Drying Technology, 30: 1323–1331, 2012

ISSN: 0737-3937 print/1532-2300 online
DOI: 10.1080/07373937.2012.695758

Taylor & Francis
Taylor & Francis Group

Generalized Correlations for Characteristic Variables and Thermophysical Properties of Osmotically Dehydrated Fruits

A. Rodríguez[1] and R. H. Mascheroni[1,2]
[1]*Center for Research and Development in Food CryoTechnology (CIDCA), CONICET La Plata, UNLP, La Plata, Argentina*
[2]*MODIAL, Faculty of Engineering (UNLP), La Plata, Argentina*

Based on experiments on osmotic dehydration of different fruits, with diverse dehydrating solutions and working conditions, and on an extensive search of the literature on osmotic dehydration, general linear correlations between water content (WC) and soluble solids (SS) content of fruits dehydrated in sugar or alcohol solutions have been developed for each type of fruit that allows characterization of both properties with only one rapid determination of either property. A linear regression for SS vs. WC including all of the experimental data for the seven types of fruits tested (apple, strawberry, pear, kiwi, plum, nectarine, and melon) and the five solutes used in those experiments (sucrose, glucose, xylitol, sorbitol, polyethylene glycol) was obtained with a high regression coefficient.

Based on experimental data determined in this work in the range −40 to 40°C, correlations are established between heat capacity and enthalpy with water content and temperature for both fresh strawberries and strawberries that were osmotically dehydrated in different solutions. In addition, general polynomial correlations for the initial freezing temperature of fresh and osmotically dehydrated fruits as a function of water content and type of dehydrating solute are proposed.

Keywords Correlation; Enthalpy; Osmo-dehydrated fruits; Soluble solids; Water content

INTRODUCTION

Osmotic dehydration is a mild process that consists of immersing fruits or vegetables—entire, peeled, or portioned—in a sugar/sugar–salt/alcohol concentrated aqueous solution, where both partial dehydration of the tissue and solids uptake occur. The driving forces for the mass transfer are the differences in chemical potentials of water and solutes between the vegetable tissue and the dehydrating solution.[1] The water removal is carried out without a phase change in the liquid phase, which lowers energy use.[2] During subsequent processing, the energy requirements decrease due to the lower water content of the product.

The osmotic process can be used to broaden availability of fruits and vegetables and, in some cases, to enhance the soluble solids content in the final product, as a pretreatment prior to air or microwave drying,[3–7] refrigeration,[8] freezing,[9] preparing of candies and jams,[10] or frying.[11]

Moreover, the osmotic process can be employed in the development of minimally processed products,[12–14] prolonging their shelf life, with a slight reduction in water activity, and improving the microbiological stability, without changing the quality characteristics of fresh fruit considerably.

The interest in dehydration prior to further processing is due to the enhanced nutritional and organoleptic properties of the final products.[15] Osmotic dehydration, carried out at moderate temperatures, protects thermosensitive compounds such as flavors, pigments, and vitamins.[15,16] In addition, because it prevents food from coming into contact with the air, oxidation reactions[17] and loss of volatile compounds[18] are limited.

The wide diversity of raw food materials, with their different compositions and structures, sizes and shapes of pieces, and operating conditions (composition, temperature and agitation of the dehydrating solution, contact time) determined the need for extensive experimental work to characterize each particular case (food, piece, solution, operating condition). As a result, there are numerous papers in the recent literature on osmotic dehydration of fruits and vegetables, each dealing with certain fruits, dehydrating solutions, and operating conditions. Most of these papers compare their results against data from the literature, but no general correlations are provided for the prediction of variations in process variables and thermophysical properties during osmotic dehydration.[19]

It is important to develop general relations between those variables relevant to the dehydration process (water content [WC] and soluble solids [SS] content; water loss [WL] and solids gain [SG]) independent of product characteristics and process conditions. In addition, it is of high technical value to develop simple equations to predict the variation in thermophysical properties such as heat capacity (C_p) and enthalpy (H) with temperature and water content and initial freezing point (T_{cr}) with water content that are

Correspondence: R. H. Mascheroni, CIDCA, Calle 47 y 116, 1900 La Plata, Argentina; E-mail: rhmasche@ing.unlp.edu.ar

valid independent of the fruit or vegetable used. At present, this type of information is not available in the literature except for a linear correlation between WC and SS for kiwi dehydrated in sucrose.[19] Different authors found a partial linear relation between WL and SG.[19,20]

Regarding thermophysical properties, there is little specific information on osmotic dehydration (OD) of fruits and vegetables. Only a few sets of data from the literature[21–26] or from previous works by this research group[19,27–30] are available and only for reduced sets of fruits, dehydrating solutions, and operating conditions.

Therefore, the objectives of this work were to

1. Determine WC and SS for strawberries dehydrated in sucrose and xylitol solutions and apple in polyethylene glycol (PEG) solutions of different molecular masses.
2. Determine the enthalpy and heat capacity of fresh and osmotically dehydrated strawberries with different WC and SS contents in the range of −40 to 40°C.
3. Develop general correlations between WC and SS of osmodehydrated fruits.
4. Obtain correlations for enthalpy and heat capacity as a function of WC and temperature and of initial freezing point as a function of WC for fresh and osmodehydrated fruits.

EXPERIMENTAL METHODS

Osmotic Dehydration

Strawberries (*Fragaria ananassa* cv. Aromas) were bought at the market and immediately refrigerated at 0°C. Before dehydration, fresh fruits were exposed to room temperature for 1 h. Then they were washed, drained, and cut into slices of 2 mm thickness. These were introduced in flasks with the osmotic solution (sucrose at 60% ± 1% (w/w) or xylitol at 60% ± 1 (w/w)) and shaken at a constant temperature of 35 ± 2°C for the scheduled periods (1, 2, 4, 8, 12 h) in a thermostatic bath (model TT 400, Ferca, Argentina) with linear stirring (100 cycles per minute).

Apples (*Malus domestica* cv. Granny Smith) followed the same procedure except for the thickness of slices. Apples were cut into 10-mm-thick slices and dehydrated in solutions of PEG of 400 and 6,000 Da of molecular mass at 30 ± 2°C for the scheduled periods (2, 4, 6, 8, 16, 24, and 72 h).

The WC of fresh and OD samples was determined by drying in a vacuum oven (model OVA031 XX1.5, Gallenkamp, UK) at 70 ± 2°C until a constant weight was reached.

SS content was measured in an Abbe refractometer (No. A77341, Bellinham + Stanley Limited, England) and read in °Brix.

In addition, weight reduction (WR), WL, and SG were calculated according to mass balances:

$$WR = \frac{100\ (m_i - m_f)}{m_i} \tag{1}$$

$$WL = \left[\left(1 - \frac{\mathrm{TS^o}}{100}\right) - \left(1 - \frac{\mathrm{TS}}{100}\right)\left(1 - \frac{\mathrm{WR}}{100}\right)\right] \times 100 \tag{2}$$

$$SG = \left[\left(1 - \frac{\mathrm{WR}}{100}\right)\frac{\mathrm{TS}}{100} - \frac{\mathrm{TS^o}}{100}\right] \times 100 \tag{3}$$

In Eqs. (1)–(3) m_i and m_f are the initial and final mass of the sample, and TS° and TS are the initial and current values of the total solids content (%).

Differential Scanning Calorimetry Determinations

Samples (fresh or dehydrated) were mashed and homogenized and small subsamples (10–25 mg each) were then sealed in the specific sample holders (capsules) for differential scanning calorimetry (DSC) evaluation. Three samples were prepared for each dehydration time and the results of these runs were averaged to obtain values for data interpretation.

Tests were conducted on a differential scanning calorimeter with automatic data recording and evaluation (DSC model Q100, TA Instruments, New Castle, DE). Samples were stabilized at −40°C and heated from −40 to 40°C at a rate of 2°C min^{-1}, because the low heating rate minimizes the temperature lags likely to occur in the event of a poor thermal contact of the sample–capsule–base system.[31] The lower temperature level of −40°C was considered sufficient to cover the typical temperature range of most industrial processes. In addition, below −40°C, the additional amount of water frozen is negligible. For frozen foods, measurements are always performed when heating (thawing) the samples, because during freezing it is common for subfreezing to occur, which leads to erroneous values in measured properties.

Heat capacity C_p was determined using Universal Analysis V1.7F software (provided by TA Instruments). Enthalpy was calculated by integrating the experimental data of C_p vs. temperature, taking −40°C as the datum $H_{-40} = 0$.

The initial freezing temperature T_{cr} was determined as the position of the thawing peak in the experimental heat capacity vs. temperature plot, as described in previous works.[25,27] This is probably the less accurate of the measured properties, because this point cannot be determined with good precision even when the DSC is calibrated against pure materials of known melting points (sapphire and bidistilled water).[28]

The variation in enthalpy between −40°C and T_{cr} (H_{cr}) was determined for each sample. It can be considered as a characteristic value for the total change in enthalpy during freezing or thawing and also appears as a parameter in some prediction equations.

CALCULATIONS

Soluble Solids Content as a Function of Water Content

In a previous work,[19] a linear relationship was determined between WC and SS for samples of diverse shapes

and sizes of kiwi dehydrated in sucrose solutions of different concentrations and temperatures, suggesting that this relationship is inherent to the food and solute type and independent of the characteristics of the food (shape, size) and process conditions (temperature, concentration, mixing). These results belonged to four sets of data as indicated by Tocci and Mascheroni.[19] The obtained regression is given by Eq. (4):

$$SS = -0.8979\ WC + 87.68; \quad R^2 = 0.9637 \tag{4}$$

Solute Gain as a Function of Water Loss

Floury and coworkers[20] determined a linear relation between WL and SG during OD of mango. Tocci and Mascheroni[19] found similar relations during OD of kiwi in sucrose solutions. Results from both papers suggested that this relationship could be specific to food characteristics (shape, size). In addition, they postulated a linear relation between SG and WL provided that cell membrane permeability remains constant during dehydration (low degree of dehydration).

Enthalpy and Specific Heat

Most equations from the literature for the prediction of enthalpy and heat capacity at a temperature below T_{cr} are based on the theoretical Clausius-Clapeyron relationship.[32–34] To be able to deal with experimental data, some empirical versions are used because neither the average molecular weight nor the exact composition of solutes are known, and this relationship also implies ideal behavior of solutes, which is not true for dehydrated foods. Therefore, the prediction equations used were similar to those proposed by Schwartzberg,[35] adapted by Succar and Hayakawa[36] and already used for OD kiwi.[19]

$$C_p = A + B/(-T)^n \tag{5}$$

$$H = A(T + 40) + B/(n-1)[1/(-T)^{n-1} - 1/40^{n-1}] + C \tag{6}$$

for $T < T_{cr}$ and

$$C_p = E \tag{7}$$

$$H = D + E(T - T_{cr}) \tag{8}$$

for $T \geq T_{cr}$, where C_p is the heat capacity [kJ/(kg°C)]; H is the enthalpy (kJ/kg); T is the temperature (°C); T_{cr} is the initial freezing temperature (°C); and A, B, C, D, E, and n are fitted constants. Under ideal measuring conditions, the value of D should be equal to H_{cr}; that is, the enthalpy at T_{cr}.

For high water content foods such as fresh fruits, vegetables, and meats, the values of n and C in Eqs. (5) and (6) should be close to 2 and 0, respectively.[36] Dehydrated foods are expected to have lower values of n due to deviations in the behavior of the food compared to that of ideal solutions.[36]

RESULTS AND DISCUSSION

Objectives 3 and 4 of this article are to obtain prediction equations valid for a wide variety of fruits and dehydrating solutions and conditions. One of the goals was to determine whether the type of solute tested (sucrose, glucose, xylitol, sorbitol, and polyethyleneglycols of different molecular weights) had an influence on the values of SS vs. WC and T_{cr} vs. WC, which is probably due to the influence of molecular weight, hydration properties, size and shape of the molecule, etc., on diffusion rate, water-holding capacity, freezing point depression, etc., for equal SS contents.

Soluble Solids Content as a Function of Water Content

In part of our calculations (see Fig. 1) we used experimental data from Saurel,[37] who dehydrated fresh or frozen-thawed apple slices (variety Granny Smith) in PEG of different molecular masses (from 200 to 2,000 Da) and at different concentrations (45, 55, 65, and 75 °Brix) and included our own data, obtained as specified previously, with PEG of 400 and 6,000 Da of molecular mass.

As can be seen from Fig. 1 and from the obtained linear regression with $R^2 = 0.988$, all data clearly belong to the same universe and molecular mass has no clear influence on the variation in SS with WC (the same also applies to pretreatment—freezing/thawing or no pretreatment—and solution concentration).

In parallel we performed an extensive study on experimental data (our own and those from the literature[38–57]) for osmotic dehydration of fruits under different conditions (sample shape and size), osmotic agent, solution concentration and temperature, stirring, etc., for which the data for SS vs. WC were provided. We chose the fruits for which

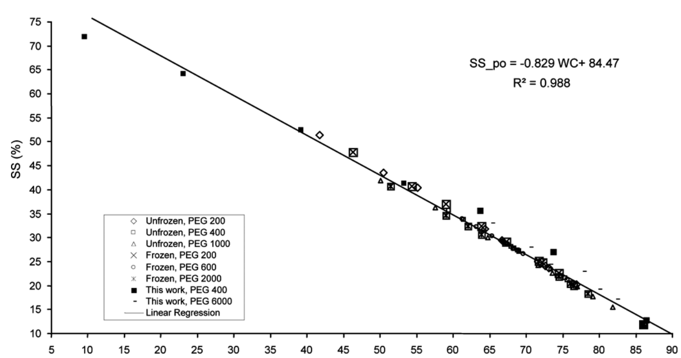

FIG. 1. Variation in SS content with WC for apple Granny Smith, fresh and dehydrated in solutions of PEG of different concentrations, and linear regression equation for SS vs. WC.

the most information was available (apple, kiwi, pear, nectarine, plum, melon, and strawberry). Those data were analyzed independently for each fruit and the results of SS vs. WC are shown in Figs. 2–10, together with the linear regression for each type of fruit. In all cases the source of data is specified, together with the type of solute and, when used, the pretreatment employed. If the solute is not specified, it was sucrose.

In the case of apples—fruit for which the most information was available—we performed a detailed study in relation to the type of solute (PEG, sucrose, or glucose). The experimental data and linear regressions for each of three solutes are presented in Figs. 1 to 3. In addition, we used the whole set of data (171 pairs SS vs. WC) to obtain a general linear correlation for apple. This is presented in Fig. 4 together with those for the different solutes. As can be seen from these figures there were small differences for the three solutes and all data can adequately be described by a general correlation with equivalent accuracy to that of the individual ones (all with R^2 of about 0.98).

In a similar way, the results for kiwi, pear, nectarine, plum, melon, and strawberry are presented in Figs. 5 to 10.

It can be clearly seen that—even including experimental data with measuring errors in WC and/or SS determination (as those with an amount of water plus solutes far higher than 100%)—all of the analyzed cases showed linear regressions with high regression coefficients and no definite trends according to fruit variety or process conditions.

It seems that for each fruit the slope of the linear regression was determined by characteristics specific to that fruit (insoluble solids content, structure), but the differences induced by type of fruit, solute, and processing conditions were minimal. This is so because it is possible to develop a general linear correlation that includes all fruits using only one parameter (WC or SS); we made use of the whole data

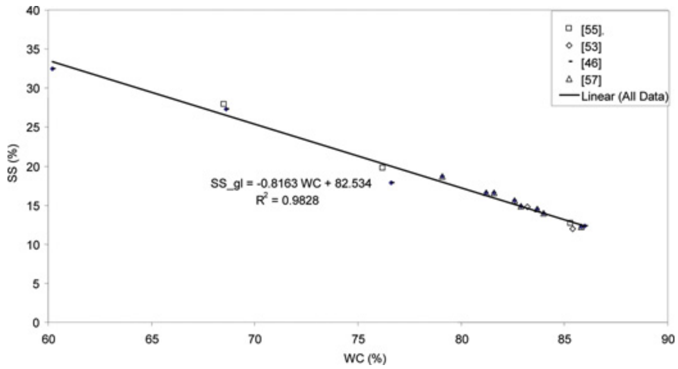

FIG. 3. Variation in SS content with WC for apples of different varieties (Granny Smith, Red Delicious), fresh and dehydrated in solutions of glucose of different concentrations, and linear regression equation for SS vs. WC (color figure available online).

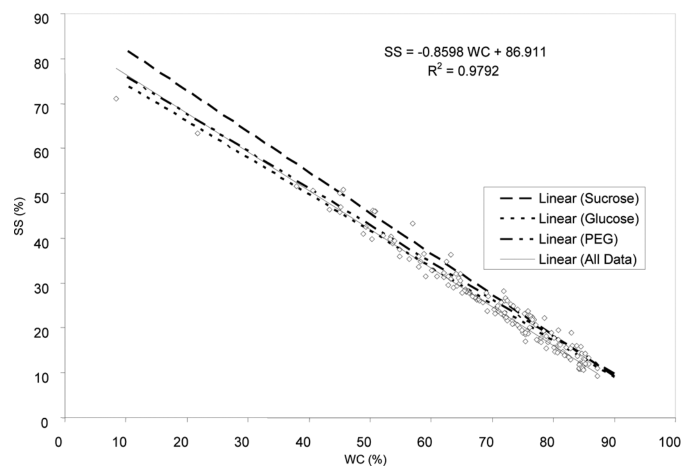

FIG. 4. Variation in SS content with WC for apples of different varieties (Granny Smith, Red Delicious, Fuji), fresh and dehydrated in solutions of different solutes; linear regression equation for SS vs. WC for all data; and comparison with linear regressions for PEG, sucrose, and glucose.

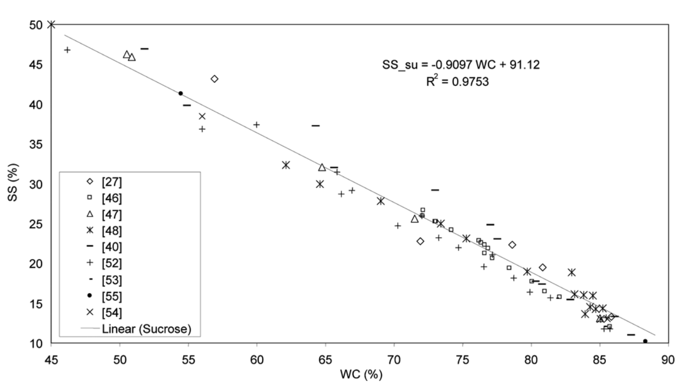

FIG. 2. Variation in SS content with WC for apples of different varieties (Granny Smith, Red Delicious), fresh and dehydrated in solutions of sucrose of different concentrations, and linear regression equation for SS vs. WC.

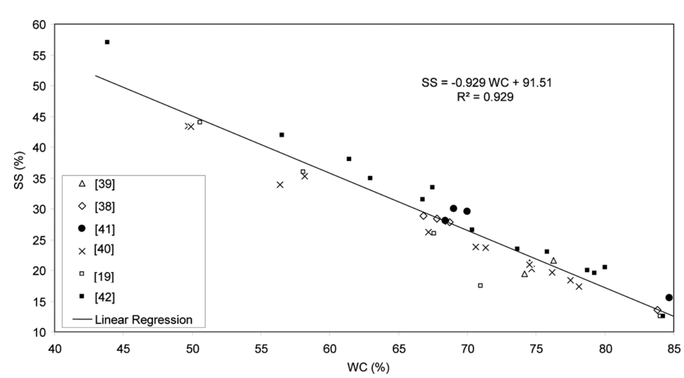

FIG. 5. Variation in SS content with WC for kiwifruit, fresh and dehydrated in solutions of sucrose of different concentrations, and linear regression equation for SS vs. WC.

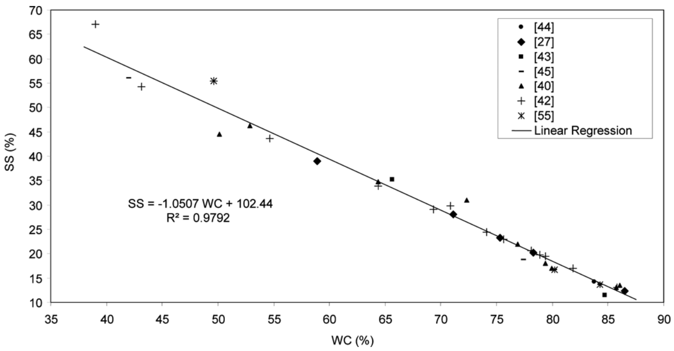

FIG. 6. Variation in SS content with WC for pears of different varieties (Packham's Triumph, D'Ánjou, Blanquilla), fresh and dehydrated in solutions of sucrose of different concentrations, and linear regression equation for SS vs. WC.

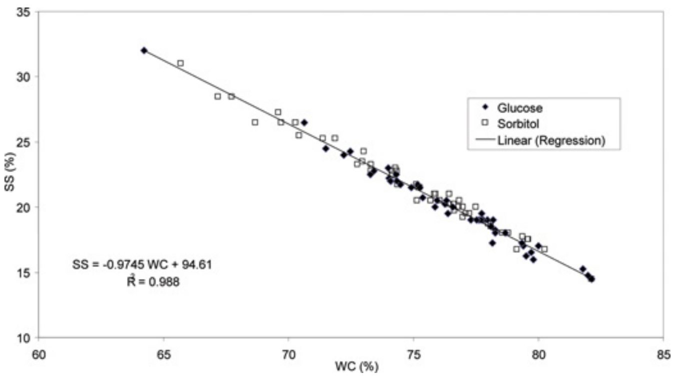

FIG. 7. Variation in SS content with WC for nectarines, fresh and dehydrated in solutions of glucose or sorbitol, and linear regression equation for SS vs. WC (color figure available online).

set of 431 experimental points for the seven different fruits studied. The linear correlation obtained:

$$SS = -0.9808\ WC + 96.441;\ R^2 = 0.9872 \qquad (9)$$

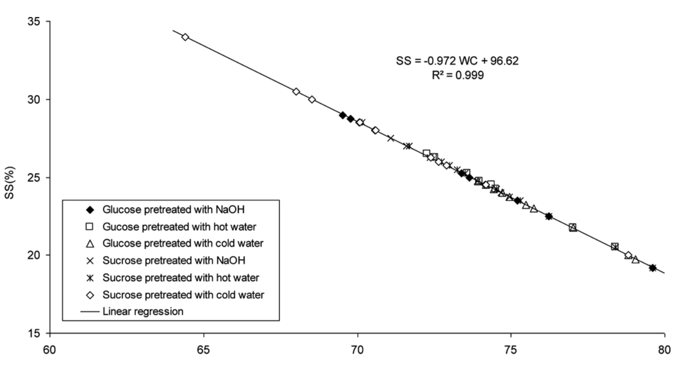

FIG. 8. Variation in SS content with WC for plums, with different pretreatments, fresh and dehydrated in solutions of glucose or sucrose, and linear regression equation for SS vs. WC.

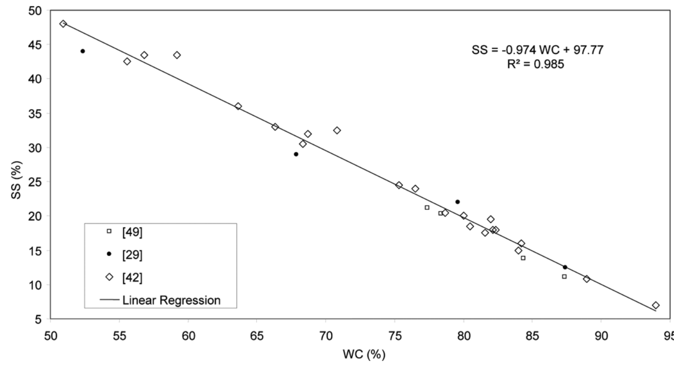

FIG. 9. Variation in SS content with WC for melons, fresh and dehydrated in solutions of different concentrations, and linear regression equation for SS vs. WC.

has an equivalent accuracy to that of the individual regressions for each fruit or solute type (Fig. 11).

From these results it seems clear that for osmotic dehydration of any fruit (those analyzed in this work or any other), the determination of only one component (water or soluble solids) is sufficient to characterize its composition within the range of error of experimental determinations.

Solute Gain as a Function of Water Loss

Information from the literature[19,20] predicted a linear relation between these variables; meanwhile, cell wall functionality remains. At high WL and SG rates tend to increase, and the ratio of SG to WL is no longer linear.

All of the data analyzed in this work (results not shown) confirmed that the linear relation is generally valid for all fruits and solutes for WL up to 40–50%, but it also depends on the operating conditions because both magnitudes (WL and SG) are, in fact, integrated mass transfer rates. Therefore, sample shape and size, solute concentration, stirring, etc., have an influence on these magnitudes and no general correlations—even for a unique type of fruit or solute—can be obtained.

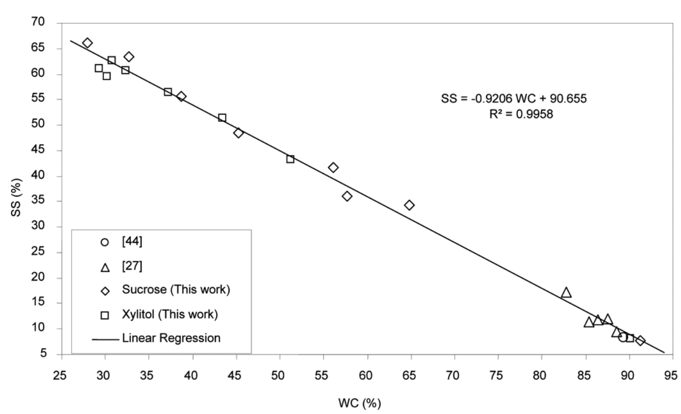

FIG. 10. Variation in SS content with WC for strawberries, fresh and dehydrated in solutions of sucrose or xylitol, and linear regression equation for SS vs. WC.

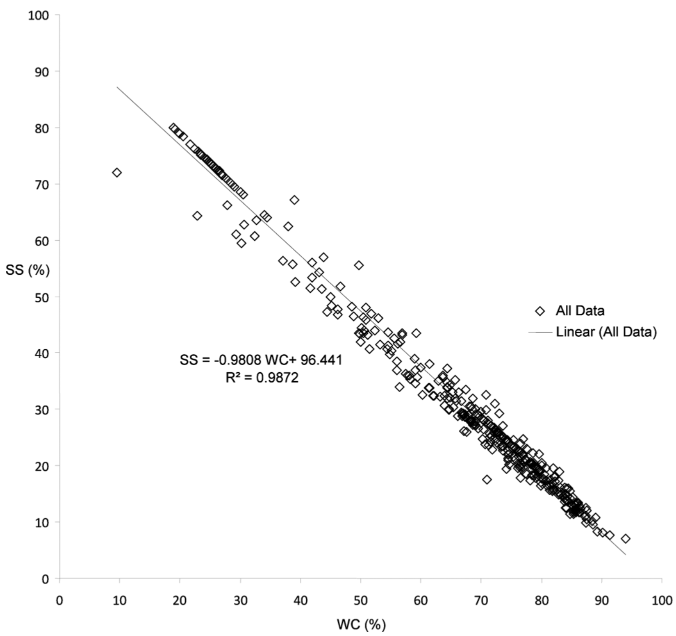

FIG. 11. Variation in SS content with WC for all fruits tested, fresh and dehydrated in solutions of different solutes, and linear regression equation for SS vs. WC for all data.

Initial Freezing Temperature as a Function of Water Content

It is to be expected that T_{cr} is a function of composition, not only of WC but also of SS, and of the type of solute. The dependence on SS is implicit due to its linear relation to WC. As noted previously, there is little information in the literature on T_{cr} of OD fruits, which was summarized in Tocci and Mascheroni.[19]

The DSC experiments were also used to determine the initial freezing point (T_{cr}) of fresh strawberry slices or strawberries that were osmodehydrated in solutions of sucrose or xylitol. These results are presented in Figs. 12 and 13 together with the logarithmic and second-order polynomial regressions of T_{cr} vs. WC, which were those of higher regression coefficients. As can be seen, for both types of regressions high accuracy was obtained for each solute with only one parameter (WC).

Because the data for T_{cr} vs. WC for strawberry dehydrated in sucrose solutions followed the trend found for kiwifruit,[19] we looked for general correlations for T_{cr} vs. WC. In this regard, all of the available data for different fruits and solutes were used (those determined in this work as well as those cited in Introduction). A careful discrimination of results showed that all of the data for different fruits but with the same solute in the dehydrating solution can be included in only one polynomial correlation with a high regression coefficient for the cases of sucrose and xylitol but less accurately for glucose (probably because the range of WC covered by the data is narrow). Figure 14

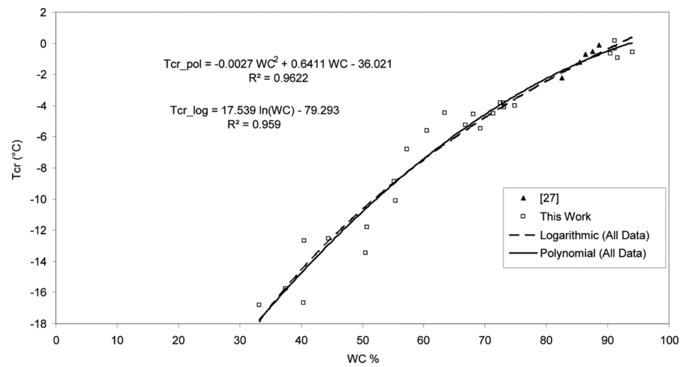

FIG. 12. Experimental data for initial freezing temperature T_{cr} vs. water content WC for strawberries, fresh and dehydrated in sucrose solution, and regression equations for T_{cr} vs. WC.

presents the experimental data and the polynomial regressions obtained.

These results clearly show that both water content and type of solute have a direct influence on freezing point depression. On the other hand, the type of fruit seems to have no discernible influence, which is coherent with the results for the relation SS vs. WC. In any case, more experimental data are necessary to produce sufficient information to obtain more general and accurate relationships.

Heat Capacity and Enthalpy as a Function of Water Content

We determined the DSC pattern of fresh and osmodehydrated strawberry in sucrose solution covering the range of WC from that of fresh fruit (about 90%) to 37%, a very low value, near the limit of non-freezability. The curves obtained for H vs. T, which follow the expected trend, are presented in Fig. 15, with lower H at lower T and WC and with the change in slope (at T_{cr}) moving to more negative values as WC decreases.

The experimental values of H_{cr} (H at T_{cr}) for each sample, which are descriptive of the amount of energy needed for freezing the fruit, are provided in Table 1.

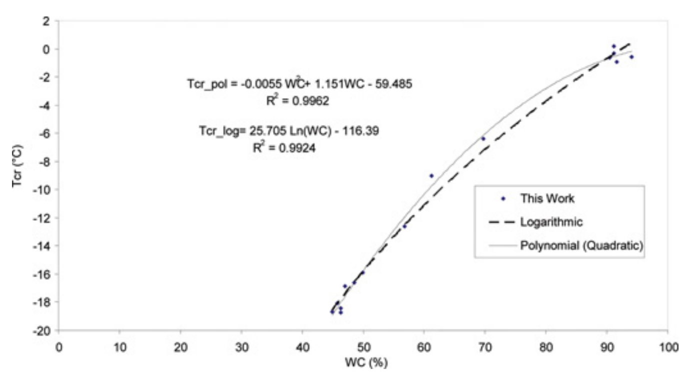

FIG. 13. Experimental data for initial freezing temperature T_{cr} vs. water content WC for strawberries, fresh and dehydrated in xylitol solutions, and regression equations for T_{cr} vs. WC (color figure available online).

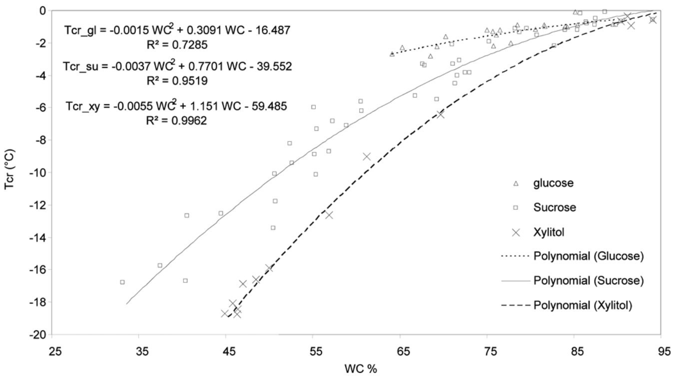

FIG. 14. Experimental data for initial freezing temperature T_{cr} vs. water content WC for different fruits and solutes and regression equations for T_{cr} vs. WC for each dehydrating solute.

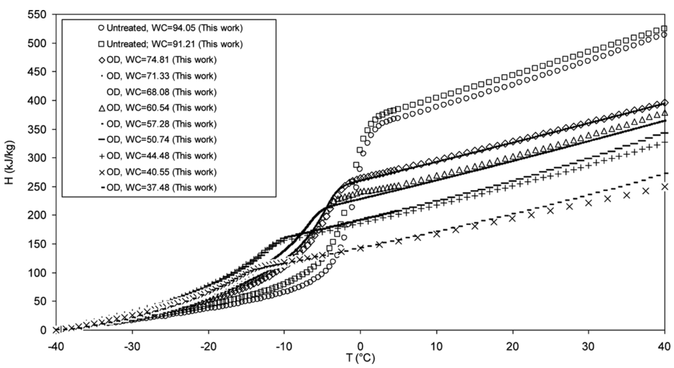

FIG. 15. Experimental data for enthalpy H vs. temperature T for strawberries, fresh and osmodehydrated in sucrose solution.

As noted previously, we performed regression of the experimental data for C_p and H vs. T following the procedures of Schwartzberg[35] and Succar and Hayakawa[36] (Eqs. (5)–(8)), which were developed for untreated foods. This method has already been proved valid for OD materials when used for kiwifruit.[19]

Table 1 presents the constants obtained for Eqs. (5)–(8) together with the respective regression coefficients. As can be seen, high coefficients were obtained for all samples, showing that these equations are simple and accurate for prediction purposes and that their theoretical basis is sound, because their use can be extended to products that were partially dehydrated and at the same time enriched in solutes.

At present, no relations for *A, B, C, n, D*, and *E* as a function of WC were obtained, which would generalize the model and simplify prediction procedures. Much more experimental data on different osmodehydrated fruits is needed if such a general relation is sought.

CONCLUSIONS

A linear correlation between SS and WC of fresh and osmodehydrated fruits was verified and the corresponding correlations were determined for kiwifruit, pear, apple, nectarine, plum, melon, and strawberry. The correlation for each fruit is independent of the type of solute, temperature, stirring and concentration of the osmotic solution, size and shape of the samples, and variety of fruit. The relation seems to depend only on the structure of the fruit and its insoluble solids content. In addition, a general correlation for SS vs. WC including all of the experimental data for the seven types of fruits tested and the five solutes used in these experiments (sucrose, glucose, xylitol, sorbitol, polyethylene glycol) was obtained with a high regression coefficient, which enables simple prediction of fruit composition during OD using a unique experimental determination (WC or SS).

WL and SG showed almost linear relations for moderate values of WL (less than 40–50%), but these relations

TABLE 1
Experimental values of T_{cr} and H_{cr} and constants *A, B, C, D, n, D*, and *E* for the models of Succar and Hayakawa, for fresh and osmodehydrated strawberries

WC (%)	A [kJ/(kg°C)]	B (kJ°C^{n-1}/kg)	C (kJ/kg)	n	R^2	T_{cr} (°C)	H_{cr} (kJ/kg)	D (kJ/kg)	E (kJ/(kg°C))	R^2
94.05	1.077	104.504	0.515	1.503	1	−0.58	241.76	344.48	4.1492	0.999
91.21	−0.307	78.378	3.370	1.071	0.998	−0.34	296.63	362.75	4.0231	0.999
74.81	0.930	283.979	−0.246	1.526	1	−4.02	210.85	263.29	3.2845	0.999
71.33	0.654	234.645	−0.988	1.385	1	−4.53	214.74	257.52	3.3586	0.999
68.08	0.804	261.303	−2.189	1.437	1	−4.55	213.11	256.40	3.3586	0.999
60.54	0.966	262.293	−0.376	1,467	1	−5.61	183.81	235.49	3.4746	0.997
57.28	1.244	338.365	−0.480	1.513	1	−6.81	187.23	227.01	3.3844	0.999
50.74	0.739	455.053	0.212	1.500	1	−11.79	142.13	190.20	3.4240	0.999
44.48	0.238	364.280	−1.492	1.379	1	−12.53	133.09	179.70	3.3300	0.999
40.55	−2.693	91.597	1.372	0.815	1	−14.60	99.97	143.40	2.9540	0.999
37.48	−3.376	144.738	−2.311	0.913	1	−15.76	93.52	142.40	3.0622	0.997

depended on the processing conditions and no general correlation was obtained for any fruit.

The T_{cr} of fresh and osmodehydrated strawberries was determined and was satisfactorily correlated with WC using a second-order polynomial regression for each solute.

Experimental data for T_{cr} for different fruits and solutes (sucrose, glucose, xylitol) were correlated as a function of WC and the type of solute. Each regression was valid for all different fruits examined in this study.

DSC determinations of C_p for fresh and osmodehydrated strawberries followed the general trend for this property, and the values were dependent on T and WC. A correlation from the literature for the prediction of C_p and H of fresh foods was satisfactorily fitted to the experimental data for OD strawberries, showing its wide validity and firm theoretical basis.

NOMENCLATURE

A, B, C, D, E, n	Constants in Eqs. (5)–(8)
C_p	Heat capacity [kJ/(kg°C)]
H	Enthalpy (kJ/kg)
m_f	Final mass (kg)
m_i	Initial mass (kg)
R^2	Coefficient of determination
SG	Solids gain (%)
SS	Soluble solids (%)
T	Temperature (°C)
T_{cr}	Initial freezing temperature (°C)
TS	Current total solid (%)
TS°	Initial total solid (%)

REFERENCES

1. Agnelli, M.E.; Marani, C.M.; Mascheroni, R.H. Modelling of heat and mass transfer during (osmo)dehydrofreezing of fruits. *Journal of Food Engineering* **2005**, *69*, 415–424.
2. Lenart, A. Osmo-convective drying of fruits and vegetables: Technology and application. *Drying Technology* **1996**, *14*, 391–413.
3. Tabtiang, S.; Prachayawarakon, S.; Soponronnarit, S. Effects of osmotic treatment and superheated steam puffing temperature on drying characteristics and texture properties of banana slices. *Drying Technology* **2012**, *30*(1), 20–28.
4. Chottamom, P.; Kongmanee, R.; Manklang, C.; Soponronnarit, S. Effect of osmotic treatment on drying kinetics and antioxidant properties of dried mulberry. *Drying Technology* **2012**, *30*(1), 80–87.
5. Karathanos, V.T.; Kostaropoulos, A.E.; Saravacos, G.D. Air drying of osmotically dehydrated fruits. *Drying Technology* **1995**, *13*, 1503–1521.
6. Pan, Y.K.; Zhao, L.J.; Zhang, Y.; Chen, G.; Mujumdar, A.S. Osmotic dehydration pretreatment in drying of fruits and vegetables. *Drying Technology* **2003**, *21*, 1101–1114.
7. Beaudry, C.; Raghavan, G.S.V.; Rennie, T.J. Microwave finish drying of osmotically dehydrated cranberries. *Drying Technology* **2003**, *21*(9), 1797–1810.
8. Mitrakas, G.E.; Koutsoumanis, K.P.; Lazarides, H.N. Impact of edible coating with or without anti-microbial agent on microbial growth during osmotic dehydration and refrigerated storage of a model plant material. *Innovative Food Science and Emerging Technologies* **2008**, *9*, 550–555.
9. Ramallo, L.A.; Mascheroni, R.H. Dehydrofreezing of pineapple. *Journal of Food Engineering* **2010**, *99*, 269–275.
10. Shi, X.Q.; Chiralt, A.; Fito, P.; Serra, J.; Escoin, C.; Casque, L. Application of osmotic dehydration technology on jam processing. *Drying Technology* **1996**, *14*(3–4), 841–857.
11. Taiwo, K.A.; Baik, O.D. Effects of pre-treatments on the shrinkage and textural properties of fried sweet potatoes. *LWT - Food Science and Technology* **2007**, *40*, 661–668.
12. Rodrigues, A.C.C.; Pereira, L.M.; Sarantopoulos, C.I.G.L. Impact of modified atmosphere packaging on the osmodehydrated papaya stability. *Journal of Food Processing and Preservation* **2006**, *30*, 563–581.
13. Torres, J.D.; Castelló, M.L.; Escriche, I.; Chiralt, A. Quality characteristics, respiration rates, and microbial stability of osmotically treated mango tissue (*Mangifera indica* L.) with or without calcium lactate. *Food Science and Technology International* **2008**, *14*, 355–365.
14. Moraga, M.J.; Moraga, G.; Fito, P.J.; Martínez-Navarrete, N. Effect of vacuum impregnation with calcium lactate on the osmotic dehydration kinetics and quality of osmodehydrated grapefruit. *Journal of Food Engineering* **2009**, *90*, 372–379.
15. Ponting, D.; Walters, G.G.; Forrey, R.R.; Jackson, R.; Stanley, W.L. Osmotic dehydration of fruits. *Food Technology* **1966**, *20*, 125–128.
16. Vial, C.; Guilbert, S.; Cuq, J. Osmotic dehydration of kiwi fruits: Influence of process variables on the color and ascorbic acid content. *Sciences des Aliments* **1991**, *11*(1), 63–84.
17. Raoult-Wack, A.L. Recent advances in the osmotic dehydration of foods. *Trends in Food Science and Technology* **1994**, *5*(8), 255–260.
18. Ponting, J.D. Osmotic dehydration of fruits—Recent modifications and applications. *Process Biochemistry* **1973**, *8*, 18–20.
19. Tocci, A.M.; Mascheroni, R.H. Some thermal properties of fresh and osmotically dehydrated kiwifruit above and below initial freezing temperature. *Journal of Food Engineering* **2008**, *88*, 20–27.
20. Floury, J.; Pham, Q.T.; Le Bail, A. A COMSOL simulation of the osmotic dehydration of mango. In *4th International Conference on Simulation and Modelling in the Food Industry, FOODSIM'2006*, Napoli, Italy, June 13–15, 2006.
21. Sá, M.M.; Sereno, A.M. Glass transitions and state diagrams for typical natural fruits and vegetables. *Thermochimica Acta* **1994**, *246*, 285–297.
22. Sá, M.M.; Figueiredo, A.M.; Sereno, A.M. T_g and state diagrams for fresh and dehydrated apple by DSC. In *Seventh International Symposium on Properties of Water*, Helsinki, Finland, June 1998.
23. Sá, M.M.; Figueiredo, A.M.; Sereno, A.M. Glass transitions and state diagrams for fresh and processed apple. *Thermochimica Acta* **1999**, *329*, 31–38.
24. Silva, S.V.; Camargo Neves, L.; Hubinger, M.D. Enthalpy of pineapple pulp on sucrose solution. In *Latin American Congress of Heat and Mass Transfer VI*, Florianopolis, Brazil, 1996 (in Portuguese).
25. Sereno, A.M. Thermal properties and state diagrams of fruits and vegetables by DSC. In *Trends in Food Engineering*; Lozano, J. E., Anon, C., Barbosa-Canovas, G. V., Parada-Arias, E., Eds; Technomic Publishing Co.: Lancaster, PA, 2000; 77–88.
26. Flores-Andrade, E.; Beristain, C.I.; Vernon-Carter, E.J.; Gutiérrez, G.F.; Azuara, E. Enthalpy–entropy compensation and water transfer mechanism in osmotically dehydrated agar gel. *Drying Technology* **2009**, *27*, 999–1009.
27. Tocci, A.M.; Spiazzi, E.A.; Mascheroni, R.H. Determination of specific heat and enthalpy of melting by differential scanning calorimetry: Application to osmodehydrated fruits. *High Temperatures - High Pressures* **1998**, *30*, 357–363.
28. Tocci, A.M.; Mascheroni, R.H. Determination by differential scanning calorimeter of the heat capacity and enthalpy of partially dehydrated fruit in concentrated sucrose–water solutions. In *1st*

Iberian-American Congress of Food Engineering, Campinas, Brazil. November 5–9, 1995 (in Spanish).
29. Tocci, A.M.; Mascheroni, R.H. Determination by differential scanning calorimeter of the enthalpy and density of osmotically dehydrated melon, kiwi and peach. In *2nd Iberian-American Congress of Food Engineering*, Bahía Blanca, Argentina, March 24–27, 1998 (in Spanish).
30. Tocci, A.M.; Mascheroni, R.H. Determination and calculation of thermal properties of osmotically dehydrated fruits and vegetables in the range of refrigeration and freezing temperatures. In *CIAR 2001, 6th Iberian-American Congress of Air Conditioning and Refrigeration*, Buenos Aires, Argentina, August 15–17, 2001 (In Spanish).
31. Callanan, J.; Sullivan, S. Development of standard operating procedures for differential scanning calorimeters. *Review of Scientific Instruments* **1986**, *57*, 2584–2592.
32. Rha, C., Ed. *Theory, Determination and Control of Physical Properties of Food Materials*; Riedel Publishing: Dordrecht, The Netherlands, 1975.
33. Mohsenin, N. *Thermal Properties of Foods and Agricultural Materials*; Gordon and Breach: New York, 1980.
34. Jowitt, R.; Escher, F.; Hallstrom, B.; Meffert, H.F.; Spiess, W.E.L.; Vos, G., Eds. *Physical Properties of Foods*; Applied Science: London, 1983.
35. Schwartzberg, H.G. Effective heat capacities for the freezing and thawing of foods. *Journal of Food Science* **1976**, *41*, 152–156.
36. Succar, J.; Hayakawa, K.I. Empirical formulas for predicting thermal physical properties of food at freezing or defrosting temperatures. *Lebensmittel-Wissenschaft und Technologie* **1983**, *16*, 326–331.
37. Saurel, R. Dehydration-impregnation by immersion in ternary solution: Study of water and solutes transfer in gels and animal products. Doctoral Thesis, Université de Montpellier, France, 1995 (in French).
38. Talens, P.; Martínez-Navarrete, N.; Fito, P.; Chiralt, A. Changes in optical and mechanical properties during osmodehydrofreezing of kiwi fruit. *Innovative Food Science & Emerging Technologies* **2001**, *3*, 191–199.
39. Torreggiani, D.; Forni, E.; Maestrelli, A.; Quadri, F. Influence of osmotic dehydration on texture and pectic composition of kiwifruit slices. *Drying Technology* **1999**, *17*(7&8), 1387–1397.
40. Marani, C.M.; Agnelli, M.E.; Mascheroni, R.H. Osmo-frozen fruits: Mass transfer and quality evaluation. *Journal of Food Engineering* **2007**, *79*, 1122–1130.
41. Talens, P.; Escriche, I.; Martínez-Navarrete, N.; Chiralt, A. Influence of osmotic dehydration and freezing on the volatile profile of kiwi fruit. *Food Research International* **2003**, *36*, 635–642.
42. Bianchi, M. Modelling and simulation of freezing and dehydrofreezing process of fruits. Master's Thesis, National University of the Litoral, Santa Fe, Argentina, 2010 (in Spanish).
43. Park, K.J.; Bin, A.; Reis Brod, F.P.; Brandini Park, T.H.K. Osmotic dehydration kinetics of pear D'Anjou (*Pyrus communis* L.). *Journal of Food Engineering* **2002**, *52*, 293–298.
44. Riedel, L. The refrigeration effect required to freeze fruits and vegetables. *Refrigeration Engineering* **1951**, *59*(2), 670–674.
45. González-Martínez, C.; Cháfer, M.; Xue, K.; Chiralt, A.Effect of the osmotic pre-treatment on the convective air drying kinetics of pear var. Blanquilla. *International Journal of Food Properties* **2006**, *9*, 541–549.
46. Nieto, A.B.; Salvatori, D.M.; Castro; M.A.; Alzamora, S.M. Structural changes in apple tissue during glucose and sucrose osmotic dehydration: Shrinkage, porosity, density and microscopic features. *Journal of Food Engineering* **2004**, *61*, 269–278.
47. Kaymak-Ertekin, F.; Sultanoglu, M. Modelling of mass transfer during osmotic dehydration of apples. *Journal of Food Engineering* **2000**, *46*, 243–250.
48. Cornillon, P. Characterization of osmotic dehydrated apple by NMR and DSC. *Lebensmittel-Wissenschaft Und-Technologie* **2000**, *33*, 261–267.
49. Maestrelli, A.; Lo Scalzo, R.; Lupi, D.; Bertolo, G.; Torreggiani, D. Partial removal of water before freezing: Cultivar and pre-treatments as quality factors of frozen muskmelon (*Cucumis melo*, cv. reticulatus Naud.). *Journal of Food Engineering* **2001**, *49*, 255–260.
50. Rodríguez, M.M.; Mascheroni, R.H.; Pagano, A.M. Dehydration of nectarines (*Prunus persica* var. Nectarine) in concentrated osmotic agents in combination with hot air drying. In *IDS 2010, Vol. C, Section XI, Drying of Food and Agricultural Products*; Tsotsas, E.; Metzger, T.; Peglow, M., Mujumdar, A.S., Series Eds.; Dechema: Magdeburg, Germany, 1415–1422.
51. Rodríguez, M.M.; Gori, L.M.; Mascheroni, R.H.; Pagano, A.M. Modeling of dehydration kinetics of European plum (*Prunus domestica* L.) by combined methods. In *IDS 2010, Vol. A, Section II, Fundamentals, Modeling, Simulation*; Tsotsas, E.; Metzger, T.; Peglow, M., Mujumdar, A.S., Series Eds.; Dechema: Magdeburg, Germany, 594–600.
52. Rodrigues, A.E.; Mauro, M.A. Effective diffusion coefficients behavior in osmotic dehydration of apple slices considering shrinking and local concentration dependence. *Journal of Food Process Engineering* **2008**, *31*, 207–228.
53. Atares, L.; Chiralt, A.; Corradini, M.G.; Gonzalez-Martinez, C. Effect of the solute on the development of compositional profiles in osmotic dehydrated apple slices. *LWT - Food Science and Technology* **2009**, *42*, 412–417.
54. Monnerat, S.M.; Pizzi, T.R.M.; Mauro, M.A.; Menegalli, F.C. Osmotic dehydration of apples in sugar/salt solutions: Concentration profiles and effective diffusion coefficients. *Journal of Food Engineering* **2010**, *100*, 604–612.
55. Moreno, J.; Simpson, R.; Sayas, M.; Segura, I.; Aldana, O.; Almonacid, S. Influence of ohmic heating and vacuum impregnation on the osmotic dehydration kinetics and microstructure of pears (cv. Packham's Triumph). *Journal of Food Engineering* **2011**, *104*, 621–627.
56. Castelló, M.L.; Igual, M.; Fito, P.J.; Chiralt, A. Influence of osmotic dehydration on texture, respiration and microbial stability of apple slices (var. Granny Smith). *Journal of Food Engineering* **2009**, *91*, 1–9.
57. Martínez, V.Y.; Nieto, A.B.; Castro, M.A.; Salvatori, D.; Alzamora, S.M. Viscoelastic characteristics of Granny Smith apple during glucose dehydration. *Journal of Food Engineering* **2007**, *83*, 394–403.