Effect of oil content of sunflower seeds on the equilibrium moisture relationship and the safe storage condition

Gisele Maciel[1, 2], Diego de la Torre[3], Natalia Izquierdo[2,4],
Gabriela Cendoya[2], Ricardo Bartosik[*3,4]

(1. *Comisión de Investigaciones Científicas (CIC) of Buenos Aires Province, Argentina;*
2. *Facultad de Ciencias Agrarias, Universidad Nacional de Mar del Plata, Balcarce, Buenos Aires Province, Argentina;*
3. *Instituto Nacional de Tecnología Agropecuaria (INTA), Balcarce, Buenos Aires Province, Argentina;*
4. *Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina.*)

Abstract: The adsorption and desorption equilibrium moisture content/equilibrium relative humidity relationships of sunflower seeds with four different oil contents (35.7%, 44.6%, 48.6% and 52.7%) were obtained for temperatures of 8, 15, 25 and 35 ℃ and moisture contents of 6.0%, 8.5%, 11.0%, 13.5%, 16.0% and 18.5%.The goodness of fit of four equilibrium moisture content/equilibrium relative humidity models (Modified Henderson, Modified Chung-Pfost, Modified Halsey and Modified Oswin) were evaluated for each oil content. The Modified Halsey model was the best for predicting equilibrium moisture content/equilibrium relative humidity relationships based on the Akaike Information Criterion, the Bayesian Information Criterion and estimated residual standard deviation. The optimized parameters for the Modified Halsey model are presented for each oil content. Results indicate that the oil content substantially affected the equilibrium moisture content/equilibrium relative humidity relationship. As the oil content increases, the equilibrium relative humidity also increases for the same moisture content, meaning that to use the right set of parameters according to the oil content of the hybrids is critical for sunflower drying, conditioning and storing. The safe storage moisture content varied from 12.0% to 7.6% for seeds with oil contents from 35.7% to 52.7%, implying that a revision of the sunflower market moisture content might be required for safe storage of hybrids with high oil content.

Keywords: Isotherms models, parameters, sunflower, oil content, safe storage, moisture content.

Citation: Maciel, G., D. de la Torre, N. Izquierdo, G. Cendoya and R. Bartosik. 2015. Effect of oil content of sunflower seeds on the equilibrium moisture relationship and the safe storage condition. Agric Eng Int: CIGR Journal, 17(2):248-258.

1 Introduction

Sunflower (*Helianthus annuus L.*) is one of the most important oilseeds in the world. The oil content of the sunflower seed depends mainly on the environmental conditions during the grain filling period, crop conditions, planting location, planting dates, foliar diseases, and the genetic potential of the variety (Izquierdo et al., 2008; Izquierdo and Aguirrezábal, 2010). In Argentina, oil content of sunflower seeds increased substantially in the last years, and could vary from 39% to 55% (ASAGIR, 2010).

The equilibrium relative humidity (e.r.h.) determines the maximum interstitial air relative humidity (r.h.) that can be reached given certain moisture content (m.c.)of the stored grain. On the other hand, the equilibrium moisture content (e.m.c.) denotes the m.c. at which a product reaches the equilibrium when it is exposed to a certain temperature and r.h.

The e.m.c. depends on temperature; r.h. of environment; characteristics of materials (variety); treatment of the samples (drying temperature, drying and rewetting methods); and composition of material (Pixton and Warburton, 1971a; Pixton and Warburton, 1971b; Chen and Morey, 1989a; Jayas and Mazza, 1991;

Received date: 2015-03-13 **Accepted date:** 2015-05-01
***Corresponding author: Ricardo Bartosik,** Researcher INTA-CONICET. Address: ruta 226 km 73,5, Balcarce (7620), pcia. Buenos Aires, Argentina. Phone number: +54-2266-439100. E-mail: bartosik.ricardo@inta.gob.ar

Brookeret al., 1992; Chen, 2000; Bartosik, 2003; Giner and Gely, 2005; Choi et al., 2010).

Several models have been developed to describe the e.m.c. relationship of grains and oilseeds. Four of the most widely used models are: Modified Henderson (1) (Thompson et al., 1968), Modified Chung-Pfost(2) (Pfost et al., 1976), Modified Halsey (3) (Iglesias and Chirife, 1976a; Iglesias and Chirife, 1976b) and Modified Oswin (4) (Chen, 1988). The ASAE Standard D245.6 (2007) provides a description of the models and the set of parameters (A, B, and C) for the different materials.

The Modified Henderson equation:

$$r.h. = 1 - \exp\left[-A(T + C)(m.c.)^{B}\right] \quad (1)$$

The Modified Chung-Pfostequation:

$$r.h. = \exp\left[-\frac{A}{T+C}\exp(-B*m.c.)\right] \quad (2)$$

The Modified Halsey equation:

$$r.h. = \exp\left[-\frac{\exp(A+B*T)}{(m.c.)^{C}}\right] \quad (3)$$

The Modified Oswinequation:

$$r.h. = \left[\left(\frac{A+B*T}{m.c.}\right)^{C}+1\right]^{-1} \quad (4)$$

Where, *r.h.* is relative humidity (decimal),*T* is temperature (℃), *A*, *B* and *C* are parameter constants of product and *m.c.* is moisture content (%, w.b.).

Reliable e.m.c. models and parameters are critical for the study of grain drying, conditioning and storing processes (Bartosik, 2003). For instance, the performance of aeration controllers for conditioning sunflower seeds to a specific m.c. depends on using the right models and the specific set of parameters. The safe storage moisture content (s.s.m.c.) is the m.c. at which mold cannot grow and damage the seed, and it is determined by an e.r.h. of the interstitial air lower than 70% (Bartosik, 2003; Giner and Gely, 2005). Thus, proper e.m.c. models and parameters are also important for determining s.s.m.c.

Material composition, and in particular oil content, affects the e.m.c. (Chapman and Robertson, 1987; Pixton and Warburton, 1971b; Mazza and Jayas, 1991;Giner and Gely, 2005). This is a critical point since it was already mentioned that sunflower seeds could vary in more than 15% points in oil content (39 to 55%). In previous works e.m.c. models were selected for sunflower seeds (Santalla and Mascheroni, 2003; Giner and Gely, 2005), but the effect of oil content was not previously explored. Thus, the present work evaluates the effect of the oil content of sunflower seeds on the performance of the most typical e.m.c. models and its consequences in the s.s.m.c. The specific objectives of this study were: 1) to determine which of the four proposed empirical models is the best for predicting the adsorption and desorption experimental values of e.r.h. of commercial sunflower hybrid Agrobel 967 with different oil contents; 2) to obtain the parameters of the best empirical model; and 3) to determine the effect of oil content on the e.m.c./e.r.h. relationship and the safe storage moisture content.

2 Materials and methods

2.1 Sample processing

Sunflower seeds (commercial hybrid Agrobel 967) cultivated during the 2009-2010 growing seasons at Balcarce Research Station, South East of Buenos Aires province, Argentina, were used. Isolated sowing was performed to avoid contamination with other hybrids and assure homogeneity. Four plots of the same hybrid were exposed to different levels of defoliation, which caused different oil contents in the seed: 35.7%, 44.6%, 48.6and 52.7%. The oil content of the seeds was determined by Nuclear Magnetic Resonance (NMR, Spinlock, Córdoba, Argentina) according to Robertson and Morrison (1979). The samples were dried at 60℃ to constant weight and the measuring temperature was of 23℃.

From each set of seeds, two sub samples were exposed to two treatments: a) desorption; and b) adsorption. All m.c. determinations were carried out by the oven method (3 hat 130℃) by triplicate (ASAE Standard S352.2, 2003), and the average value was used.

The set of samples for the desorption treatments were rewetted to 20-21% m.c.by adding distilled water. The samples were homogenized by hand mixing, and placed in double sealed bag to store in a refrigerator at 4℃ for a week for moisture homogenization. To achieve maximum homogeneity in the moisture distribution among seeds the samples were mixed by hand once a day for a period of a week. After that, the samples were placed 2 weeks in a freezer (-17℃) to further stabilize the m.c. and to prevent fungal growth (Bartosik and Maier, 2007). At the end of stabilization period the desorption samples were divided into 6 sub-samples. The sub-samples were dried exposing them at laboratory air conditions(23℃ and 60% r.h., approximately) until the following m.c. swere achieved: 6.0%, 8.5%, 11.0%, 13.5%; 16.0% and 18.5%. Finally, sub-samples were stored again in a freezer in a double sealed bag to avoid variations in the m.c. until beginning of experiment.

The set of samples for the adsorption treatment were first dried to 4.0%m.c.by exposing them to an air condition of approximately 30℃ and 20% r.h. Once dried, the sample was divided into 6 sub-samples and rewetted to 6.0%, 8.5%, 11.0%, 13.5%; 16.0% and 18.5% by adding the precise amount of distilled water. The obtained rewetted sub-samples were moisture homogenized and preserved in the same way as described for the desorption treatment.

2.2 Experimental procedure to determine the e.m.c./e.r.h. relationship of sunflower

The experimental procedure followed to determine the e.m.c./e.r.h. relationship of sunflower seed was adapted from the method described by Chen and Morey (1989a) and Bartosik and Maier (2007). Glass jars of 370ml capacity were filled with sunflower seeds with different m.c.́sof each treatment and hermetically sealed with a rubber cap. A temperature and r.h. sensor (VaisalaHMD60U/Y-M210276en-A) was previously inserted through the rubber cap into glass jar to accurately measure the temperature and r.h. of the interstitial air. The sensor was connected to data logger (HOBO H8 Outdoor, H08-008-04), which recorded interstitial air conditions every 10 min for a week. The sealed jars, with the grain sample and the temperature and r.h. sensor, were placed in a temperature chamber (ING.MAS, Rosario, Argentina). The temperature chamber was programmed in two phases within a period of 6 days: 48 h for the stabilization phase, where temperature gradually increased from 8℃ to 35℃; and the measurement phase, where temperature decreased in successive steps of 24 h each from 35℃ to 25℃, then to 15℃ and finally to 8℃. The data collected during the first 23 h of each temperature set point was discarded (considered as stabilization period) and only the data collected during the last hour before changing the temperature set point was recorded as equilibrium temperature and r.h.

Grain m.c. was measured before and after the e.m.c. experiment by oven method in triplicate (ASAE Standards S352.2, 2003).

For each of the 6 m.c.́s, 4 replicates were considered (24 sub-samples). The temperature chamber was equipped with 8 sensors, so the chamber was ran 3 times to complete the experiment.

For each one of the 6 m.c.́s a letter was randomly assigned (A, B, C, D, E and F), and the 8 sensors, identified as S1, S2, S3, S4, S5, S6, S7 and S8, were allocated among temperature chamber runs (1 to 3) and treatments (m.c.́s A to F) as shown in Table 1 to conform an unbalanced incomplete block with a statistical lahnda of 1.6.

Table 1 Sensor allocation (S1 to S8) according to the different moisture content samples (A to F) for each temperature chamber run (1 to 3)

Temperaturechamberrun	Sensor							
	S 1	S 2	S 3	S 4	S 5	S 6	S 7	S 8
1 ºrun	A	A	B	B	C	E	F	D
2 ºrun	B	E	A	D	F	C	E	C
3 ºrun	C	D	F	E	D	A	B	F

2.3 Statistical analysis of the e.m.c./e.r.h. data

The empirical models of Modified Henderson, Modified Chung-Pfost, Modified Halsey and Modified Oswin (ASAE D245.6, 2007) were evaluated to determine which one is the best in predicting the e.r.h. of sunflower hybrid with different oil contents, within a broad range of temperatures and m.c. ́s.

The non-linear mixed effect package (nlme) of the “R” program (R Development Core Team, 2012) was used to estimate the equations parameters. The selection of the best model was according to the following statistics (Phinheiro et al., 2009):

Akaike information criterion (AIC): is a measure of the relative quality of a statistical model for a given set of data. AIC considers the trade-off between the goodness of fit of the model and the complexity of the model. The best model is that with the lowest value of AIC (Akaike, 1974), and it is defined by the following equation:

$$AIC = (-2) * \log Lik + 2K \quad (5)$$

Where, K is the number of independently adjusted parameters and Lik is the value of the likelihood function at the actual estimated values of the parameters (logLik makes reference to the logarithm of that value).

Bayesian information criterion (BIC): is a criterion for model selection among a finite set of models (Schwars, 1978; Posada and Noguera, 2007). The model with lowest value of BIC was considered the best for explaining data with the minimum number of parameters. BIC is defined by the following equation:

$$BIC = (-2) * \log Lik + \log N * K \quad (6)$$

Where, N is the number of data points, K is the number of independently adjusted parameters and Lik is the value of the likelihood function at the actual estimated values of the parameters.

Estimated residual standard deviation (Re): the model with lowest value of Re was considered the best for explaining data.

Also, two standard quantitative methods, mean relative deviation (MRD) and standard error (SE),were used to compare the selected model with other models from the literature (Chen and Morey, 1989b; Mazza and Jayas, 1991; Chen, 2000; Bartosik and Maier, 2007).

MRD was calculated as:

$$MRD = \frac{100}{N} * \sum \frac{|Y-Y'|}{Y} \quad (7)$$

SE was calculated as:

$$SE = \sqrt{\frac{\sum (Y-Y')^2}{df}} \quad (8)$$

Where, Y is the measured value, Y' is the value predicted by the model and df is the degrees of freedom of the model error.

3 Results and discussion

3.1 e.m.c./e.r.h. experimental data

Tables2 and 3 show the e.m.c./e.r.h. data of the adsorption and desorption experiments for the four oil contents.

Table 2 Equilibrium temperature, relative humidity and moisture content data for the desorption experiments for sunflower seeds with four oil contents (average of 4 replicates)

35.7% Oil			44.6% Oil			48.6% Oil			52.7% Oil		
Temp. (℃)	e.r.h. (%)	e.m.c. (% w.b.)	Temp. (℃)	e.r.h. (%)	e.m.c. (% w.b.)	Temp. (℃)	e.r.h. (%)	e.m.c. (% w.b.)	Temp. (℃)	e.r.h. (%)	e.m.c. (% w.b.)
12.3	42.3	7.5	11.3	41.9	6.9	12.1	47.7	6.2	11.3	49.2	6.0
12.3	61.2	10.1	12.2	64.5	9.5	11.0	68.5	8.3	11.4	66.8	7.7
13.2	74.3	14.3	11.8	77.0	13.8	12.1	78.1	11.2	11.3	77.3	9.9
11.4	77.1	17.6	11.9	79.4	16.5	11.4	79.6	14.3	11.6	82.6	13.0
12.6	77.0	19.8	11.9	79.6	17.8	12.5	80.2	16.4	11.5	80.9	15.8
13.4	77.1	21.0	11.2	78.9	19.7	11.5	83.4	18.2	11.0	82.1	18.5
19.3	44.0	7.5	19.6	44.3	6.9	19.7	49.2	6.2	20.5	52.3	6.0
19.3	61.2	10.1	20.1	65.0	9.5	19.3	69.5	8.3	20.1	67.4	7.7
18.8	74.0	14.3	19.6	77.5	13.8	19.8	78.6	11.2	19.9	77.6	9.9
18.7	77.5	17.6	20.1	79.7	16.5	19.8	81.0	14.3	20.1	83.2	13.0
18.9	77.7	19.8	18.6	79.9	17.8	20.3	81.6	16.4	20.2	82.7	15.8
19.0	77.5	21.0	20.2	80.5	19.7	19.3	83.7	18.2	19.9	82.4	18.5
25.4	43.9	7.5	24.5	43.2	6.9	30.9	50.1	6.2	24.3	50.7	6.0
25.5	60.7	10.1	24.7	64.6	9.5	30.7	69.6	8.3	25.1	67.5	7.7
24.8	73.5	14.3	25.0	77.0	13.8	31.2	79.7	11.2	24.9	77.1	9.9
24.8	77.5	17.6	24.9	79.9	16.5	31.0	83.2	14.3	25.2	82.8	13.0
24.7	77.5	19.8	25.6	80.2	17.8	31.3	84.2	16.4	25.0	82.4	15.8
25.0	77.9	21.0	24.0	80.8	19.7	30.6	84.6	18.2	24.4	83.3	18.5
35.6	46.0	7.5	35.3	44.9	6.9	35.3	49.6	6.2	34.5	51.5	6.0
35.5	61.7	10.1	35.3	64.9	9.5	34.9	68.1	8.3	34.6	67.3	7.7
35.4	74.3	14.3	35.4	77.6	13.8	35.5	77.9	11.2	34.7	77.1	9.9
35.0	78.9	17.6	35.5	80.7	16.5	35.1	82.1	14.3	34.4	83.3	13.0
35.6	79.3	19.8	35.9	81.5	17.8	35.7	83.6	16.4	34.9	83.9	15.8
35.6	79.3	21.0	35.4	82.7	19.7	35.4	85.0	18.2	34.6	84.9	18.5

Table 3 Equilibrium temperature, relative humidity and moisture content data for the adsorption experiments for sunflower seeds with four oil contents (average of 4 replicates)

35.7% Oil			44.6% Oil			48.6% Oil			52.7% Oil		
Temp. (℃)	e.r.h. (%)	e.m.c. (% w.b.)	Temp. (℃)	e.r.h. (%)	e.m.c. (% w.b.)	Temp. (℃)	e.r.h. (%)	e.m.c. (% w.b.)	Temp. (℃)	e.r.h. (%)	e.m.c. (% w.b.)
11.4	32.3	5.8	13.4	47.3	7.3	9.9	51.7	6.6	11.6	46.9	5.7
11.7	53.4	8.6	12.9	63.1	9.2	9.8	68.3	8.5	11.9	69.7	8.0
12.1	65.6	10.8	13.0	74.4	12.2	10.0	79.1	11.2	11.6	77.8	10.8
12.2	72.1	12.6	12.6	77.2	14.8	9.8	78.5	13.5	11.4	80.6	12.8
12.4	77.4	15.3	13.2	87.0	18.4	10.1	80.3	15.2	11.7	84.2	15.5
13.8	77.1	17.8	12.7	79.2	20.4	9.9	79.6	18.5	12.0	81.8	18.1
18.5	33.7	5.8	19.9	48.9	7.3	19.0	52.8	6.6	19.3	47.9	5.7
18.7	53.2	8.6	19.5	62.9	9.2	19.6	68.5	8.5	19.4	69.6	8.0
19.2	65.7	10.8	19.9	74.7	12.2	19.7	78.7	11.2	19.3	78.6	10.8
18.5	71.7	12.6	19.6	78.1	14.8	19.5	79.3	13.5	19.3	81.5	12.8
18.2	77.3	15.3	20.0	84.3	18.4	19.7	81.1	15.2	19.4	84.1	15.5
19.2	76.9	17.8	18.0	79.4	20.4	19.2	81.1	18.5	19.6	82.5	18.1
25.7	34.0	5.8	24.4	47.3	7.3	31.6	54.5	6.6	25.4	49.1	5.7
26.0	53.7	8.6	24.6	62.3	9.2	32.0	68.8	8.5	25.7	70.2	8.0
26.2	64.9	10.8	24.9	73.5	12.2	31.8	79.0	11.2	25.4	77.4	10.8
26.0	71.5	12.6	24.6	77.7	14.8	32.2	80.9	13.5	24.8	81.1	12.8
25.9	76.2	15.3	24.7	84.2	18.4	32.0	82.5	15.2	24.7	84.4	15.5
26.3	77.2	17.8	24.8	78.8	20.4	31.9	83.7	18.5	25.1	82.8	18.1
35.5	35.6	5.8	34.8	47.8	7.3	34.5	53.5	6.6	34.5	49.7	5.7
35.5	54.8	8.6	34.9	63.1	9.2	34.6	69.1	8.5	34.8	70.3	8.0
36.0	65.4	10.8	35.3	73.5	12.2	35.1	78.8	11.2	34.6	77.7	10.8
35.6	72.1	12.6	35.2	78.4	14.8	35.1	81.0	13.5	34.3	81.4	12.8
35.5	76.5	15.3	35.1	83.4	18.4	35.2	83.6	15.2	34.2	84.9	15.5
35.9	77.9	17.8	35.7	81.7	20.4	34.6	84.3	18.5	34.4	84.5	18.1

3.2 Model selection

Table 4shows the AIC and the BIC statistics and Re related to the goodness of fit of the foure.m.c./e.r.h. models for the four oil contents.

According to AIC and BIC statistics and the Re the model with the best fit was the Modified Halsey, followed by the Modified Oswin. This was in agreement with the data reported by Mazza and Jayas (1991), Giner and Gely (2005), and Santalla and Mascheroni (2003),confirming that the Modified Halsey model is a good model for high oil content seeds.

Table 4 Akaike information criterion, Bayesian information criterion and estimated residual standard deviation for the four evaluated models and four oil contents (numbers in bolt remark the best model for each selection criterion)

EMC Model	Oil content			
	35.7%	44,6%	48,6%	52.7%
Akaike information criterion (AIC)				
Modified Henderson	-660.7819	-888.542	-829.7472	-915.9378
Modified Chung-Pfost	-853.549	-880.5399	-811.9999	-562.091
Modified Halsey	**-921.6002**	**-924.0301**	**-882.7935**	**-970.8546**
Modified Oswin	-863.7489	-894.2773	-791.3892	-935.225
Bayesian information criterion (BIC)				
Modified Henderson	-610.422	-837.103	-778.6599	-863.8179
Modified Chung-Pfost	-803.1892	-829.1009	-760.9126	-509.9711
Modified Halsey	**-872.0023**	**-872.5911**	**-831.7062**	**-918.7346**
Modified Oswin	-813.389	-842.8384	-740.3019	-883.1051
Estimated residual standard deviation (Re)				
Modified Henderson	0.01013694	0.01247521	0.01265823	0.01259325
Modified Chung-Pfost	0.00942645	0.01246492	0.01289939	0.05150633
Modified Halsey	**0.00917534**	**0.01245780**	0.01241671	**0.01193444**
Modified Oswin	0.00994275	0.01282169	**0.01119054**	0.01283357

The A, B and C adsorption and desorption parameters of the Modified Halsey model were determined for the four oil contents (Table 5).

At least one of the parameters obtained for oil contents of 35.7% and 44.6% showed significant differences among adsorption and desorption, being the difference greater for the lowest oil content (35.7%). As the oil content of the seed increased, the difference among adsorption and desorption decreased, being not statistically different for any parameter for 48.6 and 52.7% of oil, implying that the occurrence of hysteresisis affected by oil content. For the higher oil contents, a combined set of parameters (adsorption and desorption) is then offered. For 44.6% oil content the parameters were statistically different, however the magnitude of the difference between adsorption and desorption curves is unimportant, therefore, a combined set of parameters is also offered.

Table 6 shows the MRD and SE values of the goodness of fit of the Modified Halsey model for each oil content. MRD was between 0.071756 and 1.311034, and SE between 0.0094701and 0.01314778. Chen and Morey (1989b) reported MRD and SE values for the Modified Halsey model for sunflower seeds of 3.37 and 1.72, respectively, which were higher than those reported in Table 6.

Table 5 Adsorption, desorption and combined A, B and C parameters for sunflower seeds with four oil contents

Oil Content (%)	Parameter		
	A	B	C
35.7	***Adsorption*** [a]		
	2.785512	-0.001376	1.506710
	Desorption [b]		
	2.589510	-0.002956	1.362325
44.6	***Adsorption*** [a]		
	2.690894	-0.000250	1.513090
	Desorption [b]		
	2.875308	-0.002891	1.556196
	Adsorption/Desorption		
	2.882406	-0.001605553	1.580176

48.6	***Adsorption[a]***		
	2.488470	-0.003505	1.528471
	Desorption[a]		
	2.796136	-0.002772	1.691478
	Adsorption/Desorption		
	2.634855	-0.003180249	1.603767
52.7	***Adsorption[a]***		
	1.676517	-0.002806	1.262525
	Desorption[a]		
	1.999989	-0.002637	1.401750
	Adsorption/Desorption		
	1.816344	-0.002722	1.323523

*Note: equal letters denote statistically not significant differences among adsorption and desorption parameters ($p > 0.05$).

Table 6 Mean relative deviation and standard error for the Modified Halsey model for the sunflower seeds with four oil contents

Oil Content (%)	MRD	SE
35.7	1.093565	0.00947010
44.6	1.311034	0.01314778
48.6	1.196738	0.01264444
52.7	0.071756	0.01218165

3.1 Effect of oil content on e.m.c./e.r.h. relationship and s.s.m.c.

It was observed that oil content significantly affected the e.m.c./e.r.h. relationship of the sunflower seeds. Figure1 shows the isotherms at 25℃ for each oil content obtained with the parameters from Table 5 for the Modified Halsey model.

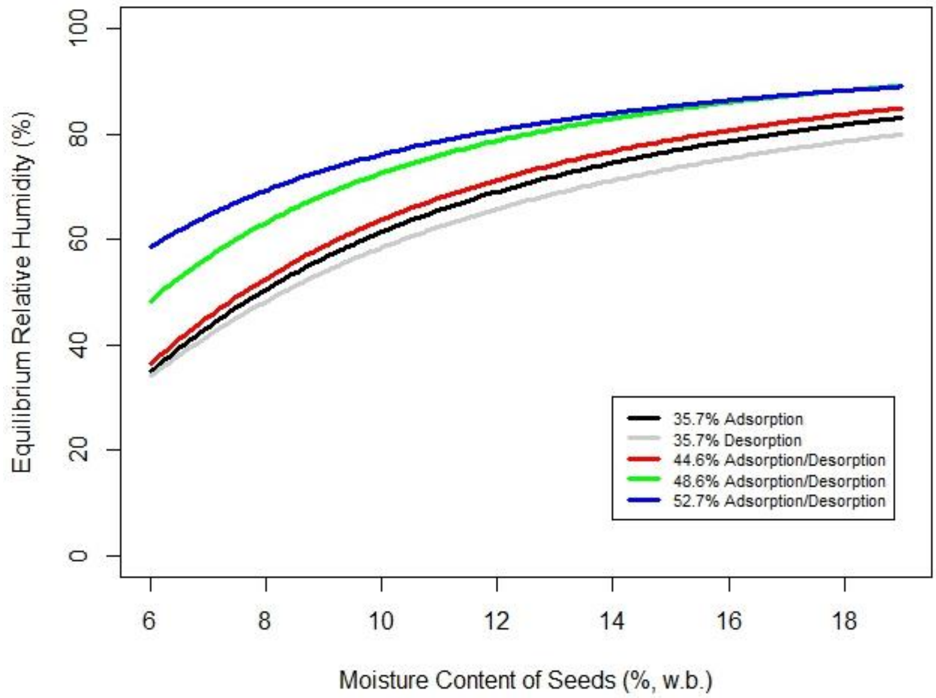

Figure 1 Isotherms of Equilibrium Relative Humidity at 25℃ for different oil contents obtained from the Modified Halsey model and the set of parameters from Table 5

For high oil contents (from 44.6% to 52.7%), a single curve corresponding to both treatments (adsorption and desorption) was plotted, while for the low oil content (35.7%) both curves wereplotted. The effect of the oil content on the e.m.c./e.r.h. relationship can be noticed in the different e.r.h. obtained for a given seed m.c. For instance, at 11% m.c. and 25℃, sunflower seeds with 35.7% oil will equilibrate at 62% (desorption), while for 52.7% of oil the e.r.h. was 78% (16 percentage points of difference). This is because seeds with higher oil contents have less ability to adsorb water, thus equilibrate at higher r.h. (Giner and Gely, 2005).In addition to that, the difference in the e.r.h. between low and high oil content is inversely related to seed m.c. For 6% m.c., sunflower seeds with low oil (35.7%) equilibrates at 34% e.r.h., while for high oil (52.7%) the e.r.h. equilibrates at58.5% (24.5 percentage points of difference). On the other hand, for 18% m.c. the difference is reduced to 9.6 percentage points (78.6 and 88.2 for the low and high oil content, respectively).

There is a wide range of oil contents in the sunflower seeds that are currently commercialized. This would imply that the appropriated set of parameters for the Modified Halsey model should be selected in function of the oil content of the seed, but, most of the time, parameters for different oil contents are not available. Using the wrong set of parameters has several practical problems during drying, conditioning and storing sunflower seeds. For instance, using the wrong set of parameters for the sunflower e.m.c. model in an aeration controller could result in substantial difference in the final m.c. achieved (overdrying), or storing sunflower seed above the s.s.m.c.

In Figure2,s.s.m.c.(e.r.h. of 70%)is shown for different oil contents as a function of storage temperature. The s.s.m.c. is greatly influenced the oil content of the seed. At 20 ℃, the s.s.m.c. for seeds with 35.7%, 44.6%, 48.6% and 52.7% of oil was of 12.0%, 10.4%, 8.6% and 7.6%, respectively. In Argentina, according to the Sunflower Quality Standards (SENASA, 1994), the market m.c. is 11% (shown in figure 2), implying that hybrids with low oil content (i.e. 35.7%) might be stored at a safe condition at any temperature, some hybrids with oil content of about 44% could be stored at a safe condition only at low temperatures (less than 5 ℃), while hybrids with high oil content (i.e. 48.6% and 52.7%) cannot be safely stored at 11% m.c., even at low temperatures. When the standards of sunflower was made (beginning of XX century), the oil content of the hybrids was substantially lower than today. This would imply that the market m.c. of sunflower seed should be revised to promote safe storage condition in this product as the oil content increased over time and, hence, the s.s.m.c. decreased.

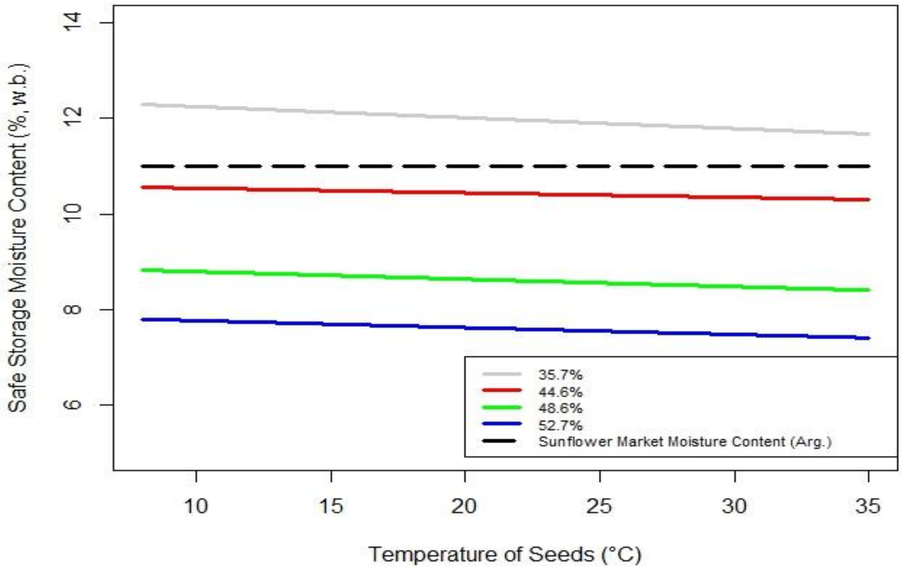

Figure 2Safe storage moisture content for different temperatures and oil contents (35.7% desorption, 44.6% adsorption/desorption, 48.6% adsorption/desorption, 52.7% adsorption/desorption)

4 Conclusions

The Modified Halsey model was the best for predicting e.m.c./e.r.h. relationships for the commercial sunflower hybrid Agrobel 967 with four oil contents (between 35.7% and 52.7%) within a broad range of temperatures and moisture contents.

The parameters for the Modified Halsey model were obtained for each of the four oil contents, and it was observed that for low oil contents (35.7%) a set of adsorption and desorption parameters was needed, while for high oil content shysteresis was not significant.

The oil content substantially affected the e.m.c./e.r.h. relationship, meaning that to use the right set of parameters according to the oil content of the hybrids is critical for sunflower drying, conditioning and storing. Based on these results, the safe storage moisture content of sunflower seeds is largely different according to the oil content, and market moisture content of new hybrids with high oil content should be revised.

Acknowledgments

The authors thank Leandro Cambareri from Instituto Nacional de Tecnología Agropecuaria (INTA) for its help in the conduction of experimental procedures. Also, the authors are grateful for the financial support of INTA (PNAIyAV 1130023 and PNCyO 1127022), CONICET and Comisión de Investigaciones Científicas (CIC) de la Provincia de Buenos Aires.

References

Akaike, H. 1974. A new look at the statistical model identification. *Transaction on automatic control*, 19(6): 716-723.

ASAE Standard. 2003. S352.2: Moisture measurement - Unground grains and seeds. St. Joseph, Mich.: ASAE.

ASAE Standard. 2007. W/Corr. 1 (R2012). D245.6: Moisture Relationships of Plant-based Agricultural Products. St. Joseph, Mich.: ASAE. 40p.

ASAGIR. 2010. Red de Evaluación de Cultivares Comerciales de Girasol de INTA. Campañas 2008/2009 y 2009/2010.Cuadernillo N º18.76 p.

Bartosik, R. E. 2003. Implementation and evaluation of a new variable heat fan and burner in-bin drying control strategy. M.S. thesis. West Lafayette, Indiana: Purdue University, Department of Agricultural and Biological Engineering. pp 72-83.

Bartosik, R., and D.Maier.2007. Study of adsorption and desorption equilibrium relationships for yellow dent, white and waxy corn types using the Modified Chung-Pfost equation. *Transactions of the ASABE*, 50(5): 1741-1749.

Brooker, D. B.,F. W.Bakker-Arkema, andW.Hall. 1992.Drying and storage of grains and oilseeds. Van Nostrand Reinhold, New York. 450 p.

Chapman, G. W., and J. A.Robertson. 1987. Moisture content/relative humidity equilibrium of high-oil and confectionery type sunflower seed. *Journal Stored Products Research*, 23 (2): 115-118.

Chen, C. 1988. A study of equilibrium relative humidity for yellow-dent corn kernels.Ph. D. thesis.University of Minnesota. St. Paul.

Chen, C. 2000. Factors which effect equilibrium relative humidity of agricultural products. *Transactions of the ASAE*, 43(3): 673-683.

Chen, C., andR. V.Morey.1989 a. Equilibrium relativity humidity relationships for yellow-dent corn.*Transactions of the ASAE*, 32(3): 999-1006.

Chen, C., andR. V. Morey.1989 b. Comparison of Four EMC/ERH Equations.*Transactions of the ASAE*, 32(3): 983-990.

Choi, B. M.,S. B.Lanning, andT. J.Siebenmorgen.2010. A Review of hygroscopic equilibrium studies applied to rice. *Transactions of the ASAE*, 53(6): 1859-1872.

Giner, S. A., andM. C.Gely. 2005.Sorptional parameters of sunflower seeds of use in drying and storage stability studies. *Biosystems Engineering*, 92(2): 217-227.

Iglesias, H. A. andJ. Chirife.1976 a. Prediction of effect of temperature on water sorption isotherms of food materials. *Journal of Food Technology*, 11: 109-116.

Iglesias, H. A., and J. Chirife.1976 b.A model for describing the water sorption behavior of foods. *Journal of Food Science*, 41: 984-992.

Izquierdo, N., G. A. A.Dosio, M.Cantarero, J.Lujan, andL. A. N.Aguirrezábal. 2008. Weight per grain, oil concentration and solar radiation intercepted during grain filling in black hull and stripped hull sunflower hybrids. *Crop Science*, 48: 688-699.

Izquierdo, N. G., andL. A. N.Aguirrezábal. 2010. Recientes avances de la ecofisiología de la calidad de aceites. Su aplicación al manejo de cultivos para obtener aceites de alta calidad. In: *Nuevos avances en ecofisiología de cultivos de granos*. Miralles, D. J.; Aguirrezábal L. N., Otegui, M. E., Kruk, B. C. & Izquierdo N. Eds. Editorial FAUBA. pp. 213-233.

Jayas, D. S., and G.Mazza. 1991.Equilibrium moisture characteristics of safflower seeds. *Transactions of the ASAE*, 34(5): 2099-2103.

Mazza, G. and D. S.Jayas. 1991. Equilibrium moisture characteristics of sunflower seeds, hulls, and kernels. *Transactions of the ASAE*, 34(2): 534-538.

Pfost, H. B., S. G.Mourer, D. S.Chung, andG. A.Milliken.1976. Summarizing and reporting equilibrium moisture data for grains. ASAE. St. Joseph, MI: ASAE. Paper No. 76-3520.

Pinheiro, J., D.Bates, S.Debroy and D.Sarkay.The r core team. 2009. nlme: Linear or Nonlinear Mixed Effects Model. R package version 3.1-96.

Pixton, S. W., and S.Warburton. 1971 a. Moisture content/relative humidity equilibrium of some cereal grains at different temperatures. *Journal Stored Products Research*, 6: 283-293.

Pixton, S. W., andS. Warburton. 1971 b. Moisture content relative humidity equilibrium, at different temperatures, of some oilseeds of economic importance. *Journal Stored Products Research*,7: 261-269.

Posada, S. L., and R. R.Noguera. 2007. Comparación de los modelos matemáticos: una aplicación en la evaluación de alimentos para animales. Facultad de Ciencias Agrarias, Universidad de Antioquia, Medellín, Colombia. *RevistaColombianade CienciasPecuarias*; 20: 141-148.

R DEVELOPMENT CORE TEAM. 2012. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria, ISBN 3-900051-07-0. Available at: http://www.R-project.org/.

Robertson, J., and W.Morrison. 1979.Analysis of oil content of sunflower seed by wide-line NMR. *Journal of the American Oil Chemists Society*, 56: 961-964.

Santalla, E., andR.Mascheroni.2003.Equilibrium moisture characteristics of high oleic sunflower seeds and kernels.*Drying Technology*, 21: 147-163.

Schwarz, G. 1978. Estimating the dimension of a model. *The annals of statistics*, 6(2): 461-464.

SENASA. 1994. Resolución N° 1075. Norma IX. Secretaría de Agricultura Ganadería y Pesca de la Nación, Buenos Aires, Argentina. Accessed: January 2015, Available at: http://www.senasa.gov.ar/Archivos/File/File4230-ry-1075-94.pdf.

Thompson, T. L., R. M.Peart, and G. H.Foster.1968. Mathematical simulation of corn drying – A new model. *Transactions of the ASAE*, 24(3): 582-586.