Development of the Enhanced Halsey Model to Predict Equilibrium Moisture Content (EMC) of Sunflower Seeds with Different Oil Contents

G. Maciel, D. A. de la Torre, M. G. Cendoya, N. G. Izquierdo, R. E. Bartosik

Abstract. *Using the right equilibrium moisture content (EMC) relationship is critical for implementing successful aeration strategies and for determining the safe storage moisture content of grains and oilseeds. The oil content of sunflower seeds substantially affects the moisture equilibrium relationship, implying that a specific set of model parameters for each oil content range should be obtained. To overcome this practical limitation, the Enhanced Halsey model was developed incorporating a new parameter (D) to characterize the effect of oil content on the original Modified Halsey model. The constants A, B, C, and D of the model were obtained for a wide range of temperatures, moisture and oil contents. The simplicity of the Enhanced Halsey model and the possibility of adapting EMC as a function of oil content make the Enhanced Halsey model valuable for engineering applications (e.g., aeration controllers) and for predicting the safe storage moisture content of seeds with different oil contents, such as sunflower.*

Keywords. *Composition, Grain, Isotherms, Oilseed, Relative humidity, Sorption, Storage quality.*

Grain equilibrium moisture content (EMC) and equilibrium relative humidity (ERH) designate the corresponding moisture and humidity values at which grain is in moisture equilibrium with the interstitial air (Maciel et al., 2015). The EMC depends on the temperature, the relative humidity (RH) of the environment, characteristics of the material (e.g., variety), treatment of the samples (e.g., drying temperature, drying and rewetting process), composition of the material, and method used for obtaining the EMC/ERH relationship (Bartosik, 2003; Brooker et al., 1992; Chen, 2000; Chen and Morey, 1989a; Choi et al., 2010; Giner and Gely, 2005; Jayas and Mazza, 1991; Pixton and Warburton, 1971a, 1971b).

The most frequently used empirical models to predict ERH based on a set of grain-specific constants, temperature, and moisture content (MC) of the grain are the Modified Henderson, Modified Chung-Pfost, Modified Halsey, and Modified Oswin models. ASABE Standard D245.6 (ASABE, 2007) provides a description of the current models and their parameters (*A*, *B*, and *C*) for different agricultural products.

It has been reported that the Modified Halsey equation is a good model for high-oil products in general (Iglesias and Chirife, 1976a, 1976b). Additionally, Maciel et al. (2015) evaluated four empirical models to predict the ERH relationships of sunflower hybrids with seed oil contents (OC) from 35.7% to 52.7% and concluded that the Modified Halsey model (MHM) was the best. Mazza and Jayas (1991) evaluated different models to predict EMC relationships for sunflower seeds, hulls, and kernels and arrived at a similar conclusion.

The original Halsey model (Halsey, 1948) described the EMC relationship as a condensation of multilayers. Temperature dependence was included by Iglesias and Chirife (1976a, 1976b) through an empirical exponential term. This yielded the so-called Modified Halsey equation (eq. 1):

$$\mathrm{RH} = \exp\left[-\frac{\exp\left(A + B \times T\right)}{\mathrm{MC}^{C}}\right] \tag{1}$$

where

RH = relative humidity (dec.)

T = temperature (°C)

A, B, and C = constants of the product

MC = moisture content (% d.b.).

The effect of OC on the ERH/EMC relationship was previously investigated. Mazza and Jayas (1991) demonstrated that EMC curves were coincidental when calculated on an oil-free basis. Giner and Gely (2005) reported that sunflower ERH increased with OC, and later Maciel et al.

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(2015) obtained specific sets of parameters for sunflower seeds with four different OC values (from 35.7% to 52.7%). Using the right EMC relationship is critical for implementing successful aeration strategies (Thorpe, 2002). Because OC affects the EMC relationship of sunflower seeds, adjusting the EMC relationship based on OC is important for targeting a specific MC during aeration. Proper EMC relationships are also important for determining the safe storage moisture content (SSMC) of grains. It is generally accepted that storage molds grow very slowly at RH values lower than 70%; thus, safe storage conditions are achieved when the product is stored at MC in equilibrium with RH of 67% or less in the interstitial air (Abadía and Bartosik, 2013). In recent years, the OC of sunflower seeds in Argentina (and in most sunflower-producing countries) has substantially increased, but the trade MC remains at 11% (SAGyP, 1994). Recommendations for SSMC are controversial because there is a wide OC range (from 39% to 55%) in the sunflower seeds currently available in the market (ASAGIR, 2010), implying that there is also a wide range of SSMC values. Because trading sunflower below the market MC implies a weight reduction in the delivered grain and a monetary loss for farmers and grain elevators, the consequence is that sunflower seeds with high OC are stored at the unsafe condition of 11% MC. As a result, every year there are storage bins with quality losses due to fungal spoilage and even fire damage.

To improve the postharvest management of sunflower seeds, better prediction is required of the EMC relationship adjusted by OC. Two approaches could be implemented: (1) develop a specific set of parameter values for hybrids with different OC values, or (2) incorporate OC as a factor to improve EMC prediction for sunflower seeds. The second approach seems to have practical advantages because the OC is usually known (or can be easily determined) and, once a single set of parameters is obtained, the EMC curve can be easily adjusted with the OC. Thus, the goal of this study was to develop an Enhanced Halsey model (EHM) by incorporating OC as a variable in order to improve the EMC prediction for sunflower hybrids.

METHODOLOGY

EXPERIMENTAL DATA

This study used experimental data generated by Maciel et al. (2015). A summary of the experimental procedure states that four plots of the same sunflower hybrid (Agrobel 967) were exposed to different levels of defoliation, which caused different OC values in the seeds: 35.7%, 44.6%, 48.6%, and 52.7% (dry basis). From each set of seeds, subsamples were exposed to two treatments (desorption and adsorption) and then conditioned to specific MC values (about 6%, 9%, 14%, 17%, 21%, and 25% d.b.; tables 1 and 2). Next, the conditioned samples were placed in glass jars of 370 mL capacity and hermetically sealed with rubber caps. A temperature and RH sensor (Vaisala HMD60U/Y-M210276en-A) was inserted through the rubber cap into the glass jar to accurately measure the temperature and RH of the interstitial air. The sealed jars, with grain samples and temperature and RH sensors, were placed in a temperature chamber (ING.MAS, Rosario, Argentina) with a programmed decreasing temperature cycle from 35°C to 8°C, allowing 24 h to achieve sorption equilibrium at each temperature. Grain MC was measured before and after the EMC experiment by the oven method in triplicate (ASABE, 2003). For each ERH/EMC pair of data, four replicates were considered. Tables 1 and 2 summarize the EMC/ERH experimental data.

MODEL CONSTRUCTION

The literature indicated that the MHM was best for pre-

Table 1. Equilibrium temperature, RH, and MC data for desorption experiments using sunflower seeds with four oil contents (average of four replicates) (from Maciel et al., 2015).

35.7% Oil			44.6% Oil			48.6% Oil			52.7% Oil		
Temp. (°C)	ERH (%)	EMC (% d.b.)	Temp. (°C)	ERH (%)	EMC (% d.b.)	Temp. (°C)	ERH (%)	EMC (% d.b.)	Temp. (°C)	ERH (%)	EMC (% d.b.)
12.3	42.3	8.1	11.3	41.9	7.4	12.1	47.7	6.6	11.3	49.2	6.4
12.3	61.2	11.2	12.2	64.5	10.5	11.0	68.5	9.1	11.4	66.8	8.3
13.2	74.3	16.7	11.8	77.0	16.0	12.1	78.1	12.6	11.3	77.3	11.0
11.4	77.1	21.4	11.9	79.4	19.8	11.4	79.6	16.7	11.6	82.6	14.9
12.6	77.0	24.7	11.9	79.6	21.7	12.5	80.2	19.6	11.5	80.9	18.8
13.4	77.1	26.6	11.2	78.9	24.5	11.5	83.4	22.2	11.0	82.1	22.7
19.3	44.0	8.1	19.6	44.3	7.4	19.7	49.2	6.6	20.5	52.3	6.4
19.3	61.2	11.2	20.1	65.0	10.5	19.3	69.5	9.1	20.1	67.4	8.3
18.8	74.0	16.7	19.6	77.5	16.0	19.8	78.6	12.6	19.9	77.6	11.0
18.7	77.5	21.4	20.1	79.7	19.8	19.8	81.0	16.7	20.1	83.2	14.9
18.9	77.7	24.7	18.6	79.9	21.7	20.3	81.6	19.6	20.2	82.7	18.8
19.0	77.5	26.6	20.2	80.5	24.5	19.3	83.7	22.2	19.9	82.4	22.7
25.4	43.9	8.1	24.5	43.2	7.4	30.9	50.1	6.6	24.3	50.7	6.4
25.5	60.7	11.2	24.7	64.6	10.5	30.7	69.6	9.1	25.1	67.5	8.3
24.8	73.5	16.7	25.0	77.0	16.0	31.2	79.7	12.6	24.9	77.1	11.0
24.8	77.5	21.4	24.9	79.9	19.8	31.0	83.2	16.7	25.2	82.8	14.9
24.7	77.5	24.7	25.6	80.2	21.7	31.3	84.2	19.6	25.0	82.4	18.8
25.0	77.9	26.6	24.0	80.8	24.5	30.6	84.6	22.2	24.4	83.3	22.7
35.6	46.0	8.1	35.3	44.9	7.4	35.3	49.6	6.6	34.5	51.5	6.4
35.5	61.7	11.2	35.3	64.9	10.5	34.9	68.1	9.1	34.6	67.3	8.3
35.4	74.3	16.7	35.4	77.6	16.0	35.5	77.9	12.6	34.7	77.1	11.0
35.0	78.9	21.4	35.5	80.7	19.8	35.1	82.1	16.7	34.4	83.3	14.9
35.6	79.3	24.7	35.9	81.5	21.7	35.7	83.6	19.6	34.9	83.9	18.8
35.6	79.3	26.6	35.4	82.7	24.5	35.4	85.0	22.2	34.6	84.9	22.7

Table 2. Equilibrium temperature, RH, and MC data for adsorption experiments using sunflower seeds with four oil contents (average of four replicates) (from Maciel et al., 2015).

35.7% Oil			44.6% Oil			48.6% Oil			52.7% Oil		
Temp. (°C)	ERH (%)	EMC (% d.b.)	Temp. (°C)	ERH (%)	EMC (% d.b.)	Temp. (°C)	ERH (%)	EMC (% d.b.)	Temp. (°C)	ERH (%)	EMC (% d.b.)
11.4	32.3	6.2	13.4	47.3	7.9	9.9	51.7	7.1	11.6	46.9	6.0
11.7	53.4	9.4	12.9	63.1	10.1	9.8	68.3	9.3	11.9	69.7	8.7
12.1	65.6	12.1	13.0	74.4	13.9	10.0	79.1	12.6	11.6	77.8	12.1
12.2	72.1	14.4	12.6	77.2	17.4	9.8	78.5	15.6	11.4	80.6	14.7
12.4	77.4	18.1	13.2	87.0	22.5	10.1	80.3	17.9	11.7	84.2	18.3
13.8	77.1	21.7	12.7	79.2	25.6	9.9	79.6	22.7	12.0	81.8	22.1
18.5	33.7	6.2	19.9	48.9	7.9	19.0	52.8	7.1	19.3	47.9	6.0
18.7	53.2	9.4	19.5	62.9	10.1	19.6	68.5	9.3	19.4	69.6	8.7
19.2	65.7	12.1	19.9	74.7	13.9	19.7	78.7	12.6	19.3	78.6	12.1
18.5	71.7	14.4	19.6	78.1	17.4	19.5	79.3	15.6	19.3	81.5	14.7
18.2	77.3	18.1	20.0	84.3	22.5	19.7	81.1	17.9	19.4	84.1	18.3
19.2	76.9	21.7	18.0	79.4	25.6	19.2	81.1	22.7	19.6	82.5	22.1
25.7	34.0	6.2	24.4	47.3	7.9	31.6	54.5	7.1	25.4	49.1	6.0
26.0	53.7	9.4	24.6	62.3	10.1	32.0	68.8	9.3	25.7	70.2	8.7
26.2	64.9	12.1	24.9	73.5	13.9	31.8	79.0	12.6	25.4	77.4	12.1
26.0	71.5	14.4	24.6	77.7	17.4	32.2	80.9	15.6	24.8	81.1	14.7
25.9	76.2	18.1	24.7	84.2	22.5	32.0	82.5	17.9	24.7	84.4	18.3
26.3	77.2	21.7	24.8	78.8	25.6	31.9	83.7	22.7	25.1	82.8	22.1
35.5	35.6	6.2	34.8	47.8	7.9	34.5	53.5	7.1	34.5	49.7	6.0
35.5	54.8	9.4	34.9	63.1	10.1	34.6	69.1	9.3	34.8	70.3	8.7
36.0	65.4	12.1	35.3	73.5	13.9	35.1	78.8	12.6	34.6	77.7	12.1
35.6	72.1	14.4	35.2	78.4	17.4	35.1	81.0	15.6	34.3	81.4	14.7
35.5	76.5	18.1	35.1	83.4	22.5	35.2	83.6	17.9	34.2	84.9	18.3
35.9	77.9	21.7	35.7	81.7	25.6	34.6	84.3	22.7	34.4	84.5	22.1

dicting the EMC relationship of sunflower seeds (Maciel et al., 2015; Mazza and Jayas, 1991); thus, this model was selected as the basis to develop the enhanced model, named hereafter the Enhanced Halsey model (EHM).

A nonlinear mixed model, which included a random effect associated with the sensor inside the chamber run, was used to separate the error variation from the variation induced by the use of different sensors and different chamber runs. This model allowed considering the heterogeneity of variance or correlation between errors but required an intricate stepwise selection of the random structure along with the structure of the error variance and covariance matrix, prior to testing the significance of the fixed parameters. The basic assumption was that the three original parameters (A, B, and C) follow a linear relationship with OC; thus, each original parameter in equation 1 was replaced with a linear equation depending on OC. A random effect of the sensor inside the chamber run on parameter A was also included. The first fitted model was:

$$\mathrm{RH} = \exp\Big(-\exp\big[\left(A + S_A + a_i\right) + \left(B + S_B\right) \times T + \left(D + S_D\right) \times \mathrm{OC} + \left(E + S_E\right) \times \mathrm{OC} \times T\big] \div \left[\mathrm{MC}^{\left(C+S_C\right)+\left(F+S_F\right)\times \mathrm{OC}}\right]\Big) \quad (2)$$

where

RH = relative humidity (dec.)

T = temperature (°C)

OC = oil content (% d.b.)

MC = moisture content (% d.b.)

A, B, and C = original parameters of MHM

D, E, and F = new parameters of EHM that incorporate the OC effects on the original parameters A, B, and C, respectively

S_A, S_B, S_C, S_D, S_E, and S_F = sorption effects on each parameter

a_i = random effect of sensor i on parameter A in each chamber run.

Experimental data (summarized in tables 1 and 2) were used to fit the new model with the non-linear mixed effect package (nlme) of the R program (R Development Core Team, 2012), and the homogeneity in the residual variance was checked with residuals plots. The likelihood ratio test in nested models was used to select the appropriate structure of variance and covariance errors and the structure of random effects parameters. Once these structures were found, the Wald test was used in a stepwise evaluation to discard non-significant fixed effects until the definitive EHM was obtained.

Performance Comparison of Enhanced and Modified Halsey Models

Two of the most used statistics to compare model performance are the mean relative percentage deviation (MRD) and the maximal restricted likelihood residual standard error (SE) (Bartosik and Maier, 2007; Chen, 2000; Chen and Morey, 1989b; Mazza and Jayas, 1991). However, because the data in this study showed heterocedasticity, SE was a function of the predicted HRE value. In addition, the SE does not take into account the variation introduced by the sensor random effect (a_i), so it was decided to use the mean prediction error (MPE), which is an alternative to the SE that incorporates both the error variance function and the variation induced by the sensors:

$$\mathrm{MRD} = \frac{100}{N} \sum \left(\frac{\left| y - \hat{y} \right|}{y} \right) \quad (3)$$

$$\mathrm{MPE} = \sqrt{\frac{\sum(y-\hat{y})^2}{N}} \tag{4}$$

where

N = number of data points

y = observation (HRE)

$\hat{y}$ = model prediction for y.

Results and Discussion

Development of Enhanced Halsey Model

First, the most complex model (eq. 2) was fitted, and from the residuals plot it was observed that the error variance increased with fitted values, showing heterocedasticity in the data (cone shape) (fig. 1a).

Several variance functions were fitted to take into account the heterocedasticity of the data, and the best was an exponential function:

$$\mathrm{var}(E_i) = \sigma_e^{\,2}\exp(2\delta\hat{y}_i) \tag{5}$$

where

E_i = error of observation y_i

σ_e^2 = common error variance

δ = parameter of the exponential function

$\hat{y}$ = model predicted value for observation y_i.

The inclusion of this variance function in the model improved the residual plot, and the p-value from the likelihood ratio test ($p = 0.0002$) confirmed that the inclusion of the error variance function was necessary (fig. 1b).

The Wald test showed that the sorption effect was not significant for S_F ($p = 0.2622$), S_C ($p = 0.6521$), S_E ($p = 0.0742$), and S_B ($p = 0.0694$), but it was significant for S_D ($p < 0.0001$) and S_A ($p = 0.0350$). The OC effect was not significant for parameters F ($p = 0.3597$) and E ($p = 0.3439$), but it was significant for parameter D ($\alpha = 0.05$). Therefore, the reduced fitted model, including an exponential variance function for the errors, was:

$$\mathrm{RH} = \exp\left(-\exp\left[(A+S_A+a_i)+B\times T + (D+S_D)\times \mathrm{OC}\right] \div \mathrm{MC}^C\right) \tag{6}$$

where

RH = relative humidity (dec.)

T = temperature (°C)

A, B, C, and D = constants of the product

OC = oil content (% d.b.)

MC = moisture content (% d.b.)

S_A, S_D = sorption effect on parameters A and D

a_i = random effect of sensor i on parameter A in each chamber run.

The results showed that the sorption effect was significant for parameters A (independent) and D (related to OC). However, the magnitude of hysteresis decreased with OC (from 2 to 4 percentage points of RH for 35.7% OC to <1 percentage point of RH for 48.6% OC) (fig. 2). This observation was consistent with Maciel et al. (2015), who found that for low OC a set of adsorption and desorption parameters was needed, while for high OC the hysteresis effect was not significant. Hysteresis was significant in the present study; thus, a set of adsorption and desorption parameters is offered. However, because the magnitude of the hysteresis effect was low (with limited practical consequences in particular for high OC), a set of combined parameters is also offered. The final model and parameters are shown in equation 7 and table 3 and resulted in MPE and MRD of 0.041 and 5.19, respectively (for the model with Ads/Des parameters).

$$\mathrm{RH} = \exp\left(-\frac{\exp(A + B\times T + D\times \mathrm{OC})}{\mathrm{MC}^C}\right) \tag{7}$$

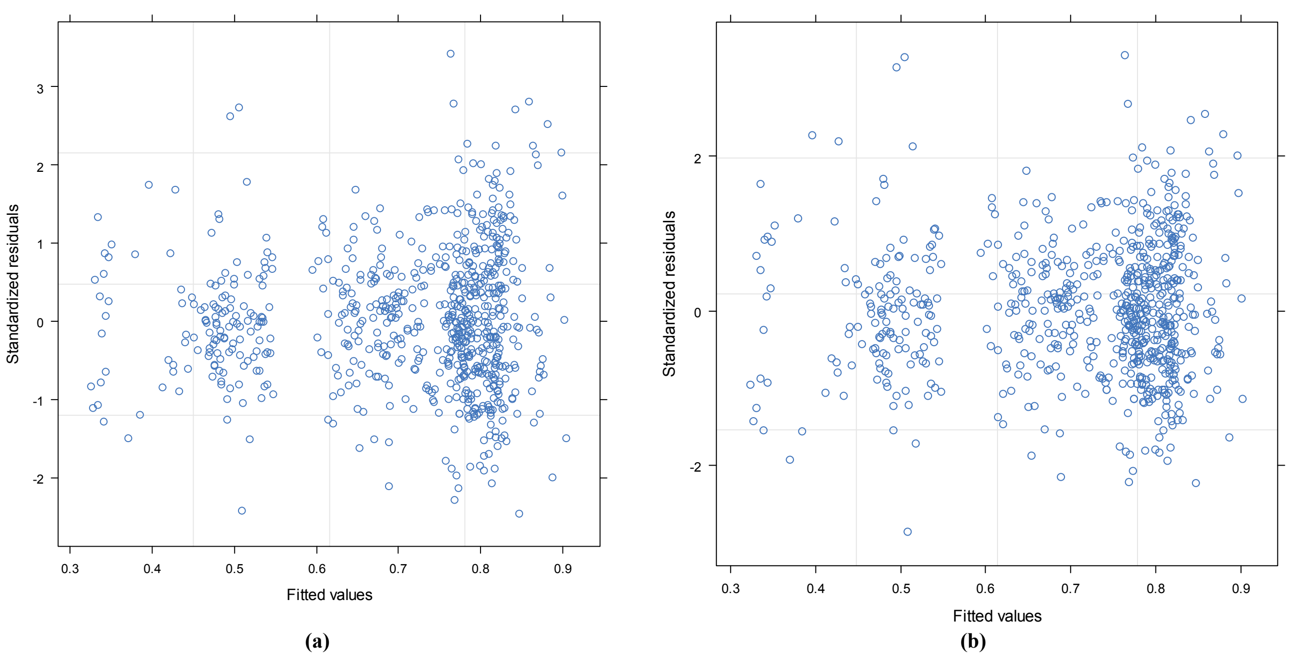

Figure 1. Standardized residuals of EHM versus fitted values (ERH, dec.) (a) without and (b) with correction of error variance heterogeneity.

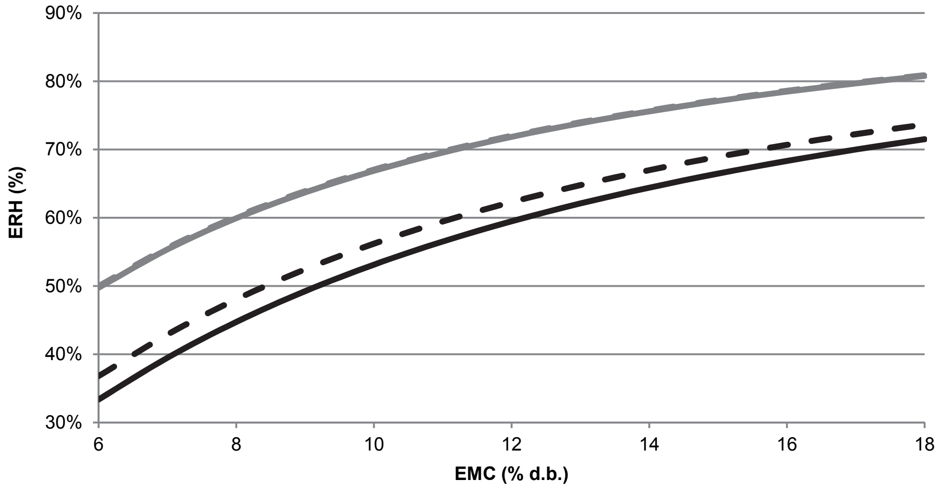

Figure 2. Desorption (solid lines) and adsorption (dashed lines) EMC/ERH relationships for sunflower seeds with 35.7% OC (black lines) and 48.6% OC (gray lines) at 20°C. Note that the Ads/Des lines for 48.6% OC are overlapped.

Table 3. Sunflower seed parameters for the Enhanced Halsey model (EHM) obtained in this study and for the Modified Halsey model (MHM) from Maciel et al. (2015) and from ASABE Standard D245.6 (ASABE, 2007), and their MPE and MRD statistics.

Model	Source	Basis	Sorption	Oil content (% d.b.)	Parameter *A*	*B*	*C*	*D*	MPE	MRD
EHM	This study	d.b.	Des.	35.7 to 52.7	3,325728	-0,002396	1,079093	-0,035057	0.040	4.95
			Ads.		2,992831	-0,002396	1,079093	-0,028352		
			Ads./Des.	35.7 to 52.7	3.126885	-0.002397	1.067407	-0.031661	0.041	5.19
MHM	Maciel et al., 2015	w.b.	Des.	35.7	2.589510	-0.002956	1.362325	-	0.029	3.54
			Ads./Des.	44.6	2.882406	-0.001605	1.580176	-	0.033	3.65
			Ads./Des.	48.6	2.634855	-0.003180	1.603767	-	0.039	4.20
			Ads./Des.	52.7	2.433091	-0.002736	1.552026	-	0.039	3.98
	ASABE, 2007	d.b.	Ads./Des.	47.0	3.2945	-0.0143	1.8641	-	0.127	17.20

where

RH = relative humidity (dec.)

T = temperature (°C)

A, *B*, *C*, and *D* = constants of the product

OC = oil content (% d.b.)

MC = moisture content (% d.b.).

Fitting and Comparison of Modified and Enhanced Halsey Models

Figure 3 plots the experimental (symbols) and predicted ERH data using the EHM (solid red line) with the Ads/Des set of parameter values shown in table 3 (for 20°C), indicating that the model predicted reasonably well the moisture relationship of sunflower seeds for different OC values (MPE and MRD of 0.041 and 5.19, respectively). As expected, when the model was fitted for a specific OC (Maciel et al., 2015) (dashed blue line), the error decreased (MPE from 0.029 to 0.039 and MRD from 3.54 to 4.20). Even though the error is lower, the difference with the error of the EHM is small. Thus, given that the error difference between the two models is low, it is important to consider the practicality of using a more general but simple model versus using the MHM and developing a specific set of parameters for each OC. On the contrary, using the single set of parameters currently offered in the ASABE Standard could lead to large errors (black solid lines), particularly for low OC samples (MPE of 0.57 and MRD of 17.2). This is because the parameters offered in the ASABE Standard (ASABE, 2007) were developed for sunflower seeds with OC of about 47%.

Effect of Oil Content on Equilibrium Moisture Content Relationship

Figure 4 shows the EMC/ERH curves for different OC values (from 35% to 55%) at 20°C predicted with the EHM. The effect of OC on the ERH was greater at low MC than at high MC. Additionally, the ERH increased by 5 percentage points when the OC increased from 35% to 40%; however, the ERH only increased by 3.8 percentage points when the OC increased from 50% to 55%, indicating that the effect of OC on ERH was greater at low OC levels.

Oil Content and Safe Storage Moisture Content

Figure 5 shows that the recommended SSMC (ERH of 67%) derived from the EHM for sunflower seeds at 20°C decreased from 13.0% to 7.6% as the OC increased from 35% to 55%. In general, for each 5 percentage point increase in OC, the SSMC decreased by 1.1 to 1.6 percentage points. The Sunflower Quality Standards of Argentina (SAGyP, 1994) historically set the market MC at 11% (solid black line in fig. 5), implying that seeds with OC of about 35% might be safely stored at any temperature, seeds with OC of about 40% could be safely stored only at temperatures below 30°C, and seeds with OC above 40% can-

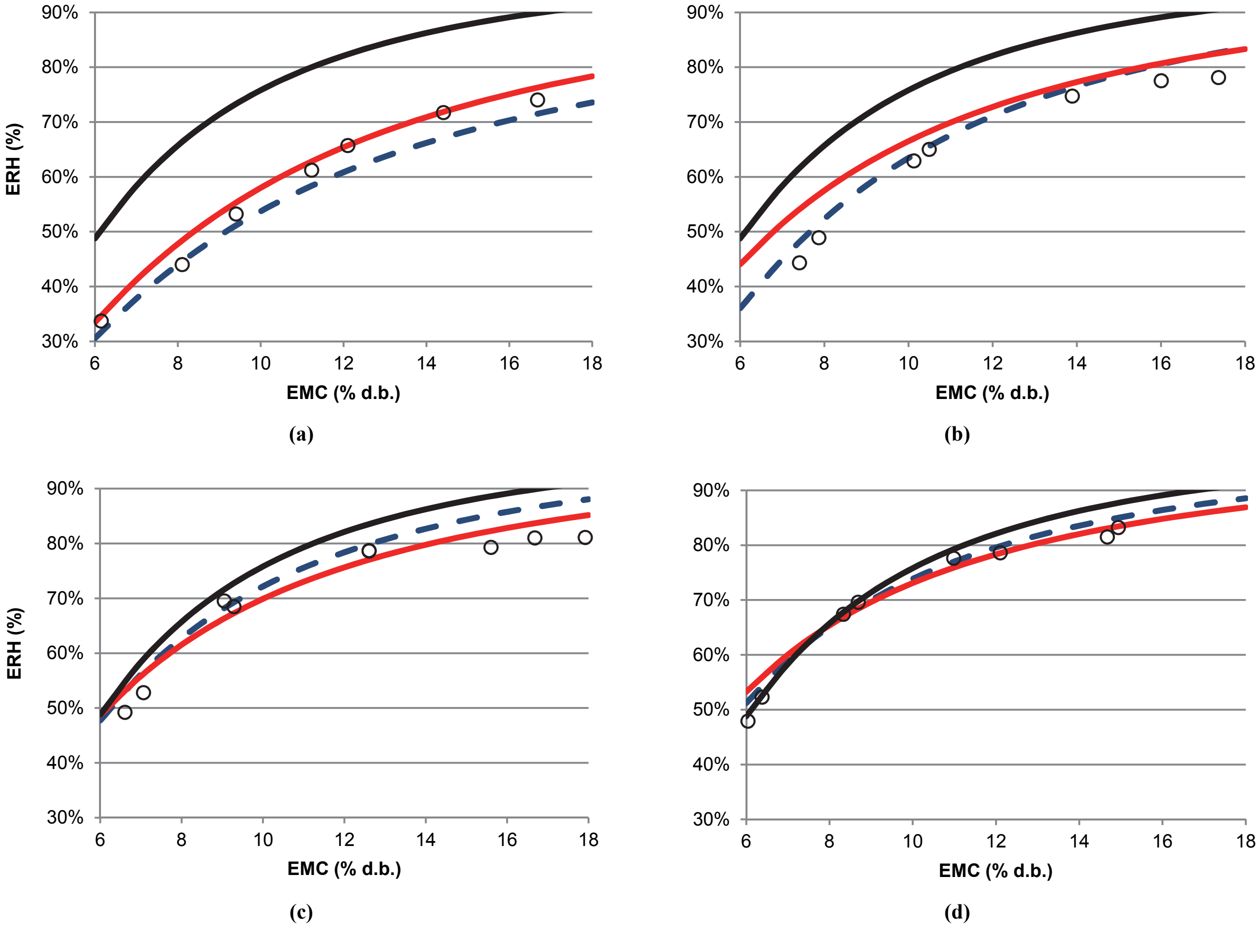

Figure 3. Observed (symbols) and predicted ERH values with the Enhanced Halsey model with the Ads/Des parameters (solid red line), with the Modified Halsey model (dashed blue line) with the parameters from table 3 for a specific OC (Maciel et al., 2015), and with the Modified Halsey model with the ASABE Standard parameters (black solid line) for OC of (a) 35.7%, (b) 44.6%, (c) 48.6%, and (d) 52.7% at 20°C.

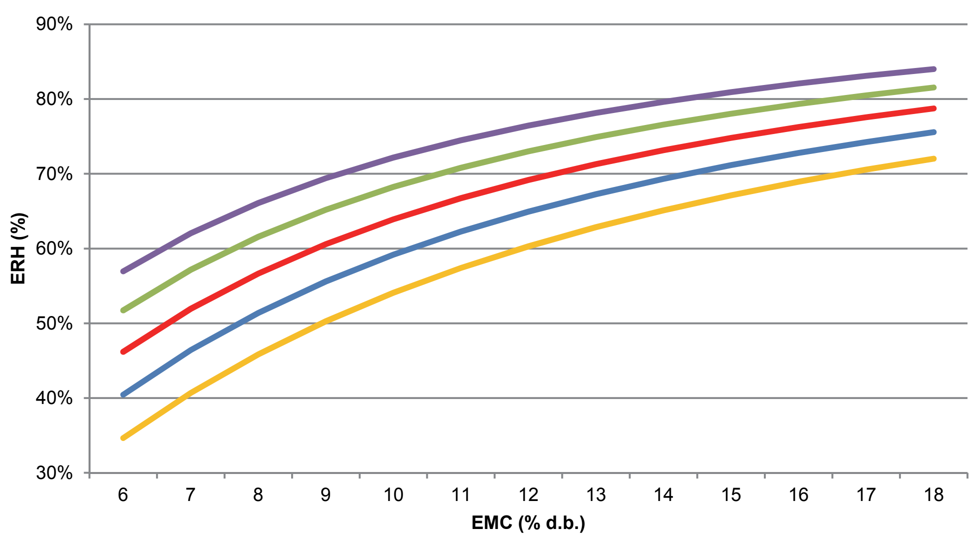

Figure 4. Predicted ERH values with the Enhanced Halsey model for sunflower seeds with different oil contents: yellow = 35%, blue = 40%, red = 45%, green = 50%, and violet = 55% (isotherm of 20°C).

not be safely stored at 11% MC. When the Sunflower Quality Standard of Argentina was originally established (beginning of the twentieth century), the OC of hybrids was substantially lower than today (about 40%). This implies that the market MC of sunflower seeds should be adjusted as a function of the OC to promote safe storage conditions for this oilseed. The EHM should be a valuable tool for predicting the SSMC of sunflower seeds with different OC,

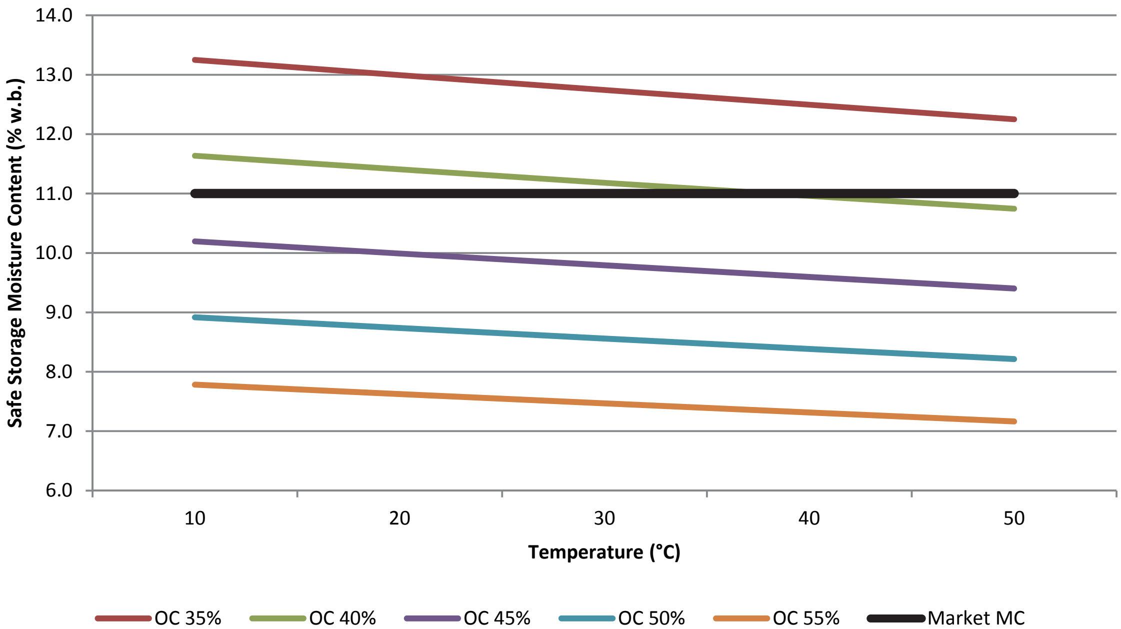

Figure 5. Safe storage moisture content (% w.b.) (ERH of 67%) predicted with the Enhanced Halsey model for five oil contents (35%, 40%, 45%, 50%, and 55%) and temperatures from 10°C to 40°C, and the market MC (11%) for sunflower in Argentina.

which, up to the present, could only be determined by obtaining specific sets of parameter values for hybrids with different OC.

Implications for Enhanced Halsey Model

Using a unique EMC/ERH relationship for sunflower seeds in aeration controllers could lead to severe overdrying if the aerated seeds have high OC, and vice versa. In addition, the SSMC could be misestimated by up to 5 percentage points if the effect of OC is not considered. These are typical problem of using the MHM with a single set of parameters. A specific set of parameters for each OC must be used if a more precise EMC prediction is required, but these parameters might not be available. Developing specific parameters implies conducting EMC/ERH experiments with specific laboratory equipment (precision ERH sensors, oven, precision scale, etc.), which requires a considerable amount of time for processing and conditioning the grain samples, conducting the experiments, and performing the statistical analysis. The EHM combines reasonable precision with practical adjustment of the EMC to different OC values. It only requires the OC of the sunflower seeds, which is usually known because OC is a factor in the official marketing standard. Thus, the EHM results are valuable for engineering applications, such as aeration controllers with fan operating strategies based on the EMC/ERH relationships, or for determining the SSMC. The parameters of the EHM presented in this study were developed from experimental data for a single hybrid; additional research is required to test the robustness of the model and better refine the model parameters. Another consideration is the use of adsorption, desorption, or combined (ads/des) sets of parameters. For low OC sunflower seeds, hysteresis should be considered, but for high OC seeds, the combined parameters (ads/des) might be appropriate. Thus, users must analyze the advantages and disadvantages of the EHM and consider hysteresis for their particular applications. If high precision is required, a specific set of parameters might be necessary; if not, the EHM adjusted by OC with the set of parameters offered in this study might be appropriate.

There are other products for which compositional values, especially OC, fluctuate due to genotype and phenotype variations (e.g., soybean, rapeseeds, etc.), leading to substantial changes in the EMC relationship. For these products, the EHM could also be implemented to improve EMC prediction in a simple and practical fashion.

Summary and Conclusions

The Enhanced Halsey model incorporates a new parameter (D) to characterize the effect of oil content in the original Modified Halsey model. The Enhanced Halsey model predicted reasonably well the effect of oil content on the ERH of sunflower seeds when compared to the traditional Modified Halsey model with a specific set of parameters for a particular oil content. Hysteresis was significant for low oil content seeds but became meaningless at high oil content. Users must analyze the precision required in EMC prediction before deciding to use the Modified Halsey model with a specific set of parameters for each oil content or using the Enhanced Halsey model. The possibility of adapting the ERH as a function of oil content makes the Enhanced Halsey model valuable for engineering applications (e.g., aeration controllers) and for predicting the safe storage moisture content of products with large variation in oil content, such as sunflower seeds.

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