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Sorption isotherms for amaranth grains

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Abstract

Compiling of EMC–ERH data for amaranth grains (*Amaranthus cruentus* L.) in the range of water activity from 0.029 to 0.979 and temperature from 25 to 90 °C was performed. Included data sets comprised experimental values of EMC–ERH that summarize 78 identified points for desorption, 53 for adsorption and 16 not discerned points that were considered for mean sorption.

Five isotherm equations for grains included in the ASAE Standards (Modified Henderson, Modified Chung–Pfost, Modified Halsey, Modified Oswin and GAB) were evaluated for their ability to fit sorption data from the literature (M_e vs. a_w for adsorption, desorption and mean sorption).

The goodness of fit for each isotherm was quantified through the correlation coefficient (R^2), the sum of squares (RSS), the standard error of the estimate (S_y), the mean relative deviation (MRD) and the plots of residuals.

The three-parameter GAB isotherm was the best and gave a good correlation ($R^2 > 0.9817$, RSS < 0.0293, MRD < 0.1380, $S_y < 0.0141$, and random residuals-plots) for the general data-fit in the range of a_w from 0.1 to 0.9, of interest in seed storage and processing. The Modified Halsey equation was rejected because it gave poor statistic parameters of agreement and patterned residual plots.

For desorption, the Modified Chung–Pfost model gave the lowest mean relative deviation; the Modified Henderson equation was the second best in describing the EMC–ERH data, followed by the Modified Oswin and GAB models. For adsorption, the GAB equation presented the lesser MRD, followed by the Modified Chung–Pfost, Henderson and Oswin models. When mean sorption data were analyzed, the Modified Chung–Pfost equation was the best.

However, when the GAB isotherm was adjusted at each temperature, a higher quality of agreement was obtained compared with the other isotherms, demonstrating the adequacy of GAB model to describe the experimental data of EMC–ERH for amaranth.

Keywords: Equilibrium moisture content; Amaranth; Water activity

1. Introduction

Amaranth is a pseudo-cereal originated in Central America that has been harvested for several centuries. In pre-Hispanic times, the native population from mainly arid regions exploited this product for food and ornaments, and harvested more than 20,000 ton/year (Tosi & Ré, 2003).

Recently, amaranth has been rediscovered by virtue of its extraordinary nutritional-characteristics: excellent quality of its proteins, high content of lysine and a good balance in other essential amino-acids, high contents of vitamins A, B_1 and C, calcium, phosphorous, magnesium and iron. Besides, due to its very low content of gluten it can be used in formulations for celiacs. The composition of its proteins is very similar to that of milk; therefore, the Food and Agriculture Organization

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(FAO) has suggested their use for human diets. NASA qualified this grain as CELSS (Controlled Ecological Life Support System) and cultivates them due their nutritious values, integral utilization, brief cycle and resistance to adverse conditions of development.

In Argentina, this grain is cultivated in the North-West regions and in the Central-South Pampas. The most appropriated zone for their growth has been proposed around a band at 20° South Latitude, from the Atlantic coast up to about 3000 m above sea level, where the annual rainfall is in the range 400–800 mm. The volume of harvest is generally between 1800 and 2300 kg/ha, and exceptionally it can reach 4500 kg/ha (Tosi & Ré, 2003).

After approximately 170 days of growth, the grains are usually harvested with high moisture contents, of about 50% (Tosi & Ré, 2003).

Post-harvest operations must be wisely managed to maintain the quality of grains. Knowledge about EMC (equilibrium moisture content)–ERH (equilibrium relative humidity) relationships is essential to design and optimize the post-harvest operations like storage, drying, aeration, handling and processing of grains.

The objectives of the present work were:

(i) to compile EMC–ERH data for amaranth grains (*Amaranthus cruentus* L.) at different temperatures and water activities;
(ii) to evaluate the suitability of five frequently used three-parameter equations recommended by the ASAE Standards (ASAE, 1999) (Modified Henderson, Modified Chung–Pfost, Modified Halsey, Modified Oswin and Guggenheim–Anderson–de Boer (GAB)) for the description of equilibrium moisture content data of amaranth grains; and
(iii) to select the best isotherm model for describing EMC–ERH for amaranth grains based on statistical analysis.

2. Isotherm equations and fitting method

2.1. Sources of EMC–ERH data

Experimental data of EMC–ERH (M_e vs. a_w) of the species *Amaranthus cruentus* L. were taken from literature (Lema, Palumbo, Adaro, & Lara, 2001; Pollio, Tolaba, & Suárez, 1998; Tosi, Masciarelli, & Ciappini, 1994) for water sorption at 25, 30, 35, 40, 45, 50, 55, 65, 70 and 90 °C in the range of water activity from 0.029 to 0.979. The data sets (Table 1) comprised experimental values of EMC–ERH that summarize 78 points for desorption, 53 for adsorption and 16 not discerned points that were considered for mean sorption. All the information was original experimental points either cited precisely in tables or read from experimental points on figures.

The reported data of EMC–ERH for amaranth grains were obtained by static gravimetric methods with different atmospheres surrounding the product (saturated salt or saturated acid solutions). The high level of scattering of the whole data set can be seen. The dif-

Table 1
Sources of sorption data of amaranth grains (*Amaranthus cruentus* L.)

Range of temperature (°C)	Range of water activity (decimal)	Type of data[a]	Number of points	Method[b]	Reference
25–55	0.114–0.979	Ads.	53	Grav./sss.	Lema et al. (2001)
25–65	0.029–0.979	Des.	78	Grav./sss.	Pollio et al. (1998); Lema et al. (2001)
40–90	0.20–0.80	N.A.	16	Grav./sas.	Tosi et al. (1994)

[a] Ads.: adsorption; Des.: desorption; N.A.: not accounted.
[b] Grav./sss.: gravimetric with saturated salt solutions; Grav./sas.: gravimetric with saturated acid solutions.

Table 2
EMC–ERH relationships from the American Society of Agricultural Engineering (ASAE) used to analyze EMC–ERH data of amaranth grains (*Amaranthus cruentus* L.)

Isotherm equation	Expression	
Modified Henderson Eqn. (Thompson, 1967):	$a_w = 1 - \exp[-A \cdot (T + C) \cdot M_e^B]$	(1)
Modified Chung–Pfost Eqn. (Pfost, Mourer, Chung, & Milliken, 1976):	$a_w = \exp\left[-\frac{A}{T+C}\exp(-B \cdot M_e)\right]$	(2)
Modified Halsey Eqn. (Iglesias & Chirife, 1976):	$a_w = \exp\left[-\frac{\exp(A+B\cdot T)}{M_e^C}\right]$	(3)
Modified Oswin Eqn. (Chen, 1988):	$a_w = \left[\left(\frac{A+B\cdot T}{M_e}\right)^C + 1\right]^{-1}$	(4)
GAB Eqn. (Anderson, 1946):	$M_e = \frac{A_G \cdot B_G \cdot C_G \cdot a_w}{(1 - \cdot B_G \cdot a_w)(1 - B_G \cdot a_w + B_G \cdot C_G \cdot a_w)}$	(5)

a_w: water activity; T: temperature (°C); M_e: moisture content (dry basis); A, B, C: empirical constants; A_G, C_G, B_G: constants of GAB (monolayer moisture content, first adsorption layer and multilayer, respectively).

ferences among the reported data would be attributed to differences in grain maturity and history, and to the different techniques used for measuring EMC–ERH (Brooker, Bakker-Arkema, & Hall, 1981; Chen & Jayas, 1998).

2.2. Models for the data analysis

The EMC–ERH data for amaranth grains (*Amaranthus cruentus* L.) were analyzed using five three-parameter isotherms that have been adopted as standard equations by the American Society of Agricultural Engineering (ASAE) for describing EMC–ERH data for cereals and oilseeds (ASAE, 1999): Modified Henderson, Modified Chung–Pfost, Modified Halsey, Modified Oswin and GAB equations. These equations are given in Table 2.

2.3. Comparison methods

The goodness of fit for each isotherm was quantified through five standards: the correlation coefficient (R^2), the residual sum of squares (RSS), the standard error of the estimate (S_y), the mean relative deviation (MRD) and the plots of residuals.

The residual sum of squares (RSS) is defined as follows:

$$\mathrm{RSS} = \sum_{i=1}^{m} (M_\mathrm{e} - \hat{M}_e)^2 \tag{6}$$

where M_e is the measured value; $\hat{M}_e$ is the value estimated through the fitting equation and m is the number of data points.

The standard error of estimate (S_y) is the conditional standard deviation of the dependent variable and has the form:

$$S_y = \sqrt{\frac{\sum_{i=1}^{m} (M_\mathrm{e} - \hat{M}_e)^2}{\mathrm{df}}} = \sqrt{\frac{\mathrm{RSS}}{\mathrm{df}}} \tag{7}$$

where 'df' are the degrees of freedom of the fitting equation. If a large data set is available, the last expression can be simplified to

$$S_y \cong \sqrt{\frac{\mathrm{RSS}}{m}} \tag{8}$$

The mean relative deviation (MRD) is an absolute value that was used because it gives a clear idea of the mean divergence of the estimated data from the measured data:

$$\mathrm{MRD} = \frac{1}{m} \sum_{i=1}^{m} \frac{|M_\mathrm{e} - \hat{M}_e|}{M_\mathrm{e}} \tag{9}$$

The plotting of the residuals ($M_\mathrm{e} - \hat{M}_e$) against the independent variable was also used as a measure of the adjustment in the range of analysis. If the model is correct then the residuals should be only random independent errors with a zero mean, constant variance and arranged in a normal distribution.

Even though a model can be presumed accurate from the regression analysis, before constructing inferences, the underlying hypotheses of the analysis must be proven. If the residuals plots indicate a clear pattern, the model should not be accepted. All the information is contained in the residuals, then the analysis of residuals in front of the predicted values is a valuable tool for diagnosis.

In general terms, low values of R^2, high values of RSS, S_y and MRD, and clear patterns in the residual plots mean that the model is not able to explain the variation in the experimental data.

3. Results and discussion

The coefficients for each equation were evaluated using the Non-Lin module of Systat (Wilkinson, 1990). This procedure is an algorithm for minimum sum-of-squares regression of m nonlinear equations with n variables.

In the first step, the fitting of the five isotherms of ASAE was carried out for the complete pool of recorded experimental data. Table 3 shows the results of each isotherm equation and their associated statistical parameters (ASE and ASE% represent the standard error and the percent standard error of the estimate of the parameter).

The coefficients of the Modified Henderson, Modified Chung–Pfost, Modified Halsey and Modified Oswin equations from Table 3 were used to predict the water activity at different temperatures (Fig. 1a–j). The GAB equation does not handle the dependency of EMC with temperature; therefore, only one curve can be drawn for the whole range of temperatures.

This fitting can be only used to describe the average sorption behavior because it resulted from the fitting of the whole data set provided by different sources, experimental techniques, and temperature and water activity ranges.

Table 3 shows that relatively high values were found for the correlation coefficient for all the models ($R^2 > 0.9803$), showing in the first analysis that all the equations can be considered valid. However, the fact that some models can be deemed unsuitable by other statistical criteria means that the value of R^2 is not by itself a solid or robust analysis index (Sun & Woods, 1994).

Following this concept, it can be observed in Table 3 that the Modified Halsey equation gave higher values of residual sum of squares (RSS), standard error of the estimate (S_y) and mean relative deviation (MRD), and the smallest values of R^2. These results should suggest that this is not the most appropriate model for description of the experimental data. In a similar fashion, the Modified Henderson, Modified Chung–Pfost and Modified

Table 3
Coefficients of Modified Henderson, Modified Chung–Pfost, Modified Halsey, Modified Oswin and GAB equations for amaranth grains (*Amaranthus cruentus* L.) in the range of temperature from 25 to 90 °C and water activity from 0.029 to 0.979

Equation	Parameters			Statistics of fitting				
	A	B	C	R^2	RSS	S_y	MRD	Residuals
Modified Henderson	0.3709 ASE = 0.1025 ASE% = 27.6	1.7604 ASE = 0.0567 ASE% = 3.2	95.4653 ASE = 30.348 ASE% = 31.8	0.9864	0.6367	0.0663	0.1581	Random
Modified Chung–Pfost	562.89 ASE = 111.96 ASE% = 19.9	20.98 ASE = 26.50 ASE% = 126.3	89.41 ASE = 0.64 ASE% = 0.7	0.9871	0.6043	0.0648	0.1485	Random
Modified Halsey	−4.2840 ASE = 0.1812 ASE% = 4.2	−0.0079 ASE = 0.0019 ASE% = 24.1	1.6938 ASE = 0.0695 ASE% = 4.1	0.9803	0.9247	0.0800	0.2135	Patterned
Modified Oswin	0.0988 ASE = 0.0010 ASE% = 1.0	−0.0003 ASE = 0 ASE% = 0	2.5121 ASE = 0.0869 ASE% = 3.5	0.9854	0.6845	0.0693	0.1749	Random
GAB	A_G	B_G	C_G	R^2	RSS	S_y	MRD	Residuals
	0.0634 ASE = 0.0035 ASE% = 5.5	0.7218 ASE = 0.0196 ASE% = 2.7	11.1997 ASE = 2.2202 ASE% = 19.8	0.9817	0.0293	0.0141	0.1380	Random

Oswin equations also showed higher values of RSS, S_y and MRD, accompanying lower values of R^2 compared with those corresponding to the GAB equation. Then, at first examination, the GAB equation appears the most suitable model for experimental data modelling.

Isotherm equations that gave values of MRD less than 0.05 have been considered to be a good fit (Lomauro, Bakshi, & Labuza, 1985). Therefore, MRD and S_y criteria do not always provide the same ranking for all EMC–ERH models (Chen & Morey, 1989). Finally, it is obvious that a single statistical parameter cannot be used to select the best model and the assessment of model must always be made based on multiple statistical criteria (Jayas & Mazza, 1993).

In order to complete the statistical analysis, for those equations which in the prior inquiry were not rejected, the residuals were examined at different temperatures by plotting them against measured values: a_w for Modified Henderson, Modified Chung–Pfost, Modified Halsey, Modified Oswin equations and M_e for GAB equation. Uniformly scattered data points arranged in bands around zero for the residual plots for the Modified Henderson, Modified Chung–Pfost, Modified Oswin and GAB equations, and a patterned residuals plot for Modified Halsey equation were obtained.

On the other hand, the GAB equation shows a distribution of residuals around zero, in a very narrow band compared to other models. This result confirms the previous presumptions about the GAB equation, showing it as a superior model to describe EMC–ERH data of amaranth. The rest of the models, either because they exhibited definite patterns in the residual plots (Modified Halsey) or random residual values in a wide band around zero, were considered to have a poorer agreement with the experimental data.

As the experimental data fell into three groups—desorption, adsorption and mean sorption—as a second step, the data were adjusted separately for each group. The results are shown in Table 4.

It can be seen that the adjustment of the data, classified by origin (desorption, adsorption and mean sorption) led to lower values of mean relative deviation (MRD) than did the initial fitting for the pool of data. Then, the degree of agreement of all models increased. It can also be noted that Modified Halsey equation presented patterned residual plots for desorption as well as for adsorption and mean sorption, as was the previous conclusion about this model.

Discarding the Modified Halsey equation, the MRD statistics of the other models were compared. It can be seen that for desorption the Modified Chung–Pfost equation gave a mean relative error lower than 10% (MRD = 0.0963); followed by the Modified Henderson (MRD = 0.1095), Modified Oswin (MRD = 0.1140) and GAB (MRD = 0.1216) equations.

For adsorption, the GAB equation showed a minor mean relative deviation (MRD = 0.0833), followed by the Modified Chung–Pfost (MRD = 0.0941), Modified Henderson (MRD = 0.0962) and Modified Oswin (MRD = 0.1163) models. Except for the Modified Oswin, the other models yielded random residual plots.

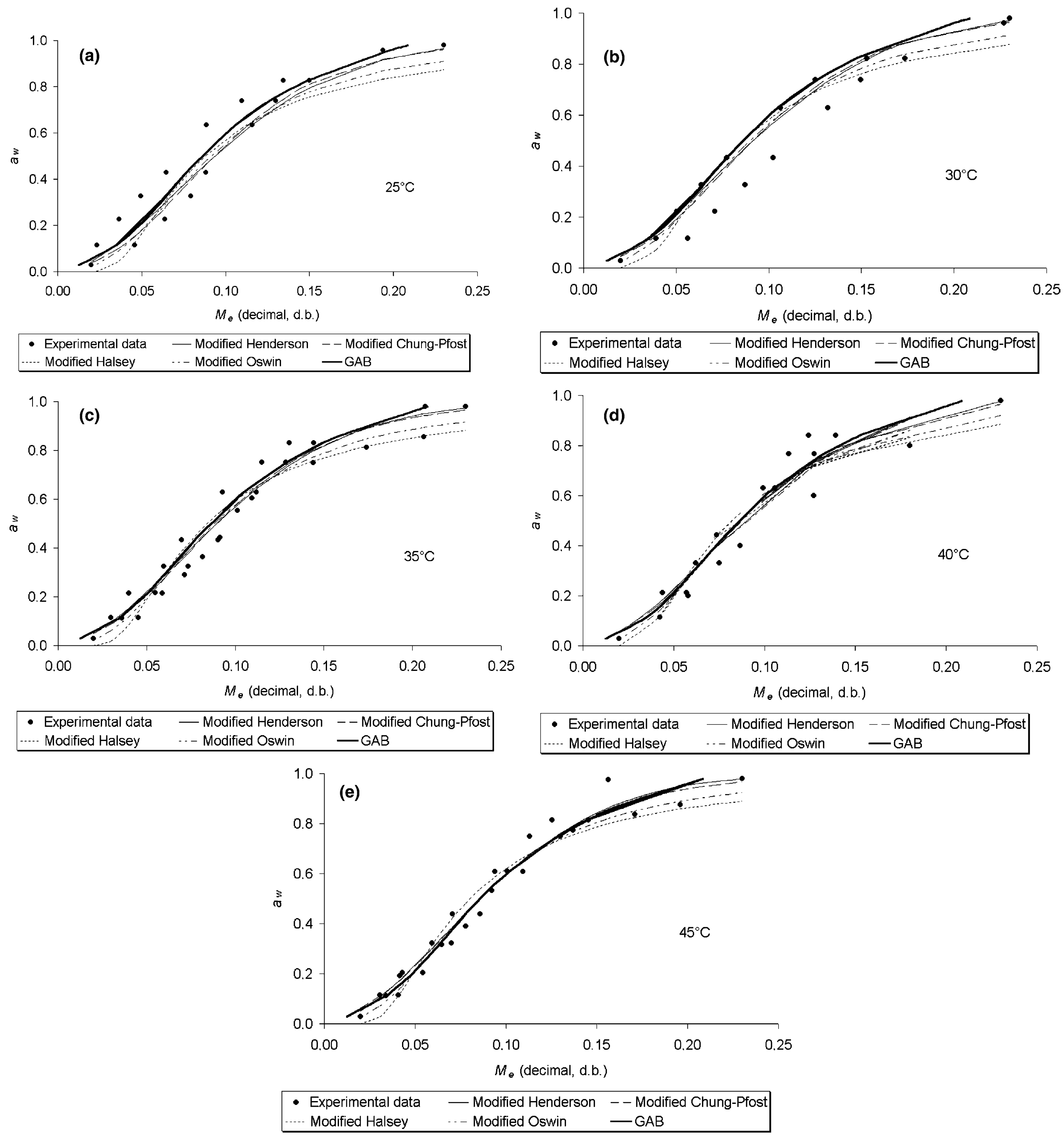

Fig. 1. Experimental and predicted data using the general fit of the Modified Henderson, Modified Chung–Pfost, Modified Halsey, Modified Oswin and GAB equations EMC–ERH of amaranth grains (*Amaranthus cruentus* L.).

When mean sorption was analyzed, it was observed that the Modified Chung–Pfost equation again yielded the least mean relative deviation (MRD = 0.0330), followed by the Modified Henderson (MRD = 0.0438), Modified Owsin (MRD = 0.0682) and GAB equations (MRD = 0.1298). But the Modified Oswin model once more yielded a possible patterned residual plot, denoting an inferior agreement with the experimental data.

Considering in full the preceding analysis, however, it must not be forgotten that the fitting of the three-parameter GAB isotherm did not take account of the effect of temperature. Therefore, direct statistical comparison of the GAB equation against the other four

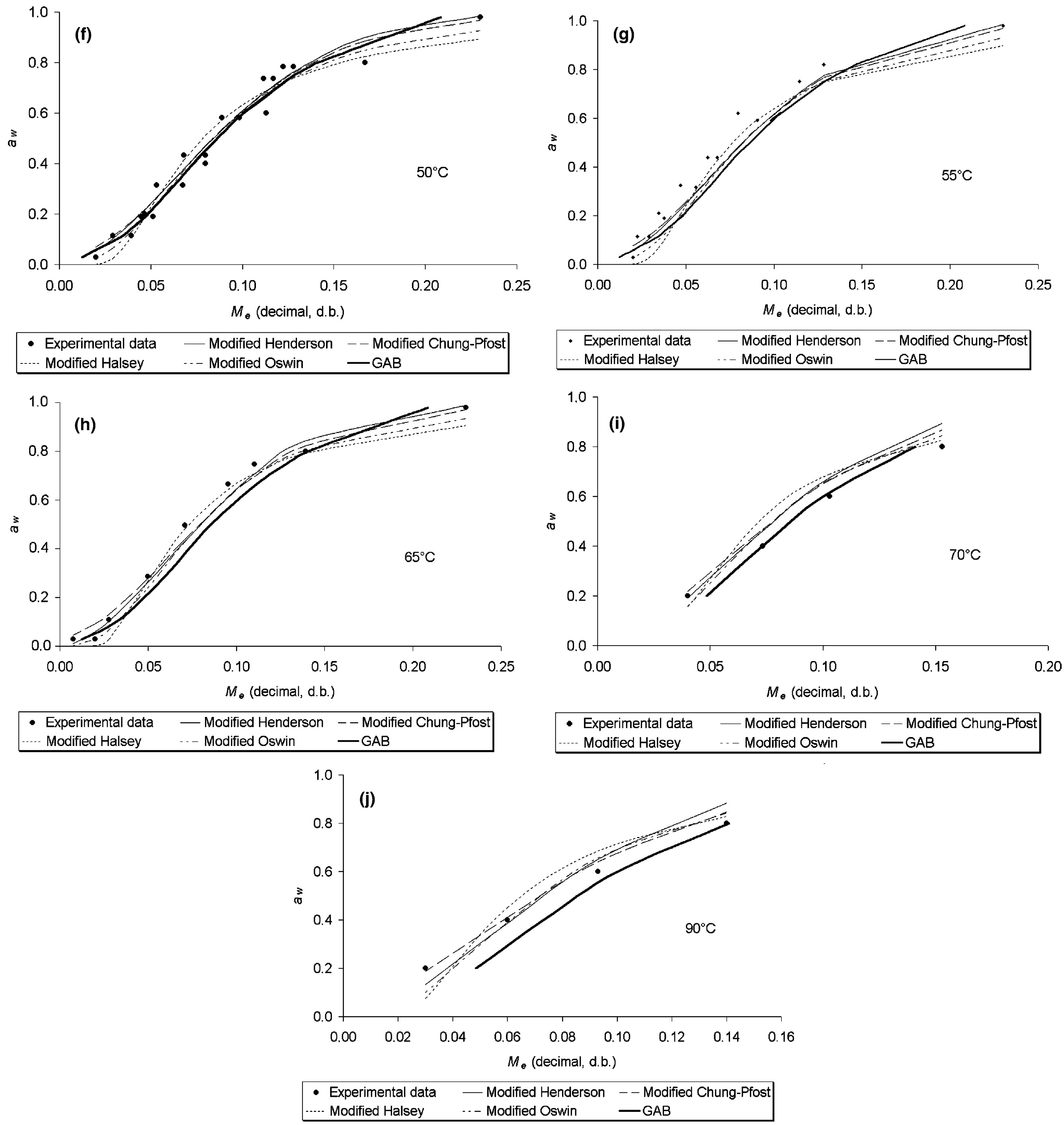

Fig. 1 (*continued*)

equations can only discriminate between them if the model has already been considered appropriate.

The parameters of the GAB equation may each be a function of T (Jayas & Mazza, 1993; Shatadal & Jayas, 1990), resulting in the need to adjust the values for each parameter (A_G, B_G and C_G) at each temperature (25, 30, 35, 40, 45, 50, 55 and 65 °C for desorption, 25, 30, 35, 40, 45, 50 and 55 °C for adsorption and 40, 70 and 90 °C for mean sorption). The results of this fitting are presented in Table 5 with the corresponding statistics.

Table 5 shows higher R^2 and lower MRD, RSS and S_y values compared with the values obtained in Table 4 for the fitting of the GAB equation to the full data of desorption, adsorption and mean sorption that did not consider the effect of T on equilibrium. Also, all

Table 4
Coefficients of Modified Henderson, Modified Chung–Pfost, Modified Halsey, Modified Oswin and GAB equations for Desorption, Adsorption and Mean Sorption of water from amaranth grains (*Amaranthus cruentus* L.) in the range of temperature from 25 to 90 °C and water activity from 0.029 to 0.979

Equation	Parameters			Statistics of fitting				
	A	*B*	*C*	R^2	RSS	S_y	MRD	Residuals
Desorption								
Modified Henderson	1.1499 ASE = 0.2228 ASE% = 19.4	1.9639 ASE = 0.0580 ASE% = 2.9	24.2105 ASE = 7.0623 ASE% = 29.2	0.9939	0.1491	0.0447	0.1095	Random
Modified Chung–Pfost	328.7558 ASE = 30.9902 ASE% = 9.4	22.1104 ASE = 0.5642 ASE% = 2.6	21.7709 ASE = 0.5846 ASE% = 2.7	0.9952	0.1189	0.0400	0.0963	Random
Modified Halsey	−4.3608 ASE = 0.1981 ASE% = 4.5	−0.0170 ASE = 0.0024 ASE% = 14.1	1.9225 ASE = 0.0811 ASE% = 4.2	0.9896	0.2552	0.0583	0.1756	Patterned
Modified Oswin	0.1212 ASE = 0.0008 ASE% = 0.7	−0.0008 ASE = 0 ASE% = 0	2.8301 ASE = 0.0839 ASE% = 3.0	0.9943	0.1398	0.0436	0.1140	Possible patterned
GAB	A_G	B_G	C_G	R^2	RSS	S_y	MRD	Residuals
	0.0637 ASE = 0.0037 ASE% = 5.8	0.7320 ASE = 0.0218 ASE% = 3.0	15.1821 ASE = 3.7543 ASE% = 24.7	0.9867	0.0122	0.0127	0.1216	Random
	A	*B*	*C*	R^2	RSS	S_y	MRD	Residuals
Adsorption								
Modified Henderson	0.2707 ASE = 0.1238 ASE% = 45.7	1.7740 ASE = 0.0519 ASE% = 2.9	181.8291 ASE = 95.5738 ASE% = 52.6	0.9957	0.0758	0.0387	0.0962	Random
Modified Chung–Pfost	1098.7389 ASE = 1130.7 ASE% = 102.9	23.1640 ASE = 0.7677 ASE% = 3.3	225.6053 ASE = 132.718 ASE% = 58.8	0.9956	0.0765	0.0387	0.0941	Random
Modified Halsey	−4.6504 ASE = 0.2582 ASE% = 5.6	−0.0040 ASE = 0.0034 ASE% = 85.0	1.6845 ASE = 0.0876 ASE% = 5.2	0.9885	0.2010	0.0632	0.1809	Patterned
Modified Oswin	0.0826 ASE = 0.001 ASE% = 1.2	−0.0002 ASE = 0 ASE% = 0	2.4861 ASE = 0.0910 ASE% = 3.7	0.9940	0.1057	0.0458	0.1183	Possible patterned
GAB	A_G	B_G	C_G	R^2	RSS	S_y	MRD	Residuals
	0.0544 ASE = 0.0036 ASE% = 6.6	0.7511 ASE = 0.0200 ASE% = 2.7	10.5661 ASE = 2.7185 ASE% = 25.7	0.9895	0.0053	0.0100	0.0833	Random
	A	*B*	*C*	R^2	RSS	S_y	MRD	Residuals
Mean sorption								
Modified Henderson	0.2530 ASE = 0.0430 ASE% = 17.0	1.5028 ASE = 0.0475 ASE% = 3.2	40.2005 ASE = 10.294 ASE% = 25.6	0.9987	0.0062	0.0224	0.0438	Random
Modified Chung–Pfost	335.7783 ASE = 23.709 ASE% = 7.1	17.1099 ASE = 0.3758 ASE% = 2.2	39.8367 ASE = 7.1152 ASE% = 17.9	0.9994	0.0030	0.0141	0.0330	Random

(*continued on next page*)

Table 4 (*continued*)

Equation	Parameters			Statistics of fitting				
	A	*B*	*C*	R^2	RSS	S_y	MRD	Residuals
Modified Halsey	−3.1627 ASE = 0.2471 ASE% = 7.8	−0.0106 ASE = 0.0022 ASE% = 20.8	1.3974 ASE = 0.0960 ASE% = 6.9	0.9938	0.0296	0.0480	0.1050	Patterned
Modified Oswin	0.1251 ASE = 0.0015 ASE% = 1.2	−0.0006 ASE = 0 ASE% = 0	2.1099 ASE = 0.0959 ASE% = 4.5	0.9976	0.0117	0.0300	0.0682	Possible patterned
GAB	A_G	B_G	C_G	R^2	RSS	S_y	MRD	Residuals
	0.0753 ASE = 0.0263 ASE% = 34.9	0.7265 ASE = 0.1312 ASE% = 18.1	5.8055 ASE = 3.8359 ASE% = 66.1	0.9872	0.0023	0.0141	0.1298	Random

Table 5
Coefficients of GAB equation for Desorption and Adsorption of water from amaranth grains (*Amaranthus cruentus* L.) at different temperatures in the range from 25 to 90 °C and water activity from 0.029 to 0.979

T (°C)	A_G	ASE_{A_G}	B_G	ASE_{B_G}	C_G	ASE_{C_G}	R^2	RSS	S_y	MRD
*Desorption**										
25	0.070	0.003	0.676	0.014	19.913	3.330	0.9997	3.2×10^{-5}	0.0008	0.0191
30	0.078	0.002	0.689	0.010	21.490	2.833	0.9998	2.3×10^{-5}	0.0020	0.0142
35	0.077	0.011	0.678	0.050	10.792	4.846	0.9906	2.4×10^{-3}	0.0141	0.0619
40	0.078	0.005	0.568	0.035	14.476	1.922	0.9997	1.7×10^{-5}	0.0021	0.0164
45	0.056	0.005	0.807	0.031	17.242	6.822	0.9965	6.0×10^{-4}	0.0070	0.0648
50	0.070	0.003	0.619	0.025	14.079	1.307	0.9999	6.7×10^{-6}	0.0004	0.0088
55	0.065	0.005	0.664	0.031	7.800	0.971	0.9998	1.1×10^{-5}	0.0016	0.0223
65	0.044	0.005	0.858	0.048	12.841	5.121	0.9980	9.7×10^{-5}	0.0049	0.0955
*Adsorption**										
25	0.052	0.002	0.778	0.009	7.352	0.948	0.9998	2.0×10^{-5}	0.0020	0.0223
30	0.056	0.001	0.789	0.007	16.424	2.455	0.9998	2.1×10^{-5}	0.0020	0.0179
35	0.051	0.003	0.776	0.015	13.102	3.841	0.9990	9.1×10^{-5}	0.0040	0.0442
40	0.086	0.010	0.494	0.056	7.588	0.862	0.9997	3.3×10^{-6}	0.0009	0.0213
45	0.073	0.003	0.587	0.016	8.155	0.729	0.9998	1.2×10^{-5}	0.0010	0.0168
50	0.057	0.005	0.720	0.041	10.737	2.153	0.9995	2.3×10^{-5}	0.0024	0.0282
55	0.049	0.006	0.787	0.048	7.313	2.286	0.9900	4.8×10^{-5}	0.0030	0.0231
*Mean sorption**										
40	0.079	0.009	0.742	0.048	9.186	2.955	0.9998	1.1×10^{-5}	0.0017	0.0213
50	0.076	0.006	0.736	0.029	6.538	1.050	0.9999	2.8×10^{-6}	0.0005	0.0095
70	0.074	0.012	0.715	0.061	5.378	1.524	0.9989	8.0×10^{-6}	0.0014	0.0180
90	0.084	0.007	0.670	0.026	2.936	0.266	1	$5.0.10^{-7}$	0.0004	0.0342

* Residual plots: random or not clear patterns for all temperatures.

the residual plots were uniformly scattered in a narrow band around zero. These results demonstrate the excellent quality of GAB model for describing the experimental data of EMC–ERH for amaranth.

Based on the above discussion, the GAB equation can be claimed as the best model for describing the EMC–ERH data, for desorption as well as for adsorption and mean sorption of water from amaranth. Fig. 2a–d shows the experimental EMC–ERH data at four temperatures compared with the predicted EMC–ERH values using the more appropriated isotherm: GAB.

4. Conclusions

The GAB equation was the best model for describing the EMC–ERH data, for desorption as well as for adsorption and mean sorption of water from amaranth.

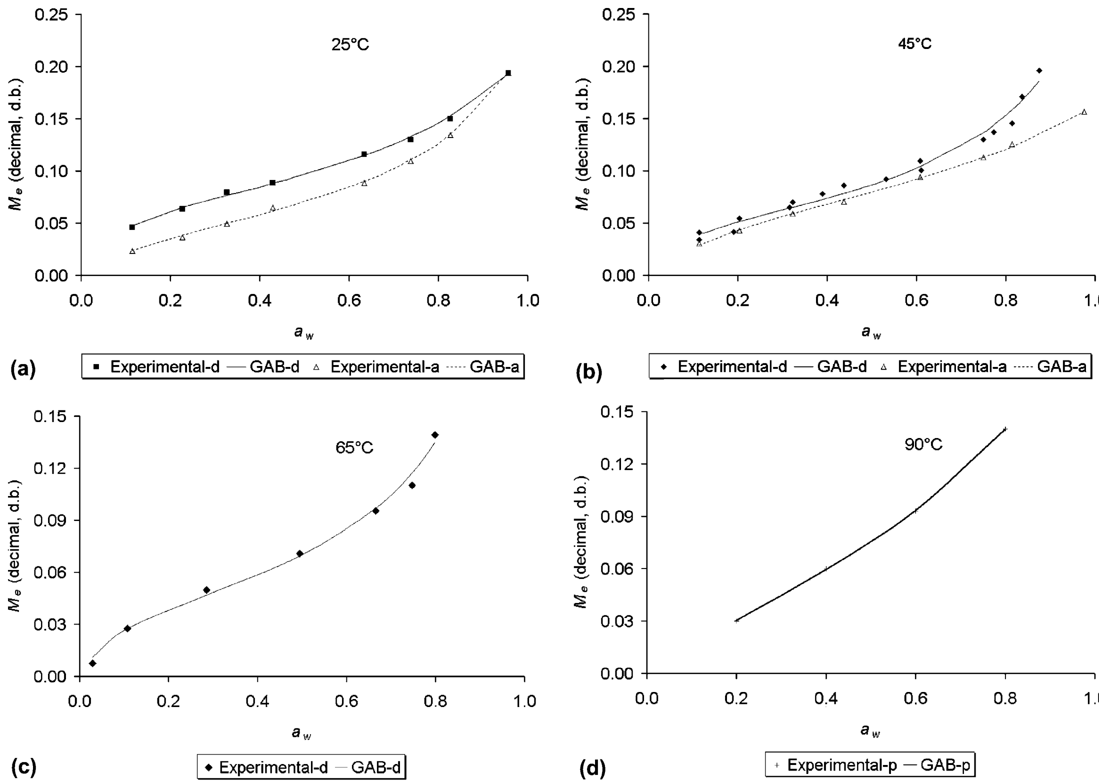

Fig. 2. Experimental EMC–ERH data at four temperatures compared with the predicted by the GAB equation EMC–ERH values (*d*: desorption, *a*: adsorption, *p*: mean sorption).

The Halsey equation was not suitable for fitting the data.

After the GAB model, the Modified Chung–Pfost equation can be considered next best for accuracy in describing the EMC–ERH data for desorption of water from amaranth, followed by the Modified Henderson equation, while the Modified Oswin equation must be rejected. For adsorption, the Modified Chung–Pfost was the next best after the GAB, followed by the Modified Henderson and Modified Oswin models. For mean sorption data, after the GAB equation, the Modified Henderson was the second best followed by the Modified Chung–Pfost; while the Oswin equation was inappropriate.

When specific regressions for the GAB model were obtained for the experimental data at each temperature, a clear increase in the accuracy of predictions was reached.

References

Anderson, R. B. (1946). Modifications of the Brunauer, Emmett and Teller equation. *Journal of the American Chemical Society, 68*, 686–691.

ASAE. (1999). ASAE Standards, Standards Engineering Practices Data 1999. ASAE, St. Joseph, MI 49085.

Brooker, D. V., Bakker-Arkema, F. W., & Hall, C. W. (1981). *Drying cereals grains*. Westport, CT, USA: The Avi Pub. Co. Inc.

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

Chen, C., & Jayas, D. S. (1998). Evaluation of the GAB equation for the isotherms of agricultural products. *Transactions of the ASAE, 41*(6), 1755–1760.

Chen, C., & Morey, R. V. (1989). Comparison of four EMC/ERH equations. *Transactions of the ASAE, 32*(3), 983–990.

Iglesias, H. A., & Chirife, J. (1976). Prediction of the effect of temperature on water sorption isotherms of food materials. *Journal of Food Technology, 11*, 109–116.

Jayas, D. S., & Mazza, G. (1993). Comparison of five, three-parameter equations for description of adsorption data of oats. *Transactions of the ASAE, 36*(1), 119–125.

Lema, A., Palumbo, D., Adaro, J., & Lara, M. (2001). Equilibrio de sorción de Amaranto. In *Memorias del VIII Congreso Latinoamericano de Transferencia de Calor y Materia LATCYM'2001* (pp. 184–189). Veracruz, México, ISBN 698-5401-00-4.

Lomauro, C. J., Bakshi, A. S., & Labuza, T. P. (1985). Evaluation of food moisture sorption isotherm equations. Part II: Milk, coffee, tea, nuts, oilseeds, spices and starchy foods. *Lebensmittel-Wissenschaft und-Technolologie, 18*, 118–124.

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

Pollio, M. L., Tolaba, M. P., & Suárez, C. (1998). Measuring and modeling grain sorption equilibria of amaranth grains. *Cereal Chemistry, 75*(3), 297–300.

Shatadal, P., & Jayas, D. S. (1990). Moisture sorption isotherms of grains and oilseeds. *Postharvest News and Information, 1*(6), 447–451.

Sun, D. W., & Woods, J. L. (1994). The selection of sorption isotherm equations for wheat based on the fitting of available data. *Journal of Agricultural Engineering Research, 30*(1), 27–43.

Thompson, T. L. (1967). Predicted performances and optimal designs of convection grain dryers. Ph.D. thesis, Purdue University, West Lafayette, USA.

Tosi, E., Masciarelli, R., & Ciappini, M. (1994). Humedades de equilibrio del Amaranto (*Amaranthus cruentus*). *La Alimentación Latinoamericana, 203*, 73–76.

Tosi, E., & Ré, E. D. (2003). Amaranto. Su Aplicación en la Alimentación Humana. *Aposgran, 82*(2), 15–16.

Wilkinson, L. (1990). *SYSTAT: The system for statistics*. Evanston, IL: SYSTAT Inc.