of dried seed were ground with a mill (KN 195 Knifetec™, FOSS) and sieved with a N° 25 (0.71 mm) sieve (Zonytest) to obtain the required particle size (> 95 % pass through the sieve) for the analysis to meet the Argentine standard for oleaginous by-products (SAGPyA, 1999). The initial and final m.c. was determined by the oven method according to the ASAE (2003) standard (103 °C during 72 h), using a balance with a resolution of 0.01 g (Sartorius, M-Power AZ601).

Real scale drying

The real scale drying test was carried out with the same dryer described in section 2.1 with the following differences. Two batches of soybean (initial m.c. of 15 %) were used for two drying treatments at 80 °C and 115 °C, namely, the minimum and maximum air temperatures at which the dryer could be regulated. The drying process reached its conclusion when the soybean m.c. reached 9 % after 04h40 for the 80 °C treatment and 04h00 for the 115 °C treatment. The temperature reached by the seed during drying was measured every 10 min by collecting 1 kg of the sample at the outlet of the running dryer, placing it in a closed thermic container and inserting a standard alcohol thermometer in the seed. The reading was recorded after 5 min of stabilization. Next, the same sample was used to measure m.c. with a portable moisture meter, as described in section 2.1. In addition, 60 soybean seeds were individually placed in Eppendorf tubes and hermetically sealed to determine individual m.c. at the end of each drying treatment.

Soybean seed and expeller analysis

Individual seed moisture content

Individual seed m.c. was determined on the same day as sampling according to the method described by Azcona et al. (2009). Immediately after the samples arrived at the laboratory, three replicates of 20 individual seeds (60 single soybean seeds), without any visual damage, were counted. Each seed was placed in a 1.5 mL Eppendorf tube and hermetically sealed to prevent moisture variation. Next, each wet seed was weighed on an analytical balance with a resolution of 0.0001 g (OHAUS, Pioneer™ PA 214) and placed back in the tube. Next, the open Eppendorf tubes were placed in polypropylene racks in an air-forced oven at 103 °C. After 72 h, the racks were removed, the tubes were immediately closed and allowed to cool down to room temperature. Finally, the dried seeds were weighed in the same analytical balance and the individual m.c. was calculated on a dry basis.

Chemical composition analysis

The chemical composition of soybean seed and expeller samples was determined using a NIRS apparatus (NIR Systems DS2500, FOSS) with calibrations developed by the Food and Feed Laboratory of INTA Anguil, La Pampa, Argentina. The standard error of cross-validation (SECV) and coefficient of determination (R^2) of soybean were 0.31 % (w.b.) and 0.97 for m.c., 0.61 % (w.b.) and 0.93 for crude protein, and 0.33 % (w.b.) and 0.96 for oil content, respectively, and for expeller were 0.31 % (w.b.) and 0.97 for m.c., 0.51 % (w.b.) and 0.96 for crude protein, and 0.31 % (w.b.) and 0.99 for oil content, respectively.

Oil extraction efficiency

The OEE of the process was calculated from the soybean and expeller oil contents as follows:

$$OEE = (Oil_{SB} - Oil_{SBE}) / Oil_{SB} \times 100 \quad (3)$$

where: OEE is oil extraction efficiency (%), Oil_{SB}, soybean oil content (%) and Oil_{SBE}, oil content in the soybean expeller (%).

Protein dispersibility index

The PDI in soybean seed was determined according to an official method (AOCS, 1993), with certain experimental modifications. Briefly, 2 g ± 0.0001 of ground and sieved samples were weighed (OHAUS, Pioneer™ PA 214) and placed in a 50 mL Falcon tube. To each sample, 10 mL of distilled water was added and homogenized with a glass rod to avoid the formation of foam. Subsequently, another 20 mL of distilled water was added, washing the rod to remove all possible sample residues. Each dispersion was homogenized with a high-speed rotor/stator (ULTRA-TURRAX T-25, rotor S-25N-8G, IKA Labortecknik, Staufen) at 11,000 rpm for 1 min at room temperature. Subsequently, the tube with the suspension was capped and placed in a centrifuge (5804R Series, Eppendorf™) for 20 min at 3,000 rpm (800 × g) at room temperature. The supernatant was separated and an aliquot of 1 mL of dispersed sample was taken to be analyzed by the micro-Kjeldahl method to determine its protein content. On the other hand, the nitrogen content was determined by the micro-Kjeldahl method of using approximately 150 mg of soil and sieved samples of soybean seed to calculate the total protein content.

The total protein content of the initial seed samples was estimated by measuring the nitrogen content with micro-Kjeldahl according to an official method (AOAC, 1997), considering the experimental factor 6.25 for soybean according to the following expression:

$$PC\ (\%) = TN\ (\%) \times 6.25 \quad (4)$$

where: *PC* is protein content and *TN* the total nitrogen content.

Finally, Eq. (5) was used to determine next the samples' PDI.

$$PDI\ (\%) = PC_D\ (\%)/PC_S\ (\%) \times 100 \quad (5)$$

where: *PDI* is the protein dispersibility index expressed as a percentage, PC_D the protein content of the dispersion and PC_S the protein content of the solid sample used to prepare the dispersion.

Statistical analysis

The effect of temperature on protein solubility is not constant since solubility only begins to be affected when a critical denaturation temperature is exceeded (Fennema, 1996). Therefore, the effect of the drying temperature on the PDI was analyzed with a bi-linear model fitted with a non-pre-established breakpoint. This breakpoint represents the critical temperature at which the PDI begins to be affected. The theoretical model proposed for this relationship is:

$$PDI(\%) = \begin{cases} A & (T - T_C) \leq 0 \\ A + p \times (T - T_C), & (T - T_C) > 0 \end{cases} \quad (6)$$

where: T_C is the temperature from which the trend break; A the average *PDI* level before T_C; T the drying temperature; and p the loss in *PDI* for each increase in temperature from T_C.

The function that was used to fit this model is "nls" from the "stats" package of RStudio statistical software (version 2022.07.1), which performs a least squares fit for a nonlinear model.

The soybean seed and expeller composition and quality of the real scale drying trials were characterized through descriptive statistics (means and standard deviation (SD), and the analysis of variance and the mean comparison test of the different treatments were performed ($p < 0.05$) with the "emmens" package of the RStudio statistical software (version 2022.07.1). Figures were created with RStudio statistical software and Excel (Microsoft Office Professional Plus 2016).

Results

Laboratory scale experiments

Drying kinetics curves in thin layer and estimation of drying treatment time

The average MR values obtained for the different soybean drying air temperatures and the predicted values with the Page model are shown in Figure 4. Additionally, Table 1 shows the values of the coefficients of the Page model fitted for each drying temperature, and Table 2 shows the estimated drying times, standard deviation and confidence interval ($p < 0.05$) for all drying treatments. In general, as the drying temperature increased, the drying time to reach 11.7 % m.c. decreased (corresponding to an MR of 0.6276). For 25, 40, 55, 70 and 90 °C the drying time was 44h39, 04h41, 02h20, 01h17 and 00h46, respectively.

Effect of drying treatments on soybean protein dispersibility index

The observed PDI values of the soybean dried at different temperatures and the predicted values with the bi-linear model Eq. (6) are shown in Figure 5. The unaffected PDI level (A) was 87.4 % ($p = 2e^{-16}$), the critical temperature (Tc) at which PDI starts to decrease was 69.2 °C ($p = 2.76e^{-13}$), and the loss of PDI (%) per each °C of increase above Tc (p) was –0.56 % °C^{-1} ($p = 2.81e^{-6}$).

Real scale experiments

Drying soybean seed to different final moisture contents and effect on expeller composition

The final m.c. achieved in the three batches of soybean dried under real scale conditions were 9.1, 9.7, and 10.9 %, while the control batch had an m.c. of 16.2 %. The difference between the m.c. prescribed for each treatment and that obtained was considered acceptable for a real scale drying test. There were no differences ($p > 0.05$) in composition between the four batches of soybeans, and the average protein and oil concentrations were 37.8 %

Table 1 – Values of coefficient k and n of the Page model calculated for different drying air temperatures evaluated.

Drying air temperature (°C)	k	SE k	n	SE n
25	0.004556	0.000257	0.586260	0.007748
40	0.019478	0.000405	0.562963	0.003874
55	0.020975	0.000629	0.626865	0.006437
70	0.022015	0.000430	0.701342	0.004511
90	0.019457	0.000996	0.831666	0.012325

SE = the standard error.

Table 2 – Estimated drying times to reach the desired moisture content (11.7 %) for the different temperatures with the confidence interval of the estimate ($p < 0.05$).

Drying air temperature	t_e	SE	2.5	97.5
°C	min		——— %	———
25	2678.97	33.47	2613.38	2744.56
40	281.26	1.18	278.94	283.58
55	140.66	0.86	138.98	142.34
70	77.64	0.24	77.16	78.11
90	45.54	0.38	44.80	46.28

t_e = estimated drying time; SE = standard error.

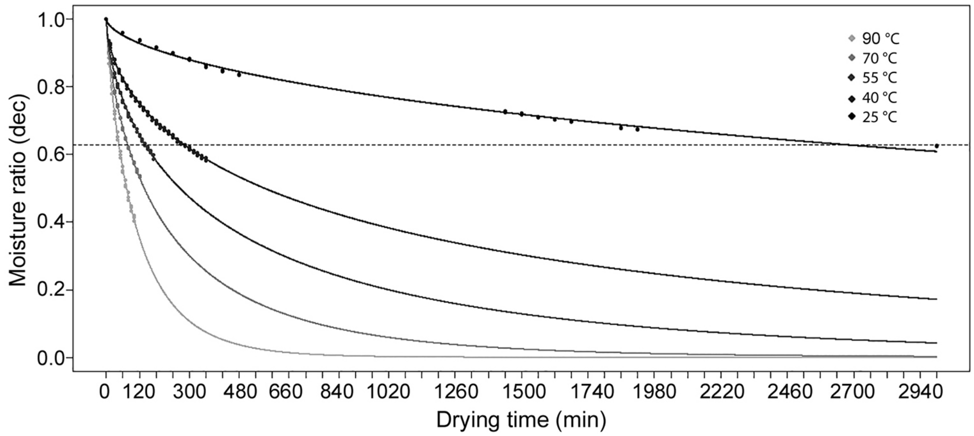

Figure 4 – Observed moisture ratio (MR) expressed as decimal (dec) and predicted values with the Page model for the different soybean drying treatments (drying time expressed in minutes). Dots represent the observed data and lines represent the fit of the Page model for each drying temperature.

(± 0.54) and 20.2 % (± 0.54), respectively. In general, processing soybean seeds at different m.cs. affected the composition of the expeller, decreasing the protein content and increasing the oil and m.c. in the expeller with increasing seed m.c. (Table 3). The expeller m.c. resulted in higher levels for soybean seed processed at 16.2 % (9.4 %), followed by 10.9 % (4.38 %) and then by 9.7-9.1 % (4.1 %). The protein content was lowest for 16.2 % m.c. (38.6 %), greater for 10.9 m.c. (41.3 %), and was the highest for 9.1 % m.c. (43.4 %). The oil content was the highest for 16.2 % m.c. (14.5 %), less for 10.9 % m.c. (8.6 %), and was the lowest for 9.7 % or lower m.c. (7.2 %).

Effect of drying treatment on oil extraction efficiency

In general, the drying treatment affected the OEE of the extruding-expelling process, showing a clear trend of increases in the OEE with decreases in the m.c. of the processed seed (Table 3). Processing the soybean seed without drying (16.2 % m.c.) resulted in an OEE of only 25.5 %, while reducing the soybean m.c. to 10.9 % increased the OEE to 58 %, and to 64.9 % when m.c. was further reduced to 9.7 %. A second order polynomic model was fitted to the data (R^2 of 0.9991) (Figure 6).

Effect of drying treatment on individual seed moisture

The data from the real scale drying treatment at 115 °C to different final m.c. are shown in Table 4. The individual seed m.c. of each treatment was always lower than the moisture measured in the bulk, and there was a clear positive relationship between both forms of moisture measurement. The control sample (16.2 % m.c.) had an SD of 0.66 implying that there is natural variability in individual seed m.c. (not caused by the drying treatment). The dispersion in the individual seed moisture values increased with the intensity of the drying treatment. Accordingly, the SD increased to 0.79, 0.84 and 1.25 for the drying treatments of 10.9, 9.7 and 9.1 % final m.c., respectively. A similar trend could be observed for the other dispersion parameters evaluated (coefficient of variation (CV) and range).

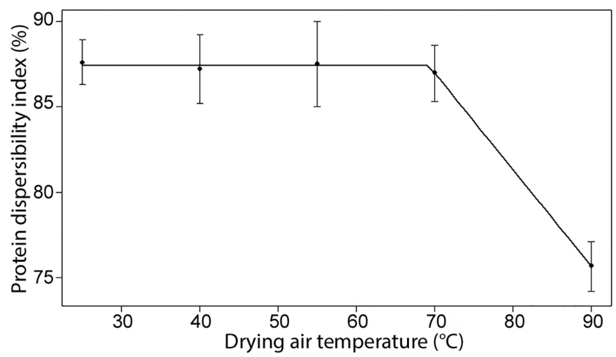

Figure 5 – Effect of drying air temperature on the protein dispersibility index (PDI) of soybeans samples. Dots are the average PDI value of the experiment (error bars are ± standard deviation), and line is the prediction with the bi-lineal model.

Table 3 – Composition of soybean expeller and oil extraction efficiency obtained from seeds dried to different final moisture contents in a real scale dryer at a constant air temperature of 115 °C.

SB m.c.	Drying time	SBE m.c.	SBE PC	SBE OC	OEE
% d.b.		———— % d.b. ————			%
9.1	04h15	3.9 ± 0.28[a]	43.4 ± 0.37[a]	6.9 ± 0.32[a]	66.2 ± 1.24[a]
9.7	04h00	4.1 ± 0.60[a]	41.4 ± 1.38[b]	7.2 ± 0.92[a]	64.9 ± 4.71[a]
10.1	02h15	4.8 ± 0.22[b]	41.3 ± 0.14[b]	8.6 ± 0.14[b]	58.0 ± 0.79[b]
16.2	Control	9.4 ± 0.46[c]	38.6 ± 0.25[c]	14.5 ± 0.23[c]	25.5 ± 1.73[c]

SB = soybean; SBE = soybean expeller; m.c. = moisture content expressed in dry basis; PC = protein content; OC = oil content; OEE = oil extraction efficiency and ± value = standard deviation. Within a column, means with different letters are different ($p < 0.05$).

The effect of real scale drying at different temperatures on individual seed m.c., SD, CV and range are shown in Table 5. Similar to what had been observed in Table 4, dispersion in the individual seed moisture values increased with the intensity of the drying treatment. The SD of the treatment at 80 °C was 0.91 and increased to 1.46 for the drying treatments at 115 °C and a similar trend can be observed for the CV and range.

Effect of drying treatment at different temperatures on soybean protein dispersibility index

The PDI of the soybean samples before drying was substantially different for the two treatments (83.7 and 73.2 % for drying treatment at 80 and 115 °C, respectively) (Table 6), probably because the batches of seeds were of different origins. Consequently, the drying effect was analyzed separately without comparing treatments. The real scale drying process did not substantially affect the PDI at 80 °C (PDI around 83 %), while at 115 °C a reduction of 2.1 percentage points was observed (from 73.2 % to 71.1 %). There was a correspondence between the drying air temperature and the seed temperature. When the drying air temperature was 80 °C, the seed temperature reached 52 °C, and when the drying air temperature was 115 °C, the seed reached 57 °C.

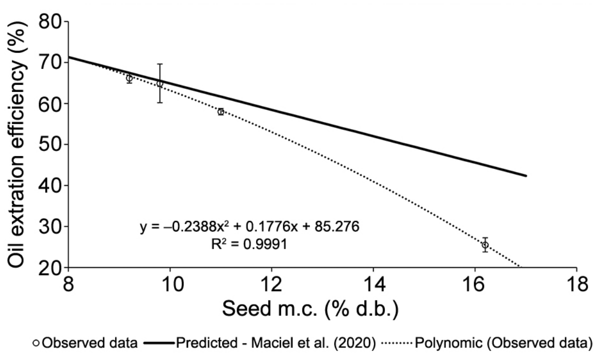

Figure 6 – Oil extraction efficiency as function of soybean seed moisture content. Seed m.c. (% d.b.) = seed moisture content expressed as percentage of dry basis. Circles are average observed values from the current study (error bars are ± SD), dashed black line is the polynomic fitting of observed data, and black solid line is predicted values from Maciel et al. (2020).

Discussion

Effect of drying treatment on oil extraction efficiency

Viscoelastic properties of soybean seeds are affected by temperature and m.c., the latter being the most important (Floyd et al., 2013). As seed m.c. increases, the viscosity of the material decreases and so does the conversion ratio of mechanical energy into heat and mechanical friction, thereby hindering the rupture of the oleosomes during the extrusion process and the subsequent extraction of oil (Chen et al., 2010). In our previous work (Maciel et al., 2020), a prediction model for OEE was developed as a function of seed moisture and oil contents. The model was fed with information of seed and expeller samples collected from many different extruding-expelling plants (with different equipment and setting). In the current study, the extruder and press used and their settings were the same for all the treatments; thus, the differences found in the OEE can be exclusively attributed to the condition of the seed. The predicted OEE with the linear model of Maciel et al. (2020) (considering a seed oil content of 20.1 %) and the data from this work with the polynomial model are shown in Figure 6. The OEE increased as soybean seed was processed at lower m.c. The former linear model predicted similar

Table 4 – Individual seed moisture content of soybean subjected to different drying treatments (presented values are average of three replicates).

Drying air temperature	m.c.[1]	Individual seed m.c.	CV	Individual seed m.c. range
°C	% d.b.	% d.b.	%	% d.b.
	9.1	8.5 ± 1.25[a]	14.8	5.1 – 13.7
115	9.7	8.8 ± 0.84[b]	9.6	6.7 – 13.8
	10.9	10.5 ± 0.79[c]	7.5	7.9 – 13.5
Control	16.2	15.8 ± 0.66[d]	4.2	13.6 – 18.2

[1]The moisture content measured as bulk, ± value = standard deviation and CV = coefficient of variation. Within a column means with different letters are different ($p < 0.05$).

Table 5 – Individual soybean seed moisture content dried at different temperatures under real scale conditions.

Drying air temperature	m.c.[1]	Individual seed m.c.	CV	Range
°C	% d.b.	% d.b.	%	% d.b.
80	9.4	10.3 ± 0.91	8.8	8.7 – 12.4
115	8.8	10.3 ± 1.46	14.1	7.4 – 13.7

[1]The moisture content measured as bulk, ± value = standard deviation and CV = coefficient of variation.

Table 6 – Protein dispersibility index in soybean seeds before and after drying at real scale experiments.

Drying condition	m.c. (% d.b.)		PDI (%)	
Drying air temperature (°C)/seed temperature (°C)/ drying time	Initial	Final	Initial	Final
80 / 52 / 04h40	13.9 ± 0.12	9.4 ± 0.39	83.7 ± 1.81[a]	82.9 ± 2.06[a]
115 / 57 / 04h00	14.5 ± 0.30	8.8 ± 0.45	73.2 ± 0.70[A]	71.1 ± 0.19[B]

PDI = the protein dispersibility index and ± value = standard deviation. Within rows means with different letters are different ($p < 0.05$). Lowercase letter are for 80 °C of drying air temperature and uppercase letters for 115 °C of drying air temperature.

results for the polynomial model, not only for m.c. below 10 %, but for higher m.c. values where the linear model had overestimated efficiency.

Based on the current and previous work results, reducing seed m.c. from 15.6 % (trading soybean seed m.c.) to 10 % would yield an OEE of about 65 %, implying an increase in OEE from 20 to 40 percentage points. Processing soybean below 10 % m.c. results in a lower marginal increase in OEE (OEE did not increase when m.c. was reduced from 9.7 % to 9.2 % - Table 3). Additionally, energy consumption for drying the seed below 10 % m.c. would substantially increase, and the throughput of the dryer decrease (De La Torre et al., 2014). Therefore, the data suggest that drying soybean below 10 % m.c. for processing is not convenient. However, the optimum m.c. for soybean seed processing depends on the relative prices of the energy demanded for drying and the oil obtained. Under a scenario of a low price for energy and a high oil price, it might be convenient to dry the seed below 10 % and vice-versa.

Effect of drying treatments on protein dispersibility index

The protein fractions 7S and 11S globulin, in interaction with the residual oil, are the main factors responsible for the functional properties of soy by-products (Heywood et al., 2002; Kinsella, 1979). These fractions are very sensitive to denaturing agents such as extreme pH, solvents, salts, and, in particular, high temperature treatments (Fennema, 1996). A number of authors have studied the effect of thermal treatments (such as drying and extruding) on the secondary structure of soy proteins (Wang et al., 2014; Zheng et al., 2020). The high temperatures (75 to 94 °C) caused protein denaturation with the consequent loss of biological activity and reduction in solubility (García et al. 1997), and the PDI in soybean meal was lower than 15 % when exposed to drying temperatures higher than 80 °C (Sangkram and Noomhorm, 2002).

Other authors have also explored the effect of temperature on soy protein quality, although not during seed drying. The effects of roasting temperature (115 °C, 130 °C and 145 °C), roasting time (5, 10 and 15 min) and particle size of soybean (whole, coarse and fine) on PDI were examined by Rafiee-Yarandi et al. (2016). The effect of extrusion temperatures (from 77 to 121 °C and from 110 to 164 °C, respectively) on the PDI was evaluated by Zhu et al. (1996) and Palić et al. (2011). Finally, different heating techniques (i.e., extrusion, fluidized bed, spouted bed and infrared radiation) have been investigated by Wiriyaumpaiwong et al. (2004) regarding moisture reduction, urease inactivation and protein solubility. However, in these studies, the effect of drying on the PDI of soybean seed was not evaluated. Therefore, the existing information is not appropriate for predicting the effect of seed drying on the PDI of soy protein. This is important since the PDI is the most used indicator by the industry to assess protein quality.

The results of the thin layer experiments agreed with those reported by Rafiee et al. (2009) for similar drying conditions. They allowed for estimating with a high degree of accuracy the drying time required to obtain the final target m.c. of 11.7 % for the different drying temperatures in the PDI experiments (12.0 % ± 1.23, 12.4 % ± 0.31, 11.9 % ± 0.2, 11.3 % ± 0.18 and 11.6 % ± 0.28 for drying temperatures of 25, 40, 55, 70 and 90 °C, respectively). According to our results (Figure 5), drying could be accomplished without compromising PDI up to a temperature of 69 °C in the drying air. The effect of drying temperatures of 60, 80 and 100 °C was evaluated by Santos et al. (2015), who concluded that the temperature that limited PDI damage was 60 °C. However, since they did not experience intermediate temperatures, it is possible that the critical temperature was somewhere between 60 and 80 °C. Consequently, based on our results and others in the literature, limiting the exposure of soybeans to drying air temperatures slightly below 70 °C could be effective for preventing PDI reduction.

The drying systems typically used for soybean seeds are high capacity (20-90 t h^{-1}) column or rack dryers operated at temperatures between 90 and 120 °C (Juan et al., 2015). Drying of soybean on a large scale had not been studied to the same extent as other crops (e.g., rice, corn or wheat). A number of works have studied the inactivation of anti-nutritional factors caused by drying, mostly in fluidized bed drying systems (Dondee et al., 2011; Moschini et al., 2013; Soponronnarit et al., 2001; Wiriyaumpaiwong et al., 2003), other studies have evaluated the increase in cracking and breakage of the seed under different drying conditions (Coradi et al., 2020; Hartmann Filho et al., 2016b; Wiriyaumpaiwong et al., 2003), and other authors have evaluated the effect of different types of thermal treatments on the nutritional and functional quality of germinated soybean meal (Agrahar-Murugkar and Jha, 2010). Several authors have evaluated the effect of drying on soybean seed quality from the agronomic point of view (germination, vigor, and fissures) (Anand et al., 2021; Barrozo et al., 2006; Brito et al., 2021; Hartmann Filho et al., 2016a; Jaques et al., 2022; Pfeifer et al., 2010; Souza et al., 2021). In the present study, the drying air temperatures of the real scale experiment (80 and 115 °C) were above the critical temperature for PDI damage obtained through the thin layer experiment (69 °C). However, an air temperature of 80 °C did not affect PDI and increasing the air temperature to 115 °C resulted in only a slight reduction (2.1 percentage points). This apparent contradiction can be explained by the intrinsic characteristics of both drying experiments (thin layer and full scale).

In the thin layer drying experiments, all the individual seeds are exposed to the same drying condition. Thus, the evolution of seed temperature and m.c. is also uniform among all seeds (although seeds with smaller sizes might experience a more intense drying treatment) (Giner et al., 1994; Khatchatourian, 2012). On the contrary, in a real scale drying experiment, there is a simultaneous change in the seed m.c. and temperature, and relative air humidity and temperature. These changes vary with the type of drying method implemented and the location of the seed in the drying bed (Thompson et al., 1968). Consequently, a few millimeters into the drying bed (e.g., 10 mm), the condition of the drying air had already changed (temperature decreases and relative humidity increases), affected by the heat and mass exchange with the outermost seed layer (Olesen, 1987). As a result, the average seed temperature at the end of drying was 52 and 57 °C for drying air conditions of 80 and 115 °C, respectively, below the critical temperature of 69 °C. This could be the reason why damage to the PDI of the real scale experiment was substantially lower than that of the thin layer experiment at similar temperatures.

In addition to the air temperature and the initial and final m.c., some additional factors might influence a real scale drying process, such as: initial seed temperature, air flow, grain flow and air flow relative directions (cross flow, concurrent flow, counter flow or mixed flow), and particular design characteristics of the dryer (e.g., thickness of the column in a cross flow dryer) (Brooker et al., 1992). Rack type dryers, such as the one used in the present study, were of mixed flow. This implies that the seeds, in their path down through the drying chamber, encounter the drying air from different directions (cross flow, counter flow and concurrent flow), causing a reasonably uniform drying treatment among all the seeds. Nevertheless, a certain level of variability in the drying treatment of individual seeds occurs even in mixed flow dryers. Evidence of this can be found in the variability of the individual seed m.c., which increased with the intensity of the drying treatment. For instance, the CV of the individual seed m.c. increased from 7.5 % to 14.8 % when the seeds were dried to a lower final m.c. (10.9 % and 9.1 %, respectively) at the same temperature (Table 4). Similarly, the CV of the individual seed m.c. also increased from 8.8 % to 14.1 % when the seeds were dried to the same final m.c. at higher temperatures (80 and 115 °C, respectively) (Table 5). A higher CV indicates that certain individual kernels had a significantly lower m.c. than the average (i.e. received a more severe heat treatment). This suggests that as the intensity of the drying treatment increases, there is a higher likelihood of some grains exceeding the thermal threshold that leads to damage of the protein's functional properties.

The drying air temperatures evaluated in the present study are representative for the grain dryers operated in Argentina (Abadia and Bartosik, 2013). Based on our results, a drying air temperature of 80 °C would limit the damage in the PDI of the soybean seed in mixed flow dryers such as the one considered in the current study. For cross flow and counter flow dryers, however, limiting the drying air temperature to 65 °C is a suitable general recommendation in order to maximize the throughput of the dryer while preventing PDI damage to the soybean seed (assuming a drying condition similar to that explored in this study, from 15 % initial m.c. to 9 % final m.c.). This is because in counter flow and cross flow dryers, a portion of the seed reaches the drying air temperature (Thompson et al., 1968). A private study should be carried out to precisely answer what temperature above 65 °C a given dryer can be operated without damaging the PDI, considering the technical characteristics of the machine and its working conditions.

Conclusion

The oil extraction efficiency through the extruding-expelling method under real scale conditions increased with the decrease in the moisture content of the processed seed. Soybean processed at 10 % moisture content resulted in 65 % oil extraction efficiency. Further decreases in the processing moisture content resulted in a lower marginal increase in oil extraction efficiency.

The functionality of the soy proteins began to be affected at drying air temperatures above 69 °C based on thin layer drying experiments. However, the protein dispersibility index was not affected at 80 °C under real scale drying conditions.

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Authors' Contributions

Conceptualization: Maciel, G. **Data curation:** Maciel, G. **Formal analysis:** Maciel, G.; Bartosik, R.E. **Funding acquisition:** Bartosik, R.E. **Investigation:** Maciel, G.; Bartosik, R.E. **Methodology:** Maciel, G.; Wagner, J.R.; Bartosik, R.E. **Project administration:** Bartosik, R.E. **Resources:** Bartosik, R.E. **Software:** Maciel, G. **Validation:** Maciel, G. **Supervision:** Bartosik, R.E.; Wagner, J.R. **Writing-original draft:** Maciel, G.; Bartosik, R.E.; Wagner, J.R. **Writing-review & editing:** Bartosik, R.E.; Maciel, G.; Wagner, J.R.

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