Mass transfer kinetics and quality attributes of osmo-dehydrated candied pumpkins using nutritious sweeteners

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Revised: 26 July 2017 / Accepted: 2 August 2017 / Published online: 22 August 2017
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Abstract The aim of this study was to investigate the mass transfer and quality properties changes during the osmotic dehydration (OD) step of the candying process in pumpkins. The goal was to obtain nutritious, low calorie candied pumpkins improving the time-consuming and inconsistent traditional technique. The osmotic agents were sucrose, oligofructose and mixture of sucrose–oligofructose (1:1), while the concentration of each solution was constant (70° Brix). The process temperature varied in three levels (75, 85 and 95 °C) and the duration was 180 min for sucrose and 240 min for the other osmotic agents. The determined parameters during OD include solid gain, water loss, water activity, chroma, hardness and compression work. An empirical model based on a first-order kinetic equation was developed to predict the products' properties, in which the

rate constant is a function of the process temperature. The process temperature (T_{osm}) had a significant effect on the water loss and solid gain as well as on the physiochemical characteristics of processed pumpkins. The chroma of osmo-dehydrated pumpkins was affected significantly by process parameters. Both hardness and compression work decreased until an equilibrium value was reached as time and temperature of the process increased, regardless the osmotic agent used.

Keywords Candying · Kinetics · Oligofructose · Osmotic dehydration · Pumpkin · Texture

List of symbols

A	Compression work (N·s)
A_0	Initial value of compression work (N·s)
A_{0e}	Compression work model parameter (N·s)
A_e	Equilibrium value of compression work (N·s)
A_T	Temperature effect exponent in compression work model (—)
a^*	Color parameter (—)
a_w	Water activity (—)
b^*	Color parameter (—)
C^*	Chroma (—)
C_0^*	Initial chroma value (—)
C_{0e}^*	Chroma model parameter (—)
C_e^*	Equilibrium chroma value (—)
C_T^*	Temperature effect exponent in chroma model (—)
F	Hardness of material (N)
F_0	Initial value of hardness (N)
F_{0e}	Hardness model parameter (N)
F_e	Equilibrium value of hardness (N)
F_T	Temperature effect exponent in hardness model (—)
K_0	Water loss model parameter for rate constant (min^{-1})

Electronic supplementary material The online version of this article (doi:10.1007/s13197-017-2786-2) contains supplementary material, which is available to authorized users.

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k_A	Rate constant of compression work model (min^{-1})
k_O	Solids gain model parameter for rate constant (min^{-1})
k_{OA}	Compression work model parameter (min^{-1})
k_{OC^*}	Chroma model parameter (min^{-1})
k_{C^*}	Rate constant of colour parameter (min^{-1})
k_{OF}	Hardness model parameter (min^{-1})
k_F	Rate constant of hardness parameter (min^{-1})
K_{SG}	Rate constant of solid gain during the osmotic process (min^{-1})
K_T	Temperature effect exponent for rate constant in water loss model (—)
k_T	Temperature effect exponent for rate constant in solids gain model (—)
k_{TA}	Temperature effect exponent for rate constant in compression work model (—)
k_{TC^*}	Temperature effect exponent for rate constant in chroma model (—)
k_{TF}	Temperature effect exponent for rate constant in hardness model (—)
K_{WL}	Rate constant of water loss during the osmotic process (min^{-1})
M	Mass of material after time t of osmotic treatment (kg)
M_0	Initial mass of fresh material (kg)
m	Dry mass of material after time t of osmotic treatment (kg)
m_0	Dry mass of fresh material (kg)
OD	Osmotic dehydration (—)
R^2	Coefficient of determination (—)
SG	Solids gain (kg/kg)
SG_e	Solid gain at infinite process time (kg/kg)
T_{osm}	Temperature of osmotic dehydration ($^{\circ}\text{C}$)
t	Processing time (s)
WL	Water loss (kg/kg)
WL_e	Water loss at infinite process time (kg/kg)
Y_{eO}	Water loss model parameter (kg/kg)
y_{eO}	Solids gain model parameter (kg/kg)
Y_{eT}	Temperature effect exponent in water loss model (—)
y_{eT}	Temperature effect exponent in solids gain model (—)

Subscripts

A	Compression work index
C	Chroma index
e	Equilibrium
F	Hardness index
o	Initial
osm	Osmotic dehydration
T	Temperature

Introduction

Pumpkin (*Cucurbita moschata*) is a seasonal crop and its mature fruits are extensively used in many parts of the world, including Greece, as part of the local cuisine, mainly handled as ingredient for soups, salads, sauces, pies and desserts (Guiné and Barroca 2012). It is an important source of beneficial nutrients such as vitamin A and carotenoids, especially beta-carotene and lutein, (González et al. 2001), while it also contains high levels of pectin, vitamin C and minerals (Jacobo-Valenzuela et al. 2011). In Greece, candied pumpkin, a traditional Greek dessert, is prepared by using osmotic dehydration (OD), followed by air-drying.

Osmotic dehydration (OD) is an effective technique for the partial removal of water from fruits and vegetables, leading to a significant increase of product's stability (Fernandes et al. 2006; Yadav and Singh 2014). During OD, mass transfer occurs between the plant tissue and the surrounding solution, including two main mass fluxes, water loss and sugar uptake. The OD process could be used in the production of traditional candied products with lower water activity and longer shelf-life (Abraão et al. 2013). Most traditional candying techniques are time-consuming and inconsistent processes, needing 7–8 days under uncontrolled conditions. Osmotic dehydration is also used as a pre-treatment to conventional air drying or freezing, which not only removes water from the food, but also improves food quality and lowers energy consumption (Dermesonlouoglou et al. 2007; Garcia-Noguera et al. 2014; Warczok et al. 2007; Zhao et al. 2017). Process parameters of OD such as temperature and concentration of the osmotic solution, size and geometry of the material, solution-to-material mass ratio and level of agitation of the solution influence the efficiency of water loss, solid gain and quality of any fruit or vegetable. Several recent publications have studied the influence of these process variables on mass transfer rates during OD (El-Aouar et al. 2006; İspir and Toğrul 2009).

Due to the increasing interest in designing new, low calorie and minimally processed foods, the replacement of sugar in traditional candied products and the kinetic study of the osmotic dehydration with the use of alternative carbohydrates has become a growing challenge. In addition, the traditional techniques of candying are time consuming, needing 7–8 days under uncontrolled conditions, and there is an imperative need for process standardization and optimization, in order to generate a product of stable and superior quality, with improved nutritional and sensory attributes. In most cases hypertonic solutions of sucrose, sodium chloride, fructose, corn syrup, maltose, maltodextrin, and/or mixtures of them have been used as osmotic agents (Derossi et al. 2015; El-Aouar et al. 2006; İspir and Toğrul 2009). However, there are few reports for oligofructose or mixtures of

oligofructose and sucrose as alternative osmotic solutes in the traditional production of candied fruits.

Oligofructose is officially recognized as a natural food ingredient and is classified as dietary fiber in almost all European countries (Roberfroid 2000). One of the nutritional benefits of oligofructose is its pre-biotic effect, influencing the microbial composition of the gastrointestinal tract of the host (Rao 2001). Oligofructose is a non-digestible oligosaccharide, with exceptional dietary fiber properties and prebiotic activity (de Gennaro et al. 2000) and it can be consumed by people with diabetes. According to Vilela et al. (2016), the chemical composition of osmodehydrated fruits with healthier ingredients such as oligofructose showed that these types of alternative dehydration agents were suitable and acceptable for healthier alternatives in the case of the traditional candied fruits.

The aim of this work was to investigate the effect of different osmotic agents (sucrose, oligofructose and sucrose–oligofructose mixture with a mass ratio of 1:1) and OD temperature on the mass transfer kinetics during OD of pumpkin. Furthermore physicochemical and textural changes of the pumpkin issue were studied during the process. Mass transfer during the OD process was described using first order kinetics.

Materials and methods

Sample preparation

Pumpkins (*Cucurbita moschata*, var. Musquee de Provence) were purchased in Athens central fruit and vegetable market. The sucrose was purchased from local market, while Fibrulose® (oligofructose) was purchased from Astron Chemicals S.A. (imported from Consucra-Groupe Warcoing S.A.). Pumpkins were carefully transferred to the lab, sorted, washed and cut into $4 \times 3 \times 1$ cm slabs, using a sharp slicer. Before candying, they were blanched in hot water at a temperature of 100 °C for 3 min and immediately cooled. According to Ahmed et al. (2016) the blanching pretreatment for vegetable slices at a temperature of 100 °C resulted in an increase of effective water and sucrose diffusion coefficients and according to Lazou et al. (2016), the optimum blanching conditions for the production of traditional candied pumpkins were at higher temperatures for 3 min.

Osmotic dehydration

Fresh-cut pumpkin slabs were osmotically treated within different osmotic solutions (sucrose, oligofructose and mixture of sucrose–oligofructose 1:1) highly concentrated up to 70° Brix, freshly prepared the same day. The process

temperature was set at 75, 85, and 95 °C for time duration up to 180 min. The time period of 180 min was chosen based on preliminary experiments and a previous work published by Lazou et al. (2016), as the time needed for mass transport indices (for example Water loss, Solid gain etc.) to reach an equilibrium status. The solution to sample ratio was 10:1 (w/w) to avoid significant dilution of the osmotic medium due to water removal. At the selected sampling times, pre-weighed samples were removed from the osmotic solution and blotted gently with a tissue paper in order to remove the excess coating solution and then weighed. Four replicate samples were removed and measured each time and the average values were calculated.

Determination of physicochemical characteristics

Water content (X_w) and soluble solids (X_s) were measured in fresh and treated samples, at pre-determined time intervals, to estimate the compositional changes promoted by osmotic dehydration (OD). Moisture content was determined gravimetrically by drying at 105 °C for 24 h according to the AOAC method (1990). Soluble solids were determined by a hand refractometer (ATAGO hand refractometer, Japan).

Water activity (a_w) was monitored during the whole process using an a_w -meter (Aqua LAB 4TEV, Decagon Devices, Inc., USA). All measurements were taken from four independent specimens, and the mean values were reported.

For colour changes, measurement of CIELab values (CIE, 1978) with a Handy Colour Tester (Model H-CT, SUGA Test Instruments) was performed. A standard white plate (Calibration plate CR-200) was used to standardize the instrument under “C” illuminant condition, according to the CIE (Commission International de l’Eclairage) and chroma (C^*) was assessed, following Eq. (1):

$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \quad (1)$$

where a^* (green–red) and b^* (yellow–blue) are the colour parameters.

Texture analysis was carried out using a texture profile analyzer (TA.XT2i; Stable Micro Systems, UK), with a 60-mm compression probe and a 25 kg load cell. Compression test was performed using the following operating conditions: 3 mm/s pre-test speed, 1 mm/s test speed, 1 mm/s post-test speed, and 50% sample deformation. A force–time curve was recorded by the instrument and a textural attribute, hardness and compression work was measured. Hardness was defined as the maximum force during the direct and simple compression test of the samples and compression work was defined by the area under the force–deformation curve. An average value of 5 replicates is reported.

For the macro-structural observation, whole and sliced candied pumpkin slabs were observed and captured by Olympus Stereo Microscope with an integrated digital camera (Stereoscope SZ61, Olympus, Center Valley, PA, USA) (Lazou et al. 2016). In addition, the size and the color of the samples during the osmotic dehydration were observed by a digital camera (Sony Cyber shot DSC-W220 12.1 MP, Tokyo, Japan). The samples were placed in a specially designed room with natural daylight, while for each shot, digital camera abstained from samples 15 cm.

Experimental design

The design of experiments was a 3 (osmotic agent) $\times$ 3 (OD temperature) full factorial experimental design with two replications. The independent variables were: osmotic agent (sucrose, oligofructose and mixture of sucrose–oligofructose (1:1)) and osmotic dehydration temperature— T_{osm} (75, 85, and 95 °C).

Mass transfer and properties modelling

Mass transfer parameters and changes were followed by estimating water loss (WL) and solid gain (SG) parameters, using the following equations:

$$WL = \frac{(M_0 - m_0) - (M - m)}{m_0} \quad (\text{g of water/g initial dry matter}) \quad (2)$$

$$SG = \frac{m - m_0}{m_0} \quad (\text{g of total solids/g initial dry matter}) \quad (3)$$

where M_0 is the initial mass of fresh material before the osmotic treatment, M is the mass of pumpkin samples after time t of osmotic treatment, m is the dry mass of pumpkin after time t of osmotic treatment and m_0 is the dry mass of fresh material.

A first-order kinetic model was chosen to describe the mass transfer phenomena within the osmotic process based on the model used by Panagiotou et al. (1998). It was assumed that:

1. The mass ratio of the osmotic solution to fruit is sufficiently high such as that the osmotic solution concentration could be considered constant.
2. Initial water and carbohydrate concentration in the fruit are uniform.
3. The osmotic treatment is an isothermal and an equilibrium process.
4. There are no significant diffusional processes other than water diffusion from the fruit into the osmotic solution and the solute agent diffusion from the osmotic solution into the fruit.

5. These two flows (water from the fruit into the solution and solute agent from the solution into the fruit) were considered to be independent of each other.

Water loss kinetic model

$$\frac{d(WL)}{dt} = -K_{WL}(WL - WL_e) \quad (4)$$

Solid gain kinetic model

$$\frac{d(SG)}{dt} = -K_{SG}(SG - SG_e) \quad (5)$$

where WL_e is the water loss at an infinite process time, SG_e is the solid gain at an infinite process time, K_{WL} is the rate constant of water loss during the osmotic process, K_{SG} is the rate constant of solid gain during the osmotic process and t is the processing time.

At zero time there is neither water loss nor solid gain, and so the equations were integrated to the following:

$$WL = WL_e[1 - \exp(-K_{WL} \cdot t)] \quad (6)$$

and

$$SG = SG_e[1 - \exp(-K_{SG} \cdot t)] \quad (7)$$

As proposed by Panagiotou et al. (1998), the effect of process variables (osmotic dehydration temperature) on mass transfer phenomena during osmotic dehydration can be incorporated into the following empirical equations based on the central processing conditions regarding temperature (85 °C):

$$K_{WL} = K_0 \left(\frac{T_{osm}}{85} \right)^{K_T} \quad (8)$$

$$K_{SG} = k_0 \left(\frac{T_{osm}}{85} \right)^{k_T} \quad (9)$$

$$WL_e = Y_{e0} \left(\frac{T_{osm}}{85} \right)^{Y_{eT}} \quad (10)$$

$$SG_e = y_{e0} \left(\frac{T_{osm}}{85} \right)^{y_{eT}} \quad (11)$$

where K_0 , K_T , Y_{e0} , Y_{eT} are the proposed parameters for the mathematical model of WL and k_0 , k_T , y_{e0} , y_{eT} the proposed parameters for SG.

Non-linear regression analysis method was used for parameter estimation, K_0 , K_T , Y_{e0} , Y_{eT} , for WL, and k_0 , k_T , y_{e0} , y_{eT} , for SG with Statistica software (Statistica Release 7, Statsoft Inc. Tulsa, OK, USA).

Chroma change during osmotic dehydration process was modeled with a first order kinetics equation as used by Krokida et al. (2001):

$$\frac{dC^*}{dt} = -k_c \cdot (C^* - C_e^*) \quad (12)$$

where C^* is the chroma (Eq. 1), C_e^* the equilibrium value, k_{C^*} the rate constant (min^{-1}) of each colour parameter, and t is the immersion time (min). At zero time each sample had an initial value of chroma C_0 , so solving Eq. (12) the following mathematical equation is generated:

$$\frac{(C^* - C_e^*)}{(C_0^* - C_e^*)} = \exp(-k_{C^*} \cdot t) \quad (13)$$

The equation that was used is:

$$C^* = C_e^* + (C_0^* - C_e^*) \cdot \exp(k_{C^*} \cdot t) \quad (14)$$

The effect of process OD temperature on chroma change during osmotic dehydration can be introduced using the following empirical equations in a similar way to Eqs. (8)–(11):

$$k_{C^*} = k_{0C^*} \cdot \left(\frac{T_{osm}}{85}\right)^{k_{TC^*}} \quad (15)$$

$$C_e^* = C_{0e}^* \cdot \left(\frac{T_{osm}}{85}\right)^{C_T^*} \quad (16)$$

where k_{0C^*} , k_{TC^*} , C_{0e}^* and C_T^* are the proposed parameters for the mathematical model of chroma.

A first order kinetics equation is also proposed to describe changes of textural characteristics, namely the hardness and the energy needed for the first fracture of the pumpkin (compression work) during the osmotic dehydration:

$$\frac{dF}{dt} = -k_F \cdot (F - F_e) \quad (17)$$

where F is the parameter of hardness, F_e the equilibrium value, k_F the rate constant (min^{-1}) of hardness parameter, t is the time of the osmotic treatment (min).

$$\frac{dA}{dt} = -k_A \cdot (A - A_e) \quad (18)$$

where A is the work needed for compression of the sample until 50% of its initial height, A_e the equilibrium value, k_A the rate constant (min^{-1}), t is the time of the osmotic treatment (min).

At zero time each sample had an initial value of hardness F_0 and of work A_0 , and therefore Eqs. (17) and (18) read:

$$\frac{(F - F_e)}{(F_0 - F_e)} = \exp(-k_F \cdot t) \quad (19)$$

and

$$\frac{(A - A_e)}{(A_0 - A_e)} = \exp(-k_A \cdot t) \quad (20)$$

The equations that were used are the following:

$$F = F_e + (F_0 - F_e) \cdot \exp(-k_F \cdot t) \quad (21)$$

and

$$A = A_e + (A_0 - A_e) \cdot \exp(-k_A \cdot t) \quad (22)$$

The effect of process OD temperature on hardness and work needed for compression of samples during osmotic dehydration can be incorporated using the following empirical equations, in a similar pattern to chroma (Eqs. 15, 16) and mass transfer parameters (Eqs. 8–11):

$$k_F = k_{0F} \cdot \left(\frac{T_{osm}}{85}\right)^{k_{TF}} \quad (23)$$

$$F_e = F_{0e} \cdot \left(\frac{T_{osm}}{85}\right)^{F_T} \quad (24)$$

and

$$k_A = k_{0A} \cdot \left(\frac{T_{osm}}{85}\right)^{k_{TA}} \quad (25)$$

$$A_e = A_{0e} \cdot \left(\frac{T_{osm}}{85}\right)^{A_T} \quad (26)$$

where k_{0F} , k_{TF} , F_{0e} and F_T are the proposed parameters for the mathematical model of hardness and k_{0A} , k_{TA} , A_{0e} and A_T are the proposed parameters for compression work.

Nonlinear regression analysis was also used for chroma and hardness parameter estimation, in a similar way to mass transfer parameters (WL and SG).

Results and discussion

Fresh samples of pumpkin had a moisture content of $96.4 \pm 0.7\%$ and soluble solids of $3.0 \pm 0.3^\circ$ Brix. After candying with a sucrose concentrated solution, at 150 min immersion time, osmo-dehydrated pumpkin had a moisture content of approximately $54.7 \pm 2.6\%$ and soluble solids of $47.2 \pm 0.9^\circ$ Brix depending on the temperature of the osmotic dehydration. On the other hand, the moisture content of pumpkin processed with oligofructose and a 1:1

mixture of sucrose–oligofructose solutions were 63.3 ± 4.9 and $57.9 \pm 6.8\%$, respectively, while the soluble solids were $42 \pm 4.1^\circ$ Brix for samples of pumpkin osmotically treated with oligofructose and $43.2 \pm 3.9^\circ$ Brix for those treated with a mixture of sucrose and oligofructose (1:1). Between the three osmotic agents, values of equilibrium for the moisture content were different, while for the soluble solids the respective values were quite similar.

Effect of osmotic solution temperature on water loss and solid gain of osmodehydrated pumpkin

The values of R^2 confirmed that water loss and solid gain were well described using the proposed mathematical model Eqs. (6)–(11). The estimation of the parameters K_o , K_T , Y_{e0} , Y_{eT} , k_o , k_T , ye_o and ye_T provided an acceptable agreement between experimental and calculated values (Table 1). Figure 1 shows the influence of OD temperature (75, 85 and 95 °C) and immersion time on water loss and solid gain during the osmotic dehydration of pumpkin in sucrose, oligofructose and the mixture of sucrose–oligofructose solutions. Lines in Fig. 1 represent the predicted values of water loss and solid gain for each sample. According to Fig. 1, pumpkin during OD, for water loss and solid gain, needs approximately 150 min to reach the equilibrium values. This is evident for all 3 different osmotic agents. The values of water loss are higher than the values of solid gain. The evaluation of the OD curves showed that the temperature (T_{osm}) had affected both water loss and solid gain parameters. For water loss, it was observed that as the process temperature (T_{osm}) increased, the higher WL values were obtained, a finding that agrees with Abraão et al. (2013). Their research showed that the maximum values for water loss and solid gain were observed for pumpkins processed at the highest concentration of sucrose solution and at high temperature (60° Brix and 60 °C). According to Rastogi and Ragharvarao (2004) and Luchese et al. (2015), higher process temperatures promote an increase of solids incorporation, but this did not occur in this study, in the case of sucrose. It was observed only in the case of oligofructose and a mixture of sucrose and oligofructose (1:1) solutions. Figure 1B indicates that for SG parameter, at the first minutes of the OD with sucrose, maximum values were achieved for the minimum process temperature ($T_{osm} = 75$ °C). However, in the end of the OD with sucrose, for all the 3 different process temperatures, the value of solid gain reached the same level. After 150 min of OD in sucrose syrup for $T_{osm} = 75$ °C solid gain reached a values of 4.564 ± 0.240 , for $T_{osm} = 85$ °C, 4.387 ± 0.006 and 4.413 ± 0.070 g SG/g initial dry mass of pumpkin for $T_{osm} = 95$ °C. The samples osmodehydrated with

oligofructose and the mixture of sucrose and oligofructose showed the highest level of water loss, while OD solution containing merely oligofructose led to the highest increase in soluble solids. Also, in this case, the progressive increase of the process temperature (T_{osm}), from 75 to 85 °C and, finally, to 95 °C, had as a result a significant increase of the solid uptake. This observation contradicts with Matusek et al. (2008), where oligofructose led to lower values of water loss and solid gain than sucrose and with Nambiar et al. (2016), where samples of Indian gooseberry suffered a marginal solid uptake, with a further increase of temperature from 40 to 50 °C. The increasing effect of process temperature in solid gain has been also observed during the osmotic dehydration of papaya cubes, in the temperature range from 30 to 50 °C and in the case of peach slices processed at sucrose solution (Jain et al. 2011; Yadav et al. 2012). The specific properties of the plant tissue (pumpkin) and the higher temperature range of the osmotic dehydration used in this research can be the cause of the different observations. There is a significant effect of temperature in the case of oligofructose and the mixture of oligofructose/sugar. The temperature increase leads to an increase of the values of solid gain observed after the first 50 min. However, in the case of water loss, even in the first 20 min of the OD, the process temperature effect was evident. On the other hand, SG equilibrium values slightly varied depending on the OD solute, with sucrose, at all temperatures and oligofructose (at the highest temperature of 95 °C) leading to the highest SG at equilibrium. This is expected in the case of sucrose, since it has the lowest molecular weight amongst the osmotic agents studied. Oligofructose, on the other hand, being a fructan with a variable Degree of Polymerization (DP), ranging from 2 to 8, is reported to have a molecular weight between 342 and 1638 Dalton (Da) (Heimbach 2011). Therefore, the slightly different SG value reached at equilibrium can be attributed to the small difference of the molecular size of the three osmotic agents. The molecular size of the osmotic solute has a large impact on the osmotic dehydration and this had also been observed by Lazarides et al. (1997) in the case of apparent mass diffusivities for apple and potato and Brochier et al. (2015) for the mass loss in the case of yacon tissue.

Effect of osmotic solution temperature on water activity, chroma and hardness of osmodehydrated pumpkin

The water activity of osmotically dehydrated pumpkins was found to decrease during processing for all cases studied (Fig. 2). The samples treated with oligofructose and the mixture (sucrose and oligofructose 1:1) syrups, showed the highest levels of final water activity value. At

Table 1 Results of parameter estimation for water loss (WL), solid gain (SG), chroma (C^*), hardness (F) and compression work (A) of osmo-dehydrated pumpkins

Water loss	K_0 (min^{-1})	K_T	Y_{e0} (kg/kg)	Y_{eT}	R^2
Sucrose	0.0240 ± 0.0010	1.8606 ± 0.1190	17.1559 ± 0.2636	0.0519 ± 0.0610	0.998
Oligofructose	0.0295 ± 0.0008	0.6205 ± 0.2530	18.3070 ± 0.1309	-0.1337 ± 0.0760	0.999
Mixture (oligofructose:sucrose 1:1)	0.0315 ± 0.0009	-0.9468 ± 0.3293	19.2324 ± 0.1683	0.2055 ± 0.0913	0.998
Solid gain	k_0 (min^{-1})	k_T	y_{e0} (kg/kg)	y_{eT}	R^2
Sucrose	0.0217 ± 0.0010	-1.6707 ± 0.4681	4.5708 ± 0.0790	0.0071 ± 0.1687	0.998
Oligofructose	0.0150 ± 0.0006	-4.5732 ± 0.3697	4.7904 ± 0.0746	2.892 ± 0.1665	0.998
Mixture (oligofructose:sucrose 1:1)	0.0256 ± 0.0009	-1.8459 ± 0.2576	2.9237 ± 0.0256	1.0124 ± 0.0898	0.999
Chroma	k_{OC^*} (min^{-1})	k_{TC^*}	C_{0e}^*	C_T^*	R^2
Sucrose	0.0110 ± 0.0010	-1.9270 ± 0.8320	26.4390 ± 0.5220	1.5270 ± 0.1860	0.971
Oligofructose	0.0120 ± 0.0005	-4.7690 ± 0.3590	28.3370 ± 0.2260	1.6010 ± 0.0710	0.988
Mixture (oligofructose:sucrose 1:1)	0.0087 ± 0.0005	1.9090 ± 0.6070	27.1520 ± 0.3520	1.0930 ± 0.1290	0.991
Hardness	k_{0F} (min^{-1})	k_{TF}	F_{0e} (N)	F_T	R^2
Sucrose	0.043 ± 0.002	2.868 ± 0.486	1.332 ± 0.049	-2.784 ± 0.363	0.988
Oligofructose	0.045 ± 0.002	5.846 ± 0.432	0.857 ± 0.043	-3.897 ± 0.524	0.994
Mixture (oligofructose:sucrose 1:1)	0.025 ± 0.002	7.323 ± 0.809	1.106 ± 0.107	-3.605 ± 1.112	0.985
Compression work	k_{0A} (min^{-1})	k_{TA}	A_{0e} (N*s)	A_T	R^2
Sucrose	0.037 ± 0.001	1.276 ± 0.372	2.758 ± 0.183	-4.279 ± 0.624	0.987
Oligofructose	0.026 ± 0.001	5.148 ± 0.196	1.139 ± 0.121	-9.915 ± 0.838	0.997
Mixture (oligofructose:sucrose 1:1)	0.569 ± 0.002	0.563 ± 0.363	3.145 ± 0.128	-7.219 ± 0.350	0.991

150 min of the treatment with oligofructose they reached the values of 0.9754 ± 0.0001 , 0.9756 ± 0.0007 and 0.9722 ± 0.0002 for 75, 85 and 95 °C, respectively. For the mixture (sucrose and oligofructose 1:1) syrup, the values were 0.9623 ± 0.0002 , 0.9525 ± 0.0003 and 0.9443 ± 0.0003 for 75, 85 and 95 °C, respectively. The greatest reduction of water activity during the osmotic dehydration was achieved with sucrose solution (0.9455 ± 0.0005 for 75 °C, 0.9366 ± 0.0006 for 85 °C and 0.9392 ± 0.0007 for 95 °C). Another recent study with lemon slices osmodehydrated with oligofructose and stevia syrup showed similar results. The level of water activity (a_w) was the highest after 1440 min of immersion ($a_w = 0.978 \pm 0.004$) (Rubio-Arrea et al. 2015b). Similar results were shown in studies with orange slices (Rubio-Arrea et al. 2015a).

The colour saturation of the pumpkin was affected by both the time of immersion and process temperature. The values of R^2 confirmed that chroma parameter was well described using mathematical model of Eqs. 13–16. The mathematical model was sufficiently fitted to the experimental data and the estimation of the parameters K_{OC^*} ,

K_{TC^*} , C_{0e}^* and C_T^* gave an acceptable agreement between experimental and calculated values (Table 1). Figure 3A shows the influence of temperature (75, 85 and 95 °C) of the osmotic solution and immersion time on chroma during the osmotic dehydration of pumpkin in sucrose, oligofructose and the mixture of sucrose–oligofructose syrups. The lines in this figure represent the predicted values of chroma in each case.

Chroma of osmo-dehydrated pumpkins increased with the time of immersion. The temperature of the osmotic dehydration had a significant effect on chroma changes, whereas the different osmotic agents did not seem to significantly affect color degradation. The highest values were obtained, for all three osmotic solutes, by the OD treatment at 95 °C, while the lowest values were calculated by osmotic dehydration at 75 °C. This could be due to water removal from the pumpkin samples according to Falade et al. (2007), as the same observation was reported for samples of watermelon. These results are also in accordance with Abraão et al. (2013), where the chroma of osmodehydrated pumpkin had been affected by treatment at higher temperatures because of an increase in the

Fig. 1 Effect of osmotic temperature and process time on water loss (A) and solid gain (B) of candied pumpkins: **a** sucrose syrup, **b** mixture sucrose–oligofructose syrup and **c** oligofructose syrup

Fig. 2 Effect of osmotic temperature and process time on a_w of candied pumpkins: **a** sucrose syrup, **b** mixture sucrose–oligofructose syrup and **c** oligofructose syrup

translucency of the osmodehydrated pumpkins. Additionally, the blanching, as a pretreatment, inactivates enzymes that degrade color pigments.

The values of R^2 confirmed that the hardness and the energy needed for pumpkin slabs' compression was well described using the proposed mathematical model. The

estimation of the parameters K_{OF} , K_{TF} , F_{0e} , F_T and K_{OA} , K_{TA} , A_{0e} , A_T gave an acceptable agreement between experimental and calculated values (Table 1). Figure 3B, C show the influence of temperature (75, 85 and 95 °C) of the osmotic solution and immersion time on hardness and energy needed for compression during the osmotic

Fig. 3 Effect of osmotic temperature and process time on quality characteristics of candied pumpkins: **A** chroma, **B** hardness and **C** compression work. For each property: **a** sucrose syrup, **b** mixture sucrose–oligofructose syrup and **c** oligofructose syrup

dehydration of pumpkin in sucrose, oligofructose and mixture of sucrose–oligofructose syrups, respectively. Lines in the figures represent the predicted values of hardness and energy in each case. The rate of change in sample hardness was reduced when the immersion of osmotic dehydration was increased, reaching an equilibrium value (Fig. 3B) and similarly the rate of change in work for sample compression decreased (Fig. 3C). The removing water and the absorption of solids changed the

mechanical properties of pumpkins. Regardless the osmotic solution, the hardness of osmodehydrated pumpkins was influenced by the thermal processing. The hardness and compression work decreased as temperature and time process increased approaching an equilibrium value after 100 min of immersion. This had also been observed by Vilela et al. (2016). Their results showed that osmodehydrated fruits became more brittle and less tough as the water content was reduced and the solid content was

increased, and this may be related to the reinforcement of the cell walls due to the increase in total sugar concentration in the osmodehydrated fruit tissues. Another crucial factor for this behavior was the pretreatment of blanching prior to osmotic dehydration, which affects the structure of raw samples. Similar observations have been reported for pumpkin and other fruits (Gonçalves et al. 2007; Nimmannpipug et al. 2013). As it was observed, the hardness of samples and work for sample compression at 95 °C decreased more than at the other temperatures.

Effect of osmotic solution temperature on macro structural of osmodehydrated pumpkin

In this part of the survey, the influence of temperature (75, 85 and 95 °C) of the osmotic solution on the color and size of the pumpkin, before the osmotic treatment and after 150 min of immersion in the alternative OD syrups was studied (Tables 1S and 2S of Supplementary material.). It was observed that at higher temperature of the process the pumpkin showed the highest deformation. It had been clearly observed that as temperature increases, the color becomes darker and the size smaller. Similarly, time of immersion influences the shape and the size of pumpkin slices. Pumpkin tissue suffers deformations as a consequence of the water removed out of the matrix. This had been also reported by Mayor et al. (2011) for osmotic dehydration of pumpkins (*Cucurbita pepo* L.) in a 60% sucrose syrup at 25 °C. Independently of the process conditions (temperature of osmotic dehydration) the thickness of the samples was affected (Table 2S) as the time of immersion increased.

Conclusion

The present study investigated the candying of pumpkin (*Cucurbita moschata*) with sucrose (traditional process) and alternative osmotic solutes (oligofructose and mixture of oligofructose and sucrose), producing a low calorie osmodehydrated fruit, of improved nutritional value. An empirical model describing the mass transfer phenomena during the osmotic treatment of pumpkin slices, as expressed by water loss and solid gain parameters was proposed and was proven to adequately fit experimental data. This study showed also that there was a significant effect of process temperature on the kinetic rate of water loss and solid gain of the product in all three different syrups. The values of water loss in case of sucrose were lower than for all the other osmotic agents. On the other hand, the values of solid gain in case of sucrose and oligofructose (at the highest temperature) were higher due to the different molecular weight of the osmotic agents.

Additionally, it was observed that the process temperature affects the chroma of the osmodehydrated pumpkin samples, as well as their hardness and the work needed for compression, regardless the osmotic agent.

As a concluding remark, one could propose oligofructose and the mixture of sucrose and oligofructose as alternative osmotic solutes, replacing sucrose in the OD syrup of the traditional technique of candying. Therefore a novel osmodehydrated food could be produced, that would be suitable for a low calorie and sugar-free diet, providing also valuable nutritional attributes thanks to the incorporation of oligofructose, which is well known, among other, for its prebiotic properties.

Acknowledgements The authors wish to thank Prof. Evangelo S. Lazo for support and useful discussions.

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