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Comparison of sucrose and fructo-oligosaccharides as osmotic agents in apple

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Abstract

Fructo-oligosaccharides and sucrose were compared as osmotic agents in the osmotic dehydration of apple cv. Idared. Dehydration process of apple cubes (10 * 10 * 10 mm) was performed to determine the weight reduction (WR), moisture content (MC), water loss (WL) and solid gain (SG) over a range of osmotic solutions (40–60% w/v), temperature (40–60 °C) and processing time (20–40 min) The effective diffusion coefficient of water and solute was calculated assuming the processes to be governed by Fick's unsteady state diffusion. The effective diffusion coefficients were found to be of the order of 10^{-9} m^2 s^{-1} and were effected by the type of solute significantly. The WR, MC, WL and SG were predicted as weighted linear combinations of temperature, concentration of solute and time of OD.

Keywords: Osmotic dehydration; Fructo-oligosaccharides; Apple; Diffusion coefficient

Industrial relevance: The use of fructo-oligosaccharides (FOS) in different fruit based products is an efficient way to enrich human diet with functional component, because of the well-known health benefits of FOS. The osmotic behaviour of fructo-oligosaccharides were studied and compared to the conventional used sucrose. In view of the changes of different osmotics regarding to unit parameters of osmotic dehydration the results give possibility to industrial technology planning of products containing FOS, which are available for consumption in every season of the year and are favourable also in processed form e.g. muesli, dairy products.

1. Introduction

Osmotic dehydration is a traditional water removal process that decreases the water activity in high water content foods such as fruits. Placing foods in a hypertonic solution, two major processes take place simultaneously: water flow from the food into the solution and solute transfer from the solution into the food matrix. The natural cell surface acts as a semi-permeable membrane. Since the membrane responsible for osmotic transport is not perfectly selective, other natural solutes present in the cells such as sugars, organic acids, minerals, salts, etc. can also be leached into the osmotic solution (Giangiacomo, Torregiani & Abbo, 1987; Lerici, Pinnavaia, Dalla Rosa & Bartolucci, 1985; Lazarides, Gekas & Mavroudis, 1997). Comparing OD with other dehydration processes, when the pre-treatment is also protective, there is less heat damage in the cells and the nutritive compounds such as vitamins, pigments and flavours (Raoult-Wack, 1994).

The chemical potential of the hypertonic solution is the driving force of the diffusion. The rate of the mass transport depends on many factors such as type of pre-treatments (i.e. conventional blanching, microwave, vacuum, high electric field pulse (HELP) and high pressure (HP) treatment), the conditions of the osmotic treatment (time, temperature, use of agitation, vacuum, ultrasound), the concentration and the quality of the osmotic agent, use of combined solutions with salt (Sereno,

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Abbreviations: FOS, Fructo-oligosaccharides; MC, Moisture content, %; OD, Osmotic dehydration; SG, Solid gain, g/g; WL, Water loss, g/g; WR, Weight reduction, g/g.

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Moreira & Martinez, 2001), the solution-to-food ratio and the tissue structure of the food (Torreggiani, 1993; Rastogi & Raghavarao, 1994, 1997; Fito et al., 2001; Rastogi, Angersbach & Knorr, 2000).

It is very common in literature to consider any finite geometry as infinite flat plate configuration limiting the diffusion to one direction only (Convay, Castaigne, Picaroift, & Vovan, 1983; Magee, Murphy, & Hassaballah, 1983; Beristain, Azuara, Cortés, & Garcia, 1990; Azuara, Cortés, Garcia, & Beristain, 1992; Rastoghi & Raghavarao, 1997; Matusek & Merész, 2002). When thickness of the sample is of equal magnitude to length and breadth (paralellepiped, cube, thick slice, cylinder or sphere), significant amount of diffusion takes place through peripheral sides as well. In such situations, it is very much required to account for the real geometry of the samples (Rastogi, & Raghavarao, 2004; Salvatori, Andrés, Chiralt, & Fito, 1999; Beristain, Azuara, Cortés, & Garcia, 1990; Rastogi, Raghavarao, & Niranjan, 1997). The mathematical description, modelling of the two major simultaneously countercurrent mass transfers, has several different solutions in the literature (Peleg, 1988; Azuara, Cortés, Garcia, & Beristain, 1992; Magee, Hassaballah, & Murphy, 1983; Chenlo, Moreira, Fernández-Herrero, & Vázquez, 2006; Ochoa-Martinez, & Ayala-Aponte, 2007).

Inulin and oligofructose are officially recognized as natural food ingredients and are classified as dietary fibre in almost all European countries (Roberfroid, 2000). One of the nutritional benefit of oligofructose is its pre-biotic effect: influencing the microbial composition of the gastrointestinal tract of the host (Rao, 2001).

The type of osmotic agent is a very important factor that determines the rate of diffusion. In this study, the osmotic effect of the fructo-oligosaccharides was compared to the conventionally used sucrose. The effect of some unit operation parameters was investigated on the moisture content (MC), water loss (WL), solid gain (SG) and weight reduction (WR) of the samples in addition to diffusion coefficient.

2. Materials and methods

2.1. Osmotic solution

Beneo™ P95 (ORAFTI) and commercial sucrose were used as osmotic agents. Osmotic solutions having 40, 50 and 60% (w/v) concentration were prepared by permanent stirring at 50 °C using decarbonated distilled water (pH=6.5). Beneo™ P95 is a commercial product produced by the hydrolysis of chicory inulin. The carbohydrate composition of the product is: oligofructose (degree of polymerisation: 2–8)≥93.2%; glucose+fructose+sucrose≤6.8%.

Table 1
List of independent variables and their levels

Independent variables	Levels of independent variables		
Type of osmotic agent	Sucrose	FOS	
Temperature [°C]	40	50	60
Concentration [%]	40	50	60
Time [min]	20	30	40

Table 2
The mean and error moisture content as a function of OD unit operators

	Conc.	t_{OD}	T=40 °C		T=50 °C		T=60 °C	
	(% w/v)	(min)	Means	Std. Err.	Means	Std. Err.	Means	Std. Err.
Sucrose	40	20	76.21	0.26	76.41	0.20	74.65	0.39
		30	75.07	0.10	73.85	0.06	73.53	0.21
		40	74.14	0.24	72.59	0.05	72.70	0.20
	50	20	72.53	0.57	71.07	0.24	70.92	0.59
		30	71.15	0.13	70.04	0.21	69.47	0.21
		40	69.85	0.45	69.52	0.16	67.94	0.24
	60	20	70.66	0.29	68.65	0.15	69.13	0.32
		30	68.09	0.40	66.12	0.30	67.54	0.42
		40	67.15	0.52	63.78	0.24	65.20	0.41
FOS	40	20	81.10	0.15	79.57	0.25	78.55	0.14
		30	79.80	0.18	78.44	0.47	77.28	0.66
		40	79.15	0.15	77.44	0.18	76.78	0.71
	50	20	78.44	0.40	77.52	0.28	77.03	0.47
		30	77.46	0.25	76.83	0.47	75.45	0.25
		40	77.00	0.28	75.64	0.36	72.92	0.16
	60	20	77.61	0.35	77.79	0.56	74.64	0.53
		30	74.85	0.28	75.23	0.15	72.95	0.43
		40	74.77	0.55	75.74	0.52	71.48	0.38

2.2. Sample preparation

Apples cv. Idared (riped for long term storage, moisture content 86±1% (w/w), soluble solids content 13.1±0.6 R%) were purchased on the market and stored at 1–4 °C under 90–96% RH until use. A few hours prior to use, the apples were left to equilibrate at room temperature. They were peeled manually and cut into 10×10×10 mm cubes after removing the pericarp. Apple cubes were immersed into a 1% citric-acid solution (T=25 °C; t=10 s) to inhibit enzymatic browning. The cubes were blotted on filter paper and were pre-treated.

2.3. Pre-treatment

As pre-treatment, atmospheric blanching was used. Atmospheric blanching was applied at 65 °C for 6 min by permanent agitation in GFL® 1086 waterbath (v=140 min^{-1}) in either isotonic sucrose or fructo-oligosaccharide solution. The sample-to-solution ratio was 1:10 (w/w). After blanching, apple cubes were blotted on a filter paper, weighed on an analytical scale and were subjected to osmotic dehydration.

As a result of blanching the permeability of apple tissue increases, which is favourable for the oligosaccharide-enrichment.

2.4. Osmotic treatment — experimental design and statistical analysis

The hypertonic solution and the apple cubes were put into 250 cm^3 Erlenmeyer flasks, which were immersed in a temperature and agitation (v=140 min^{-1}) controlled waterbath (GFL 1086). Sample-to-solution ratio was 1:10 (w/w) in all cases. After osmotic treatment, the solution adhered to the surface of the cubes was eliminated with filter paper and the cubes were weighed on analytical scale. Experimental conditions are presented in Table 1. Experiments were run in triplicate. All data were subjected to statistical analysis using the analysis of variance (ANOVA) test and multiple linear regression analysis by Statistica 6.1 software (StatSoft Inc. 2004).

2.5. Methods of the analysis

Mass of the samples was measured by analytical scale before and after osmotic process, and weight reduction was calculated using the equation:

$$\mathrm{WR(g/g)} = \frac{M_t - M_{OD}}{M_t \cdot \left(1 - \frac{MC_0}{100}\right)} \tag{1}$$

Moisture content of the apple cubes was determined by gravimetric method by the use of an atmospheric cabinet drier at 70 °C up to 20 h, and was calculated using the equation:

$$\mathrm{MC(\%)} = \frac{M_{\mathrm{OD}} - M_{\mathrm{f}}}{M_{\mathrm{OD}}} \cdot 100 \tag{2}$$

Water loss (WL) and solid gain (SG) were calculated using the following expressions (Tedjo, Taiwo, Eshtiaghi & Knorr, 2002):

$$\mathrm{WL(g/g)} = \frac{(M_t - S_t) - (M_{\mathrm{OD}} - M_{\mathrm{f}})}{S_t} \tag{3}$$

where

(a)=$(M_t - S_t)$ water content prior to OD (g),
(b)=$(M_{\mathrm{OD}} - M_{\mathrm{f}})$ water content after OD (g),
(a)–(b) water loss during OD (g).

$$\mathrm{SG(g/g)} = \frac{(M_{\mathrm{f}} - S_t)}{S_t} \tag{4}$$

where $(M_{\mathrm{f}} - S_t)$=solid uptake during OD (g).

For the determination of water and solute diffusivity during osmotic dehydration, the equation derived from Fick's second law for diffusion in–out a rectangular parallelepiped was used presented by Rastogi and Raghavarao (2004). They expressed for cubical configuration the presentation:

Table 3
The mean and error of water loss as a function of OD unit operators

	Conc.	t_{OD}	T=40 °C		T=50 °C		T=60 °C	
	(% w/v)	(min)	Means	Std. Err.	Means	Std. Err.	Means	Std. Err.
Sucrose	40	20	1.408	0.020	1.389	0.015	1.268	0.031
		30	1.506	0.008	1.625	0.005	1.535	0.016
		40	1.700	0.018	1.911	0.003	1.904	0.014
	50	20	1.420	0.045	1.863	0.018	1.912	0.043
		30	1.702	0.010	2.149	0.015	2.088	0.016
		40	1.786	0.034	2.231	0.011	2.391	0.017
	60	20	1.824	0.022	2.002	0.011	2.143	0.023
		30	1.963	0.030	2.360	0.022	2.351	0.030
		40	2.172	0.038	2.746	0.017	2.613	0.028
FOS	40	20	1.006	0.011	1.037	0.017	1.192	0.009
		30	1.157	0.013	1.207	0.032	1.469	0.043
		40	1.291	0.011	1.393	0.012	1.622	0.045
	50	20	1.160	0.030	1.450	0.018	1.664	0.029
		30	1.394	0.018	1.598	0.030	1.866	0.015
		40	1.452	0.020	1.805	0.022	2.159	0.009
	60	20	1.375	0.026	1.560	0.036	1.922	0.032
		30	1.646	0.020	1.895	0.009	2.188	0.025
		40	1.804	0.039	1.998	0.030	2.408	0.021

Table 4
The mean and error of solid gain as a function of OD unit operators

	Conc.	t_{OD}	T=40 °C		T=50 °C		T=60 °C	
	(% w/v)	(min)	Means	Std. Err.	Means	Std. Err.	Means	Std. Err.
Sucrose	40	20	0.781	0.020	0.768	0.015	0.984	0.031
		30	0.862	0.008	0.944	0.005	1.009	0.016
		40	0.888	0.018	0.965	0.003	0.957	0.014
	50	20	1.156	0.045	1.137	0.018	1.133	0.043
		30	1.194	0.010	1.124	0.015	1.209	0.016
		40	1.299	0.034	1.141	0.011	1.228	0.017
	60	20	1.196	0.022	1.334	0.011	1.219	0.023
		30	1.413	0.030	1.436	0.022	1.288	0.030
		40	1.418	0.038	1.480	0.017	1.402	0.028
FOS	40	20	0.417	0.011	0.392	0.017	0.437	0.009
		30	0.501	0.013	0.443	0.032	0.467	0.043
		40	0.527	0.011	0.475	0.012	0.462	0.045
	50	20	0.629	0.030	0.452	0.018	0.429	0.029
		30	0.658	0.018	0.465	0.030	0.493	0.015
		40	0.683	0.020	0.498	0.022	0.596	0.009
	60	20	0.649	0.026	0.398	0.036	0.541	0.032
		30	0.828	0.020	0.502	0.009	0.583	0.025
		40	0.783	0.039	0.428	0.030	0.615	0.021

$$M_r = \frac{(m_t - m_\infty)}{m_0 - m_\infty} = \sum_{n=1}^{\infty} C_n^3 \ \exp\left[-D_{\mathrm{ew}} t q_n^2 \left(\frac{3}{a^2}\right)\right] \tag{5}$$

$$S_r = \frac{(S_t - S_\infty)}{S_0 - S_\infty} = \sum_{n=1}^{\infty} C_n^3 \ \exp\left[-D_{\mathrm{es}} t q_n^2 \left(\frac{3}{a^2}\right)\right] \tag{6}$$

where:

$$C_n = 2\alpha(1+\alpha)/\left(1+\alpha+\alpha^2 q_n^2\right) \tag{7}$$

Considering the equilibrium approach, mass transfer and cubical configuration D_{ew} and D_{es} were estimated from the following equation:

$$(D_{\mathrm{ew}}) = [\{d(\log M_r)/dt\}/\{d(\log M_r)/d(F_{\mathrm{OW}})\}]\left(a^2/3\right) \tag{8}$$

$$(D_{\mathrm{es}}) = [\{d(\log S_r)/dt\}/\{d(\log S_r)/d(F_{\mathrm{OS}})\}]\left(a^2/3\right) \tag{9}$$

where Fourier numbers for moisture and solute diffusion are calculated as $F_{\mathrm{ow}} = D_{\mathrm{ew}} t(3/a^2)$ and $F_{\mathrm{os}} = D_{\mathrm{es}} t(3/a^2)$, respectively.

3. Results

An experimental design was used to compare sucrose and FOS as osmotic agents, to estimate the main effects of the process variables on moisture content (MC), water loss (WL), solid gain (SG), weight reduction (WR) and diffusion coefficient (D) during the osmotic dehydration of apple cubes by MLR analysis. Type of osmotic agent (A, x_1), temperature (T, x_2), solution concentration (C, x_3) and time of osmotic process (t, x_4) were selected as independent variables (Table 1).

Table 5
The mean and error of weight reduction as a function of OD unit operators

	Conc.	t_{OD}	T=40 °C		T=50 °C		T=60 °C	
	(% w/v)	(min)	Means	Std. Err.	Means	Std. Err.	Means	Std. Err.
Sucrose	40	20	0.628	0.020	0.621	0.015	0.284	0.031
		30	0.644	0.008	0.682	0.005	0.526	0.016
		40	0.812	0.018	0.946	0.003	0.947	0.014
	50	20	0.264	0.045	0.726	0.018	0.779	0.043
		30	0.508	0.010	1.025	0.015	0.879	0.016
		40	0.486	0.034	1.090	0.011	1.163	0.017
	60	20	0.628	0.022	0.668	0.011	0.924	0.023
		30	0.550	0.030	0.924	0.022	1.063	0.030
		40	0.754	0.038	1.266	0.017	1.211	0.028
FOS	40	20	0.589	0.011	0.645	0.017	0.755	0.009
		30	0.656	0.013	0.764	0.032	1.002	0.043
		40	0.763	0.011	0.918	0.012	1.160	0.045
	50	20	0.530	0.030	0.998	0.018	1.235	0.029
		30	0.736	0.018	1.133	0.030	1.373	0.015
		40	0.769	0.020	1.306	0.022	1.563	0.009
	60	20	0.727	0.026	1.163	0.036	1.381	0.032
		30	0.818	0.020	1.393	0.009	1.605	0.025
		40	1.021	0.039	1.570	0.030	1.792	0.021

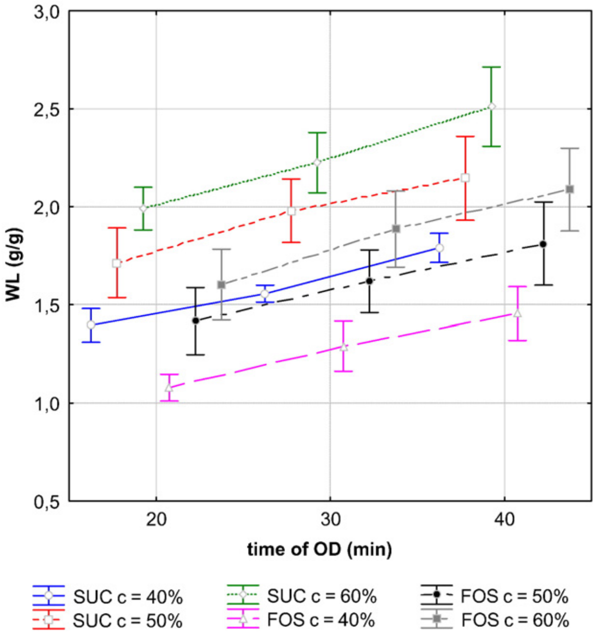

Fig. 2. Effect of process time on water loss.

Although the water and solid diffusion are independent on each other, there is a significant correlation between WL and SG only. Both WL and SG influence directly the moisture content and water activity. This effect is reflected in the high correlation coefficients between the MC&WL and MC&SG (Table 6). However, the WR is the result of difference between WL and SG, there isn't any direct connection between WR&SG, WR&WL, WR&MC. Weight reduction occurs independently from these changes in variables. Nevertheless every parameter of the OD process has significant effect on MC, WL, SG, WR (Table 7). Means and errors of response variables are summarized in Tables 2–5. The effect of OD process time on MC, WL, SG and WR are presented in Figs. 1–4.

However the general effect of temperature can be described by Arrhenius equation we have approached this effect by linear function. Due to the small difference in the absolute temperature (T=313–333 K) the exponential function can be replaced by linear function in this narrow range. Figs. 5–8 show the dependence of MC, SG, WL, WR on the T and C of solution independently on the time period of diffusion.

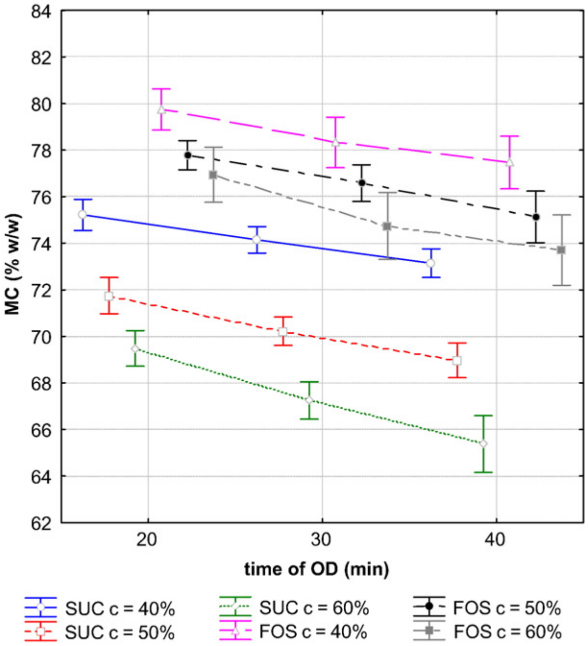

Fig. 1. Effect of process time on moisture content.

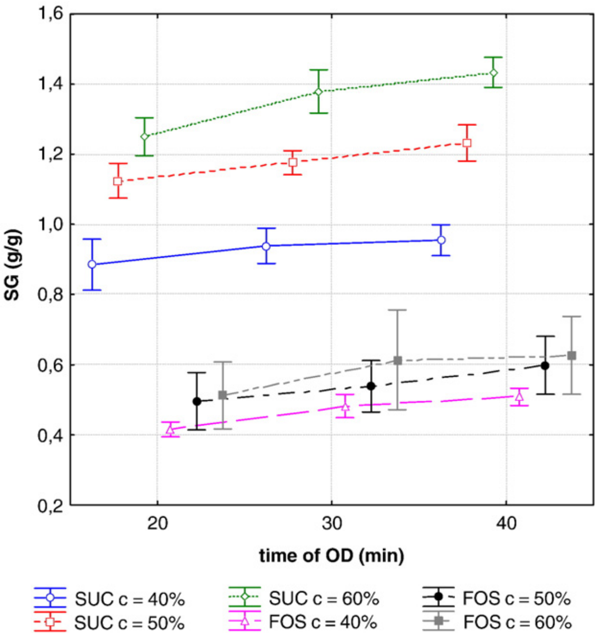

Fig. 3. Effect of process time on solid gain.

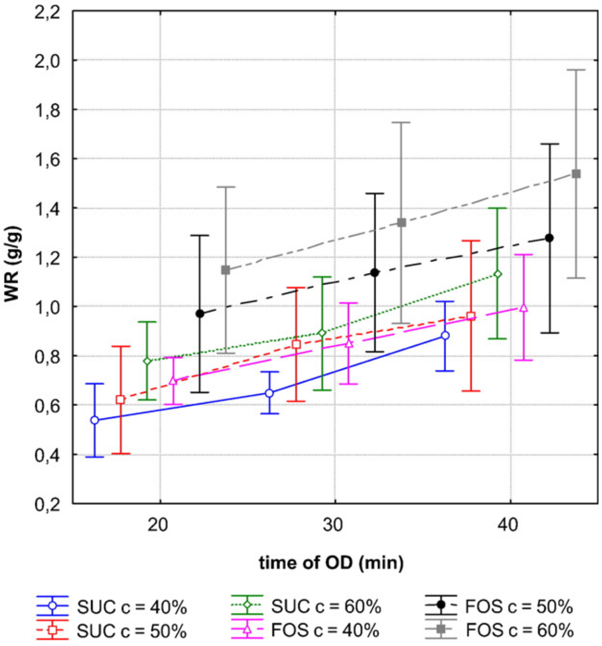

Fig. 4. Effect of process time on weight reduction.

3.1. Moisture content (MC)

Moisture content decreased with time as a result of WL and SG at both types of osmotic agents. MC decreased much more for sucrose than for FOS, and there was a significant interaction between temperature and type of osmoticum. In case of sucrose, the effect of temperature on MC was higher in the range 40–50 °C, but in case of FOS this effect was higher in the range 50–60 °C (Table 2). The multiple linear regression analysis has presented connections among the variables in the form of mathematical equations, where the coefficients of independent variables present the rate of any effect of the given variable. The MLR analysis is resulted in the following equations for MC depending on T, C, t in case of sucrose and FOS, respectively;

$$\mathrm{MC}-\mathrm{SUC}(\%\mathrm{w/w}) = 95.926 - 0.077 \times T(°\mathrm{C}) - 0.340 \times C(\%\mathrm{w/v}) - 0.150 \times t(\mathrm{min})$$

$$\mathrm{MC}-\mathrm{FOS}(\%\mathrm{w/w}) = 95,853 - 0.132 \times T(°\mathrm{C}) - 0.169 \times C(\%\mathrm{w/v}) - 0.136 \times t(\mathrm{min})$$

The equations reflect that the increase of temperature reduced MC during FOS treatment at twice higher rate compared to sucrose and the increase of solute concentration from 40 to 60% decreased MC at twice higher rate for sucrose than for FOS. The increase in sucrose concentration compared to FOS had twice greater effect on the decrease of MC (Fig. 5).

3.2. Water loss (WL)

All the ANOVA p-values are low and give significant effect of parameters as well as their interactions. These results underline the importance of choosing the appropriate combination of the unit parameters during OD.

The changes of WL depending on T and C of osmoticum are shown in the Fig. 6. Although there is a significant interaction between concentration and type of osmotic agent established by ANOVA (Table 7), the difference between the two types of osmoticum is reflected slightly in changes of WL. The almost parallel changes in WL in case of two osmoticum types with lower increase between 50% and 60% in case of FOS was observed. This causes a significant interaction of osmoticum type and concentration. On the contrary, there is a very strong interaction between temperature and type of osmotic agent. When sucrose is the osmoticum, there is notable deviation in WL between 40 and 50 °C, while there is not any difference in the range of 50 and

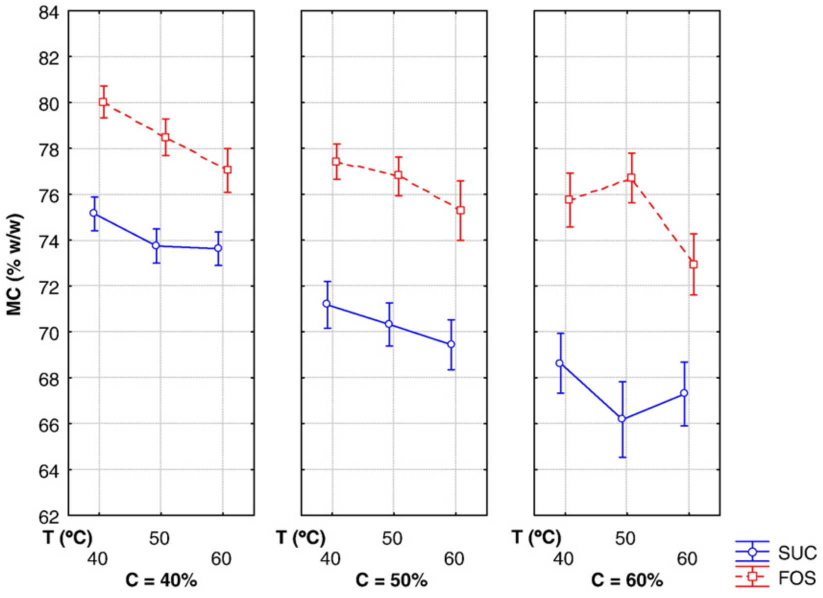

Fig. 5. Effect of process temperature and osmoticum concentration on moisture content.

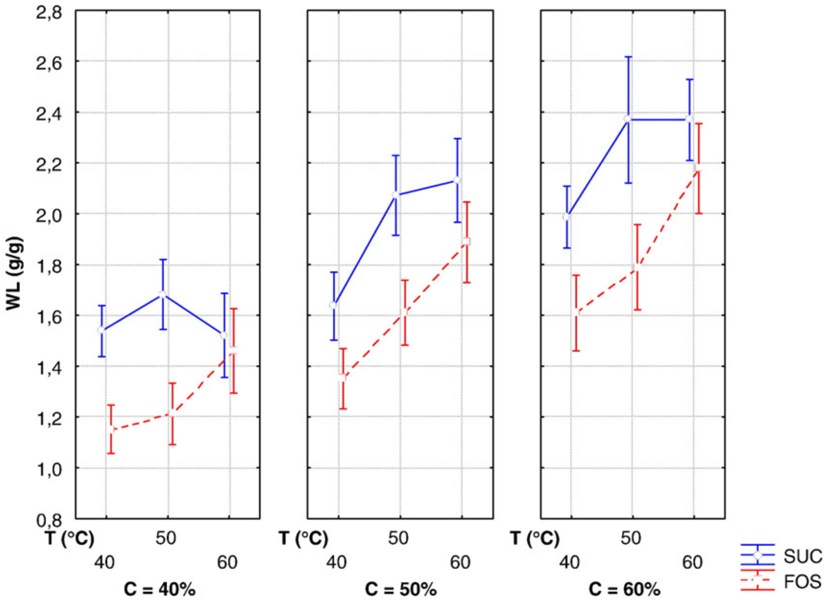

Fig. 6. Effect of process temperature and osmoticum concentration on water loss.

60 °C. In contrast, in case of FOS, WL rocketed between 50 and 60 °C, however, it increased only slightly in the range of 40–50 °C. The changes resemble to those of MC. The results of multiple linear regression analysis support these observations presenting a slightly significant difference between the solutes as a function of the unit operation parameters.

$$\mathrm{WL}-\mathrm{SUC}(\mathrm{g/g}) = -1.121 + 0.014 \times T(^\circ\mathrm{C}) + 0.033 \times C(\%\mathrm{w/v}) + 0.022 \times t(\mathrm{min})$$

$$\mathrm{WL}-\mathrm{FOS}(\mathrm{g/g}) = -1.683 + 0.024 \times T(^\circ\mathrm{C}) + 0.029 \times C(\%\mathrm{w/v}) + 0.021 \times t(\mathrm{min})$$

3.3. Solid gain (SG)

The rate of solid gain is lower than that of water loss. The SG values are lower than those of water loss, while the accuracy of their measurement is similar. The SG values in case of FOS are less than half of the SG values in case of sucrose, consequently, the probability of solute inflow is significantly lower. Few of the interactions are significant on solid gain, so the probability of second type error is higher. These results are in agreement with El-Aouar, Azoubel, Barbosa and Xidieh Murr (2006), when water loss and solid gain take place simultaneously.

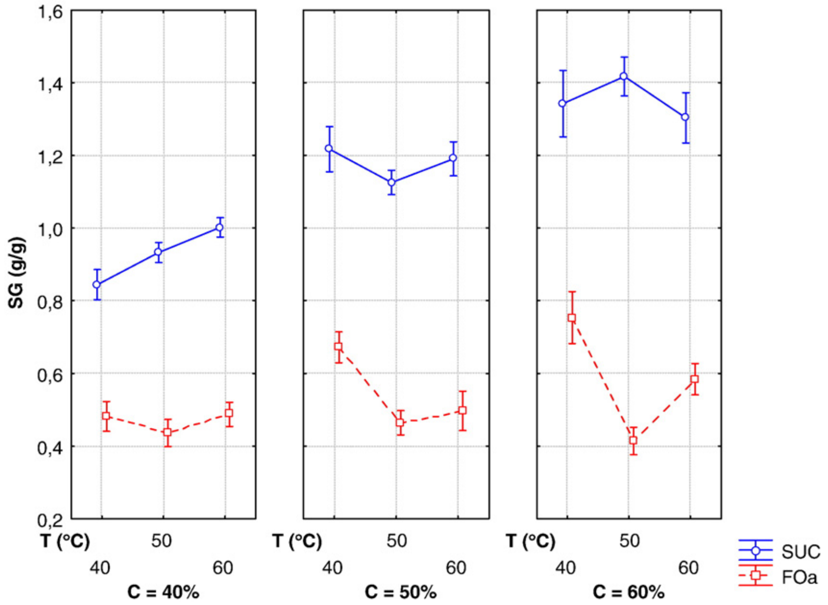

Fig. 7. Effect of process temperature and osmoticum concentration on solid gain.

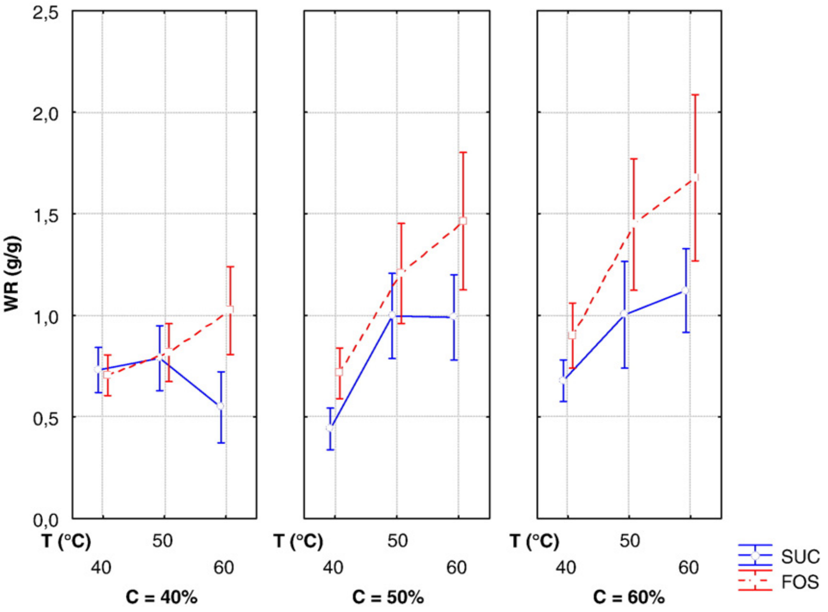

Fig. 8. Effect of process temperature and osmoticum concentration on weight reduction.

The increase in sucrose concentration affected SG more than that in FOS concentration (Fig. 7). The significant interaction between osmoticum type and concentration is much higher than that obtained for WL established in ANOVA. The prediction equations for SG as results of MLR are given as follows;

$$\mathrm{SG-SUC(g/g)} = -0.176 + 0.002 \times T(^\circ\mathrm{C}) + 0.021 \times C(\%\mathrm{w/v}) + 0.006 \times t(\mathrm{min})$$

$$\mathrm{SG-FOS(g/g)} = 0.372 - 0.006 \times T(^\circ\mathrm{C}) + 0.006 \times C(\%\mathrm{w/v}) + 0.005 \times t(\mathrm{min})$$

There is a significant effect of temperature and a slight interaction: the SG increased as a function of temperature in case of sucrose, however, a slight decrease was detected in case FOS.

3.4. Weight reduction (WR)

WR is independent on the other three variable (MC, SG, WL), and the difference of WL and SG results in WR. There is not any close correlation between weight reduction and water loss or solid gain, respectively. Solid gain and water loss are higher if FOS were the osmotic agent, but their difference results in lower WR. Significant interactions were observed between the type of osmotic agent and its concentration and the temperature of OD by ANOVA.

The MLR analysis resulted in the next equations for weight reduction:

$$\mathrm{WR-SUC(g/g)} = -0.994 + 0.014 \times T(^\circ\mathrm{C}) + 0.012 \times C(\%\mathrm{w/v}) + 0.017 \times t(\mathrm{min})$$

$$\mathrm{WR-FOS(g/g)} = -2.162 + 0.031 \times T(^\circ\mathrm{C}) + 0.025 \times C(\%\mathrm{w/v}) + 0.017 \times t(\mathrm{min})$$

In contrast to WL and SG, twice higher increase of WR was achieved by the higher concentration of FOS compared to sucrose. In case of FOS, WR rose from 1.15 g/g to about 1.4 g/g

Table 6
Correlation matrix of MC, WR, WL, SG (*marked correlations are significant at $p<0.05$)

	MC (% w/w)	WR (g/g)	WL (g/g)
WR (g/g)	−0.09		
WL (g/g)	−0.87*	0.48*	
SG (g/g)	−0.91*	− 0.26*	0.61*

Table 7
p-values from ANOVA test for dependent variables (marked correlations are significant at $p<0.05$)

p-values	MC	WL	SG	WR
Intercept	0.0000*	0.0000*	0.0000*	0.0000*
x_1	0.0000*	0.0000*	0.0000*	0.0000*
x_2	0.0000*	0.0000*	0.0000*	0.0000*
x_3	0.0000*	0.0000*	0.0000*	0.0000*
x_4	0.0000*	0.0000*	0.0000*	0.0000*
x_1*x_2	0.0000*	0.0000*	0.0000*	0.0029*
x_1*x_3	0.0000*	0.0000*	0.0000*	0.0579
x_2*x_3	0.0264*	0.0000*	0.0000*	0.0000*
x_1*x_4	0.3499	0.0145*	0.4986	0.9453
x_2*x_4	0.0362*	0.0000*	0.0350*	0.6062
x_3*x_4	0.0000*	0.0000*	0.0003*	0.9511
$x_1*x_2*x_3$	0.0000*	0.0000*	0.0000*	0.5630
$x_1*x_2*x_4$	0.1069	0.0003*	0.5482	0.9765
$x_1*x_3*x_4$	0.1412	0.0037*	0.1286	0.9820
$x_2*x_3*x_4$	0.2140	0.0000*	0.0123*	0.9508
$x_1*x_2*x_3*x_4$	0.9587	0.0043*	0.8481	0.9991

Table 8
Univariate tests of significance for D_{eff} with calculated p-values

	WL			SG		
	DF	*F*	*p*	*DF*	*F*	*p*
Type of osmoticum	1	13.897	0.0002	1	2.972	0.093
Temperature	2	0.036	0.965	2	1.891	0.167
Concentration	2	0.256	0.775	2	2.383	0.107
Error	36			36		

between 50 °C and 60 °C, however, in case of sucrose it remained unchanged around 0.9 g/g in this temperature range (Fig. 8).

3.5. Effective diffusion coefficient (D_{eff})

The effective diffusion coefficient (D_{eff}) was calculated for both SG and WL, representing the solute and water diffusivities, respectively. The standard deviation of D_{eff} is high due to the narrow range of independent variables (unit op. parameters). WL is dependent on the type of osmoticum at 95% significance level, but SG is dependent on the type of osmoticum, its concentration and temperature at lower levels of 90%, 89% and 83%, respectively (Table 8).

3.6. Principal component analysis (PCA)

Principal component analysis was carried out to get a complex evaluation of the results. The presented eigenvalues prove that two components can describe more than 93% of the variance in the data of WR, SG, WL and MC according to the previous discussion (Table 9). The first principal component is dominated by MC, WL, WR and the second principal component can be attributed mainly to SG (Table 10). Based on PCA, the cases of experiments show a clear picture of differences between FOS and sucrose treated samples (Fig. 9).

4. Conclusions

Fructo-oligosaccharides (FOS) and sucrose were compared as osmotic agents in OD of apple cubes. Regarding to the chemical composition and structure the osmotic behaviour of FOS differs from that of sucrose. One of the most important factors in diffusion and osmotic dehydration is the higher molecular size that could cause a lower rate of diffusion. Since blanching makes the semi-permeable membrane more permeable, the difference in mobility between FOS and sucrose due to their average molecular weight is diminished. Although the general changes in MC, WL, WR, SG due to the changes of osmoticum concentration and temperature and the process time correspond to studies of other researchers, the interaction with type of solute is significant. This interaction is more important for water loss than for solid gain, which is reflected in twice higher WL diffusivity. The diffusion of solute into the apple is lower from FOS solution than sucrose, as well as the effect of temperature and concentration. Water loss is also lower in FOS solution than in sucrose solution, but with increasing temperature and concentration WL is increased much more by FOS than sucrose.

Table 9
The explained and cumulated effects of principal components

PC	Eigenvalue	Explained %	Cumulated %
1	2.6800	67.00	67.00
2	1.0688	26.72	93.72
3	0.2274	5.69	99.40
4	0.0238	0.60	100.00

Table 10
The linear attributes of the principal components

Attribute	PC1	PC2
MC	0.9715	0.1327
WR	−0.7884	0.5090
WL	−0.9675	0.1045
SG	−0.4226	−0.8838

Nomenclature

α	The solution to sample cube ratio
a	Geometric parameter of apple cubes
D_{es}	The effective diffusivity of solute
D_{ew}	The effective diffusivity of water
m	Moisture content (indices 0, t, ∞ mean the values at time 0, t, ∞)
M_0	The initial sample weight, g
M_t	The sample weight after blanching and prior to OD, g
M_{OD}	The sample weight after OD at time t, g
M_{f}	The weight of the dried sample after OD, g
M_r	The moisture ratio
MC_t	The sample moisture content after blanching and prior to OD, %
s	Solid content (indices 0, t, ∞ mean the values at time 0, t, ∞)
S_t	The solid content of sample after blanching, g
S_r	The solute ratio

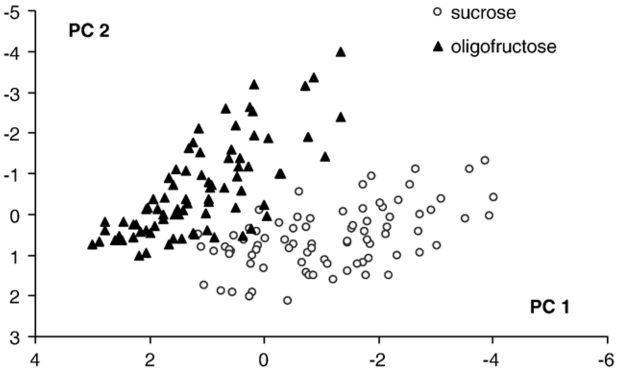

Fig. 9. Plot for principal component analysis (PCA).

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