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Osmotic Dehydration for the Production of Novel Pumpkin Cut Products of Enhanced Nutritional Value and Sustainability

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Featured Application: Strained Yoghurt (SY) Whey (acid whey) is a by-product of nutritional value that cannot be easily utilized by the industry. The limitations (low pH, high Biochemical Oxygen Demand (BOD)) have caused SY Whey to be directed toward non-food uses, and valuable nutrients of the whey remain outside the human consumption channel. The reintroduction of SY Whey into the food chain would improve sustainability of Greek yoghurt production. The use of SY Whey as an osmotic solvent during the osmotic dehydration of fruits and vegetables can contribute towards that direction. The osmotic behavior of SY Whey (as osmotic solvent along with other ingredients: galacto-oligosaccharides, trehalose, ascorbic acid) showed that SY Whey can lead to the production of high quality semi-dried or dried (pumpkin) products for uses such as snack foods or other food formulations (muesli, dairy products). It could be concluded that the pasteurized SY Whey could be used as an alternative osmotic solute for the partial dehydration of fruits (in this study pumpkin) not affecting the sensory characteristics of the final osmosed fruit product.

Abstract: The quality and preservability of fresh-cut fruits can be improved by osmotic dehydration (OD). In this study, the impact of Strained Yoghurt Whey (SY Whey) (along with other osmotic solutes) on mass transfer kinetics (water loss, solid gain, water activity decrease), quality attributes (color, texture, sensory characteristics, vitamin C), and microbial stability during OD and subsequent refrigerated storage (5–15 °C) of OD-processed pumpkin cuts was studied. The effect of temperature (35–55 °C), time (10–240 min), and type of osmotic solvent was evaluated to select the optimal processing conditions (55 °C–120 min; WL: 9-99-10.86 g w./g i.d.m. SG: 1.47–1.79 g s./g i.d.m., a_w: 0.89). The use of SY Whey vs. water as solvent enhanced the mass transfer phenomena increasing the solids uptake diffusion coefficient by 20%. Water and whey osmosed samples were of similar quality (32–38% increase of hardness, total sensory quality score: 7.9–8.2/9.0, vitamin C content: 77–81 mg/100 g). At all studied storage temperatures, $OD_{SY\ Whey}$ samples presented lower quality degradation rates compared to the respective OD_{Water} samples (e.g., almost half for hardness change). The shelf life of both OD processed pumpkin cuts exceeded 90 days at 5–15 °C (no microbial growth) supporting the applicability of SY whey as novel osmotic solvent.

Keywords: *Cucurbita pepo* L.; strained yoghurt whey; osmosis; mass transfer; quality modelling

1. Introduction

It has been reported that within 10 years the demand for strained (Greek or Greek-style) yoghurt has increased three times in Europe, Canada, and US (FAO 2016). As a side consequence the increasing volumes of the effluent byproduct of acid whey has recently received attention. Strained Yoghurt Whey (SY Whey) is a multi-component liquid containing valuable components of the milk (e.g., lactose, minerals, small amounts of proteins, high amounts of lactic acid). The low pH (4.5–5.1) and high Biochemical Oxygen Demand (BOD) limit the options for cost-effective solutions for the utilization, disposal, or further use of the SY Whey. It is currently used as animal feed or in anaerobic digesters for energy production [1]. Currently, it is mostly used as animal feed or as energy source [2]. Some value-added options for the SY Whey utilization are the isolation of valuable components (such as proteins), the isolation of lactose, and the production of galacto-oligosaccharides [3–5]. A very promising solution to the problem could be the re-use of the whey in food formulations, by incorporating or even converting into food products [2,6].

Osmotic dehydration (OD) is a mild, non-thermal treatment, mainly used as a pre-processing step of preservation methods (such as drying or freezing), that refers to the immersion of a food material in a hypertonic solution (of carbohydrates, salts, and other ingredients). As a result of the immersion, two main mass transfer flows take place, the water removal from the food to the concentrated osmotic solution and the solid transfer from the concentrated osmotic solution to the food [7]. The mass transfer during OD depends on the osmotic solution characteristics (type and concentration of the osmotic solute, ratio of the osmotic solution to the food), the food characteristics (structure, size, and geometry) and the process parameters (time, temperature, pressure, agitation). OD has been reported as processing step for the selective incorporation of the osmotic solutes (e.g., bioactive compounds, carbohydrates with special characteristics) into the food, resulting in a tailor-made modification of the fresh tissue characteristics (e.g., nutritional, sensory, and functional attributes) [8].

It is commonly applied to plant tissues such as fruits and vegetables as a pretreatment in combined processes [7,9]. Mass transfer kinetics or quality attributes of OD-processed fruits and vegetables were widely studied either after a sole pretreatment or after applying a combined process [9]. There are only few studies available in literature that monitor quality and microbiological attributes of OD-processed fruits and vegetables, compared to the non-processed ones, during their subsequent chilled or frozen storage [10]. OD application in fruit and vegetables helps to improve product quality (color, structure and texture, sensory attributes, vitamin C, chlorophyll, lycopene, anthocyanins and other pigments) and stability during storage, reduce energy (less energy intensive process as compared to other drying techniques), or develop new products [8,10,11].

Current trends of OD include the use of non-conventional osmotic solutes (e.g., functional ingredients, ingredients with high nutritional value/low glycemic index). The total or partial replacement of sugars (e.g., sucrose, fructose) with sugar alcohols (e.g., glycerol, sorbitol) has been reported to promote mass transfer and improve the quality of the final osmo-dehydrated fruits and vegetables (texture, moistness, and color retention) [12–17]. The use of oligofructose (fructo-oligosaccharides) with excellent dietary fiber properties as an osmotic solute has been reported [18–21]. Trehalose has received attention as an osmotic solute, due to its role to protect membranes and proteins during freezing and drying [15,19,22]. Another category of functional ingredients that have not been applied in OD process is galacto-oligosaccharides (GOS) with properties of human digestive and immune system support [23].

Pumpkin is one of the most popular seasonal fruits due to its high amounts of bioactive compounds (e.g., high content of β-carotene, minerals) and attractive sensory properties (e.g., color, texture) [24,25]. It can be consumed both immature and ripe, processed or unprocessed (e.g., boiled, canned, dried, pickled). The shelf-life of fresh-cut pumpkin is very short, since it has high moisture content (92–96) [26,27]. Quality deterioration of fresh-cut pumpkin refers to color and textural changes as well as microbial growth. The application of osmotic dehydration as a pre-processing step (e.g., of pre-drying or pre-candying step) has been reported [28–34].

In this study, the objective was the application of OD using a non-conventional multi-component solution (OS) to obtain novel intermediate moisture pumpkin cuts. SY Whey as osmotic solvent along with other solutes of special characteristics was used as OS. (a) Mass transfer kinetics (water loss, solid uptake, water activity decrease) during OD of pumpkin cuts with the use of SY Whey as OS (compared to water) and (b) the quality characteristics and shelf life stability (color, texture, total sensory quality, vitamin C, microbial growth) of the OD processed with the use of SY Whey pumpkin cuts during refrigerated storage were investigated.

2. Materials and Methods

2.1. Raw Materials

Pasteurized strained yoghurt whey (SY Whey) was provided by a Greek dairy industry (DELTA FOODS SA). SY Whey mainly comprises lactose (38.0 g/L), proteins (total: 5.56 g/L; different chemical composition of serum proteins), salts (especially calcium: 8.44 mM and potassium: 8.35 mM), and fat (0.47 g/L) [3]. It was stored at 4 °C before using and no microbial growth was detected over the two-week period.

Other ingredients incorporated into the OS were as follows: glycerol (Glycerine EP 212), trehalose (TREHA®), galacto-oligosaccharides (GOS) (Vivinal®—GOS Powder), ascorbic acid, sodium chloride, and calcium chloride.

2.2. Osmotic Dehydration (OD) Processing

Pumpkin (*Cucurbita pepo* L.) was supplied by a local producer from the surrounding area of Messenia, Peloponnese, cut in rectangular parallelepiped shape (2.0 × 2.0 × 0.5 cm) and immersed in the osmotic solution (OS) containing (w/w) 40% glycerol, 10% trehalose, 10% galacto-oligosaccharides (GOS), 2.0% ascorbic acid, 2.0% sodium chloride, 1.5% calcium chloride in SY Whey ($OD_{SY\ Whey}$) or water (OD_{Water},) (w_{OS}:w_{fruit} = 5:1) up to 240 min at 35, 45, and 55 °C [15,35,36].

Water and solids content (X_w and X_s) of fresh and OD-processed samples were calculated by drying (WTB BINDER 7200, Type E53, Tuttlingen, Germany) at 105 °C for 24 h. Water activity (a_w) was measured by Aqua LAB 4TEV a_w-meter (Decagon Devices, Inc., Pullman, WA, USA).

2.3. Mass Transfer Calculations

Mass transfer parameters, water loss (*WL*) and solid gain (*SG*), were estimated using the equations below (Equations (1) and (2)):

$$WL = \frac{(M_0 - m_0) - (M - m)}{m_0} \quad (1)$$

$$SG = \frac{(m - m_0)}{m_0} \quad (2)$$

where M_0 and M were the initial mass of fresh material and the mass after OD time t, m_0 and m were the dry mass of fresh material and the dry mass after OD time t.

The solution of Fick's second law for diffusion from a rectangular parallelepiped of sides 2a, 2b, and 2c, result in the following equations for the water and solids' transfer (effective diffusivity values for water and solids, D_{ew} and D_{es}) [37,38] (Equations (3) and (4)):

$$M = \frac{m_t - m_\infty}{m_0 - m_\infty} = \sum_{n=1}^{\infty} C_n^3 \exp\left[-D_{ew} q_n^2 t\left[\left(\frac{1}{a^2}\right) + \left(\frac{1}{b^2}\right) + \left(\frac{1}{c^2}\right)\right]\right] \quad (3)$$

$$S = \frac{S_t - S_\infty}{S - S_\infty} = \sum_{n=1}^{\infty} C_n^3 \exp\left[-D_{es} q_n^2 t\left[\left(\frac{1}{a^2}\right) + \left(\frac{1}{b^2}\right) + \left(\frac{1}{c^2}\right)\right]\right] \quad (4)$$

where M and S were the water and solids ratio, o, t, and ∞ represent the M and S values at time zero *0*, any time t and at equilibrium (240 min considered to be the infinite time as further treatment did not significantly affect the *WL* and *SG* values), $D_{ew/es}$ were the effective diffusivity coefficient of water/solids (m^2/s), and C_n was equal to $2\alpha(1 + \alpha)/(1 + \alpha + \alpha^2 q_n{}^2)$, where q_n's were the positive roots other than zero of equation: $\tan(q_n) = -\alpha q_n$. α was the ratio of the volume of the osmotic solution to the volume of each piece. The diffusion coefficients were calculated by using $n = 5$ in Equations (3) and (4).

The effect of temperature on $D_{ew/es}$ was then expressed by an Arrhenius-type equation (Equation (5)) [37].

$$\ln D_{\frac{ew}{es}} = lnD_{\frac{ew}{es},o1} - \left(\frac{E_a}{R}\right)\left(\frac{1}{T} - \frac{1}{T_{ref}}\right) \quad (5)$$

where $D_{ew/es,o1}$ were the effective diffusion coefficient constants of water/solids (m^2/s).

2.4. Reference OD Processing Conditions

The reference OD conditions (OD processing temperature and time conditions) were selected as the optimal conditions leading to adequate mass transfer (WL, SG) and a_w decrease as well as desired sensory (total sensory quality) and quality characteristics (instrumentally measured color and texture) of the final osmosed pumpkin cuts (to be further explained in Section 3.2).

2.5. Quality Monitoring of OD-Processed Pumpkin during Refrigerated Storage

OD-processed (at reference OD processing conditions) pumpkin cuts were stored at isothermal (5, 10, 15, ±0.2 °C) conditions (Sanyo MIR 153, Sanyo Electric, Ora-Gun, Gunma, Japan). Kinetic analysis of selected quality loss indices of fresh-cut pumpkin (color, texture, sensory properties, and microbial growth) was conducted.

2.5.1. Color

Pumpkin color was expressed by the values, L (lightness), a (from +: red to −: green), and b (from +: yellow to −: blue), and the value for total color change ΔE calculated by Equation (6):

$$\Delta E = \sqrt{(L - L_0)^2 + (a - a_0)^2 + (b - b_0)^2} \quad (6)$$

where ΔE was the value for the total color change at each sample, L and L_0 were the values for lightness at storage time t and zero, respectively, a and a_0 were the values for redness at storage time t and zero, respectively, b and b_0 were the values for the yellowness at storage time t and zero, respectively, as measured by portable colorimeter (CR-200 Chromameter, Minolta Co., Chuo-ku, Osaka, Japan). The increase of ΔE values during storage was described by a sigmoid three-parameter equation (Equation (7)).

$$\Delta E = \frac{\Delta E_{max}}{1 + \exp\left(-\frac{t - t_0}{k_{colour}}\right)} \quad (7)$$

where ΔE was the value measured at each storage temperature $T_{storage}$ at time t, ΔE_{max} was the upper asymptote, t_0 was the crossover point (time of maximum value), and k_{color} was the constant rate of ΔE increase at each $T_{storage}$.

2.5.2. Texture

Texture analysis was performed on 8–10 pumpkin samples (three replicates) (kept at room temperature for 30 min) on a non-lubricated flat platform using a knife probe with which samples are cut at a fixed rate and depth (1/3 of the initial) (by texture analyzer TA-XT2i of Stable Micro Systems, Surrey, UK). The maximum peak force (F_{max}, N) was defined as hardness [39]. A linear equation was found to describe successfully hardness values decrease as a function of storage time, t (Equation (8)):

$$F_{max} = F_{max,0} - k_{texture} * t \quad (8)$$

where F_{max} and $F_{max,0}$ (N) were the values measured for hardness at each storage temperature $T_{storage}$ at time t and at time zero and $k_{texture}$ was the constant rate of hardness decrease at each $T_{storage}$.

2.5.3. Sensory Analysis

Trained sensory panelists (8–10) of the Laboratory of Food Chemistry and Technology rated the main sensory properties of the fresh-cut pumpkin cuts: color, texture, flavor/taste, and total eating/sensory quality. Scores were given for each parameter separately on a 1–9 intensity scale (1 the lowest quality score, 9 the highest quality score). Five was set as the score for minimum acceptability. The scores for the total sensory quality during storage were mathematically modelled by apparent zero order kinetics (Equation (9)) [16,40]:

$$S = S_0 - k_{sensory} * t \tag{9}$$

where S and S_0 were the scores for the total sensory quality examined at time t at each storage temperature $T_{storage}$ and time zero, respectively, and $k_{sensory}$ was the apparent change rate of the specific sensory characteristic studied at each $T_{storage}$.

2.5.4. Vitamin C

Vitamin C (L-ascorbic acid) was determined using a High-Performance Liquid Chromatography method (Hypersil ODS column (250 × 4.6 mm) of particle size 5 µm; mobile phase: HPLC grade water with metaphosphoric acid of pH 2.2; detection at 245 nm; calibrated by external standard solution of L-ascorbic acid [41].

2.5.5. Microbiological Analysis

OD-processed samples were analyzed for the growth of total aerobic bacteria (TVC) and yeasts and molds [16]. The spread plate method was used for the enumeration of TVC on Plate Count Agar (PCA, Merck, Darmstadt, Germany) after incubation for 72 h at 25 °C, and for the enumeration of yeasts and molds on Rose Bengal Chloramhenicol (RBC, Merck, Darmstadt, Germany) after incubation for 96 h at 25 °C. Two replicates of at least three appropriate dilutions were enumerated.

2.5.6. Kinetic Modelling

Based on the kinetic modeling of each quality index (presented above), the rates of quality deterioration $k_{color/texture/sensory}$ were calculated; the temperature dependence of the rates was then modelled using the Arrhenius equation (Equation (10)) (described by the activation energy value E_a):

$$lnk = lnk_{ref} - \frac{E_a}{R}(\frac{1}{T} - \frac{1}{T_{ref}}) \tag{10}$$

where, k_{ref} was the degradation rate constant of the quality index at a reference temperature, T_{ref} (4 °C) was the common storage temperature for chilled food products (d^{-1}), T was the absolute temperature (K), E_a was the activation energy (J/mol), and R was the universal gas constant (J/mol·K).

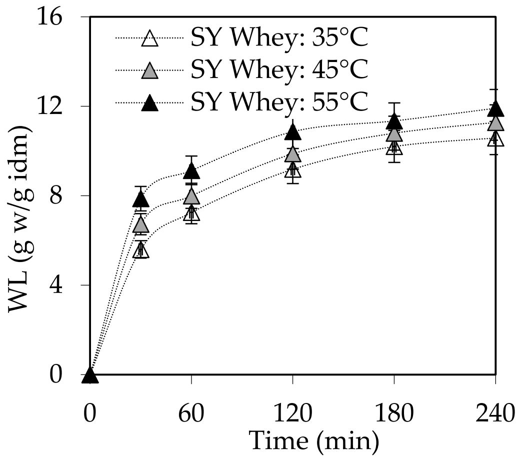
2.6. Statistical Analysis

Analysis of variance (ANOVA) at a significance level of 95% was used for the analysis of quality degradation rates of the two different OD-processed pumpkin cuts (STATISTICA® 7.0, StatSoft Inc., Tulsa, OK, USA). Significant differences were calculated according to Duncan's multiple range test (a = 0.05).

3. Results

3.1. Mass Transfer and Water Activity Decrease during OD Processing

In Figure 1a–c, water loss (*WL*) (Equation (1)), solid gain (*SG*) (Equation (2)), and water activity (a_w) decrease occurring during osmotic dehydration of pumpkin cuts in solution of SY Whey or water ($OD_{SY\ Whey}$ and OD_{Water}), at temperatures T 35, 45, 55 °C for times t up to 240 min, are presented.



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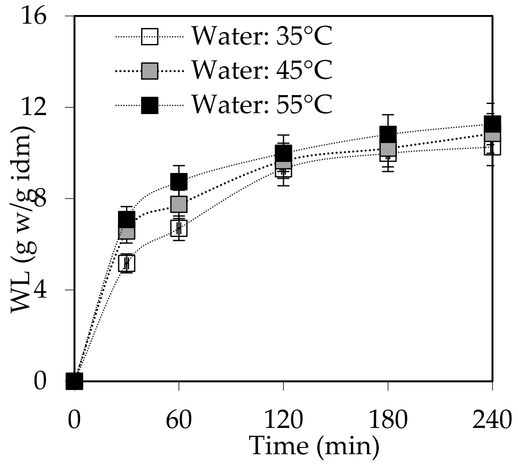

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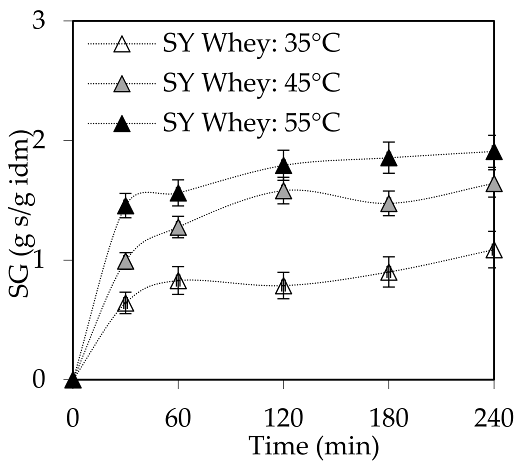

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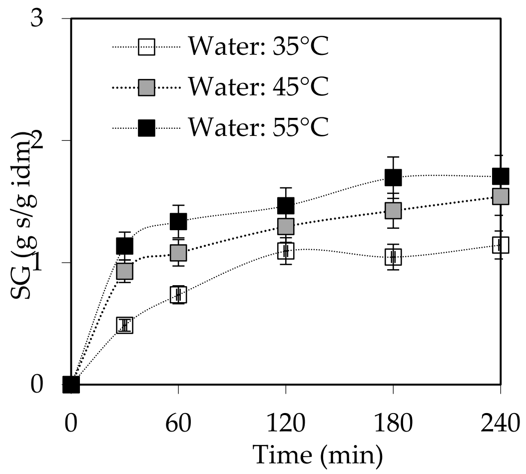

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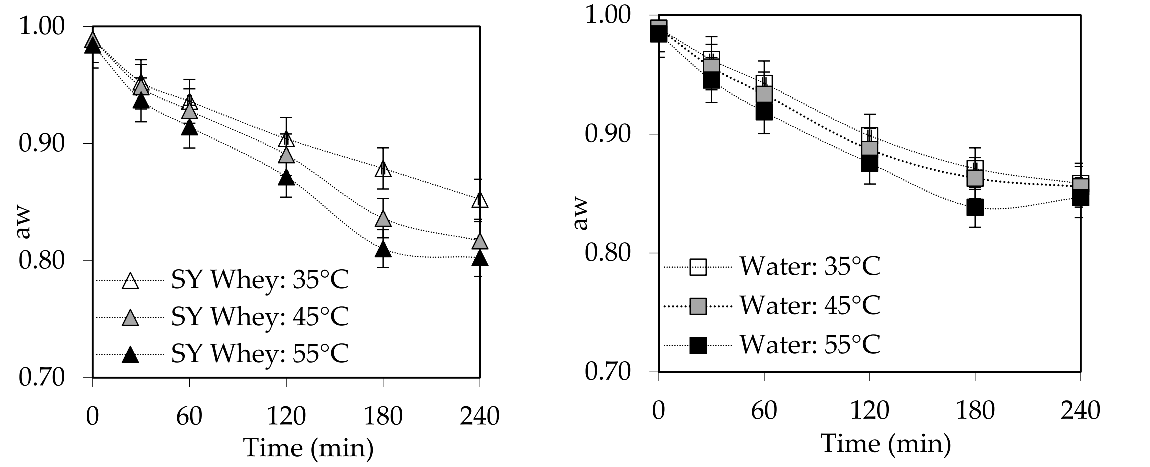
Figure 1. *Cont.*



(c1) (c2)

Figure 1. (**a**) Water loss (*WL*, g water/g i.d.m.), (**b**) solid gain (*SG*, g solids/g i.d.m.), and (**c**) water activity (a_w) during osmotic dehydration of pumpkin cuts in solution of SY Whey or water (Index 1: $OD_{SY\ Whey}$ and Index 2: OD_{Water}), at temperatures T 35, 45, 55 °C for times t up to 240 min (average ± standard error or deviation).

The experimental data for water and solid transfer was fitted to analytical solutions of Equations (3) and (4), and the respective effective diffusion coefficients D_{ew} and D_{es} for $OD_{SY\ Whey}$ and OD_{Water} samples were calculated (Table 1). The effect of OD processing temperature on $D_{ew/es}$ was then expressed by an Arrhenius-type equation (Equation (5), Table 1).

Table 1. Effective diffusion coefficients of water ($D_{ew} \times 10^{-9}$ m^2/s) and solids ($D_{es} \times 10^{-9}$ m^2/s) during osmotic treatment of pumpkin cuts for 240 min at 35, 45, and 55 °C. Samples: OD_{Water}, $OD_{SY\ Whey}$.

	Temperature (°C)	**OD_{Water}**	**$OD_{SY\ Whey}$**
D_{ew} (×10^{-9} m^2/s) (Adj. R^2)	35	2.699 ^{a} ± 0.157 (0.9948)	2.777 ^{a} ± 0.134 (0.9964)
	45	3.108 ^{ab} ± 0.216 (0.9927)	3.150 ^{ab} ± 0.264 (0.9896)
	55	3.741 ^{bc} ± 0.331 (0.9895)	3.974 ^{c} ± 0.397 (0.9871)
$D_{ew,ref}$ (×10^{-9} m^2/s) E_a (kJ/mol) (Adj. R^2)	35–55	2.914 ± 0.215 13.69 ± 1.29 (0.9913)	2.759 ± 0.245 19.42 ± 2.12 (0.9608)
D_{es} (×10^{-9} m^2/s) (Adj. R^2)	35	2.509 ^{a} ± 0.283 (0.9805)	3.115 ^{ab} ± 0.517 (0.9554)
	45	2.940 ^{ab} ± 0.329 (0.9797)	3.782 ^{b} ± 0.386 (0.9863)
	55	3.991 ^{b} ± 0.509 (0.9792)	5.589 ^{c} ± 0.753 (0.9820)
$D_{es,ref}$ (×10^{-9} m^2/s) E_a (kJ/mol) (Adj. R^2)	35–55	2.992 ± 0.323 15.00 ± 1.86 (0.9650)	3.505 ± 0.361 24.45 ±.2.80 (0.9567)

± represents the standard error. D_{ew} and D_{es} mean values with the same letter are not different ($p < 0.05$), respectively.

3.2. Selection of the Reference Osmotic Dehydration Conditions

Reference processing conditions of 55 °C and 120 min were selected for the osmotic dehydration of freshly cut pumpkin with the use of SY Whey or water (in the present study). Under these conditions, high rate of mass exchange was achieved, leading to a level of WL/SG that allows the product to retain optimum sensory characteristics. $OD_{SY\ Whey}$ and OD_{Water} samples exhibited WL 9.99–10.86 g w./g i.d.m. and SG 1.47–1.79 g s./g i.d.m., and a_w decrease approximately from 0.98 to 0.89. At the same time, $OD_{SY\ Whey}$ and OD_{Water} samples presented desired quality and sensory characteristics (based on the instrumentally measured color, texture, and the sensory scores for the total sensory quality) ($p < 0.05$) (as presented in Table 2).

Table 2. Physicochemical and quality parameters (water activity a_w, water content X_w, pH, hardness F_{max}, color parameters L, a, b, sensory evaluation score for total eating quality S, vitamin C content, C_{vitC}) of pumpkin cuts before (fresh) and after osmotic dehydration (OD) processing ($OD_{SY\ Whey}$ and OD_{Water}) at 55 °C for 120 min.

	Fresh	ODSY Whey	ODWater
Water activity (a_w)	0.9842 [a] ± 0.0008	0.8854 [b] ± 0.0035	0.8927 [b] ± 0.0012
pH	6.173 [a] ± 0.010	3.712 [b] ± 0.015	3.661 [b] ± 0.022
Hardness (F_{max}, N)	11.50 [a] ± 2.10	15.24 [a] ± 1.20	15.94 [a] ± 1.50
Color (L)	76.1 [a] ± 0.7	74.3 [b] ± 0.9	76.5 [a] ± 0.8
Color (a)	5.80 [a] ± 0.41	7.92 [b] ± 1.15	7.21 [b] ± 0.69
Color (b)	65.2 [a] ± 1.1	68.6 [b] ± 0.7	70.0 [b] ± 0.3
Total sensory quality (S, 1–9)	8.3 [a] ± 0.6	8.2 [a] ± 0.3	7.9 [a] ± 0.5
Vitamin C (C_{vitC}, mg/100 g fresh or OD material)	13.91 [a] ± 1.38	81.36 [b] ± 3.24	77.06 [b] ± 3.80

Values are mean ± standard deviation of triplicates. Values assigned with the same letter in the same row are not statistically significant.

3.3. Quality and Sensory Characteristics of Osmotically Dehydrated Pumpkin

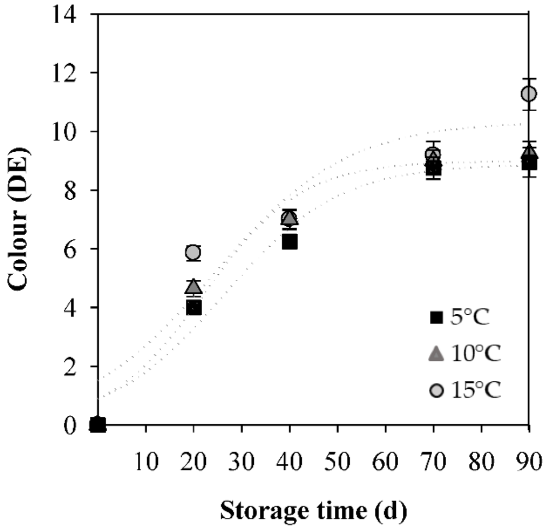
In Figure 2a–d total color change (ΔE calculated by the Equation (6)), hardness (F_{max}, N), vitamin C (%), and scores for total sensory quality (scale 1–9) of OD processed pumpkin cuts at the reference processing conditions (55 °C for 120 min) in solution of strained yoghurt whey or water ($OD_{SY\ Whey,}$ OD_{Water}) during storage at temperatures 5, 10, and 15 °C are presented.

The pumpkin color change during storage was described by the increase of the total color change value ΔE (Figure 2a_1,a_2). The maximum ΔE value was calculated for $OD_{SY\ Whey}$ and OD_{Water} samples stored at the highest temperature of 15 °C (ΔE_{max}= 12.71 and 13.81, respectively). At storage temperatures < 10 °C (after 90 days), $OD_{SY\ Whey}$ samples presented significantly lower color change values (ΔE_{max} = 7.12) (68%) compared to the respective OD_{Water} samples (ΔE_{max} = 12.02) (Figure 2a_1,a_2). The color change of respective non-processed fresh-cut pumpkin samples was described by ΔE values of 6, 7, and 8 after storage of 7 days at 5, 10, and 15 °C, respectively.

The hardness values of $OD_{SY\ Whey}$ and OD_{Water} samples were higher than the respective values of fresh-cut pumpkin samples showing that hardness was significantly increased after OD processing (15.24–15.94 N compared to 11.50 N). However, there were no statistically significant differences between $OD_{SY\ Whey}$ and OD_{Water} samples ($p < 0.05$) (Figure 2b_1,b_2). The hardness of both osmotically dehydrated samples decreased with storage time ($p < 0.05$). The effect of storage temperature was not significant for $OD_{SY\ Whey}$ (10–15 °C) and OD_{Water} samples (5–15 °C) ($p > 0.05$). The hardness values of $OD_{SY\ Whey}$ and OD_{Water} samples after 90 days of storage at temperatures from 5 to 15 °C were approximately 12.75 and 10.91 N, respectively. The hardness of fresh-cut pumpkin samples decreased from the initial value of 11.50 to 6.70–9.68 N after 7 days storage at 5–15 °C.

The vitamin C content was significantly increased after OD processing (both in SY Whey and water solutions). The improved retention (after 90 days of storage), accomplished with the application of an osmotic pretreatment, is illustrated in Figure 2c_1,c_2, (95 and 90% vitamin C retention for $OD_{SY\ Whey}$ and OD_{Water} samples, respectively). Fresh-cut pumpkin samples presented 20%, 25%, and 30% vitamin C loss, after 7 days of storage at 5, 10, and 15 °C, respectively.

Based on the kinetic modeling of each quality index (presented above), the rates of quality deterioration k_{color}, $k_{texture}$, $k_{vitaminC}$, $k_{sensory}$ (Equations (6)–(9), respectively) were calculated (Table 3). The temperature dependence of the rates was then modelled using the Arrhenius equation (Equation (10)) (described by the activation energy value E_a) (Table 3).



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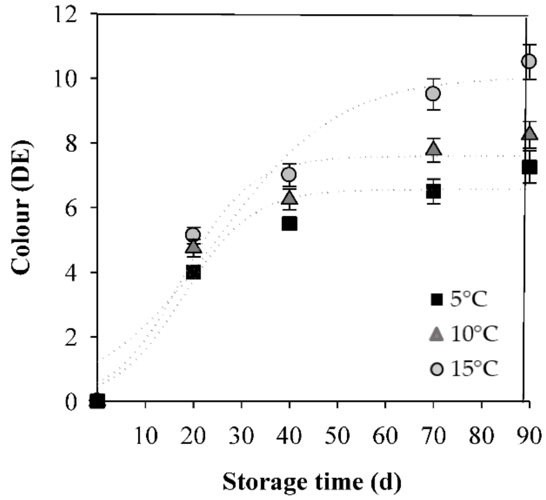

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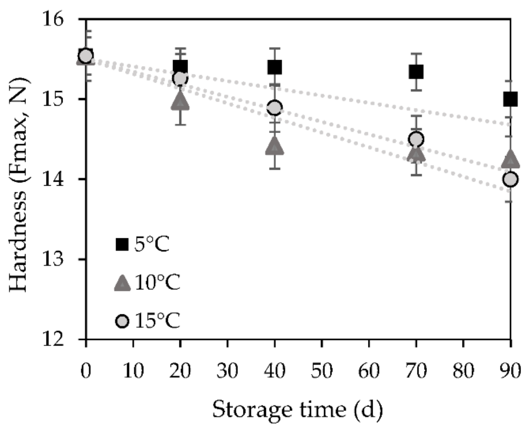

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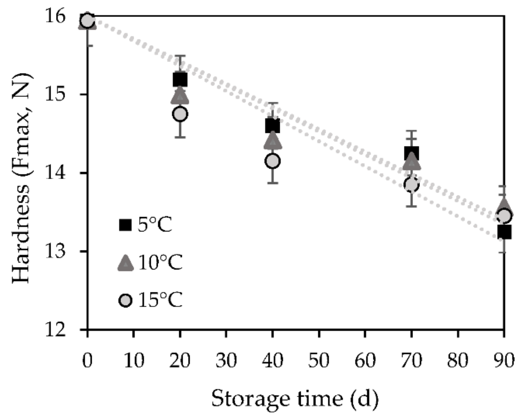

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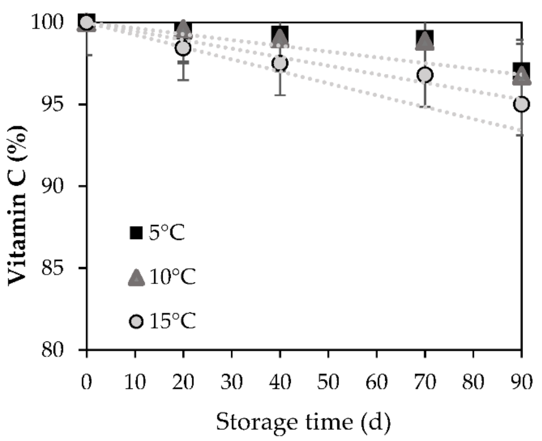
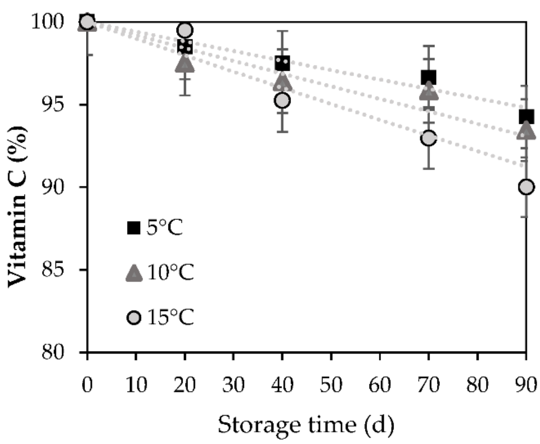
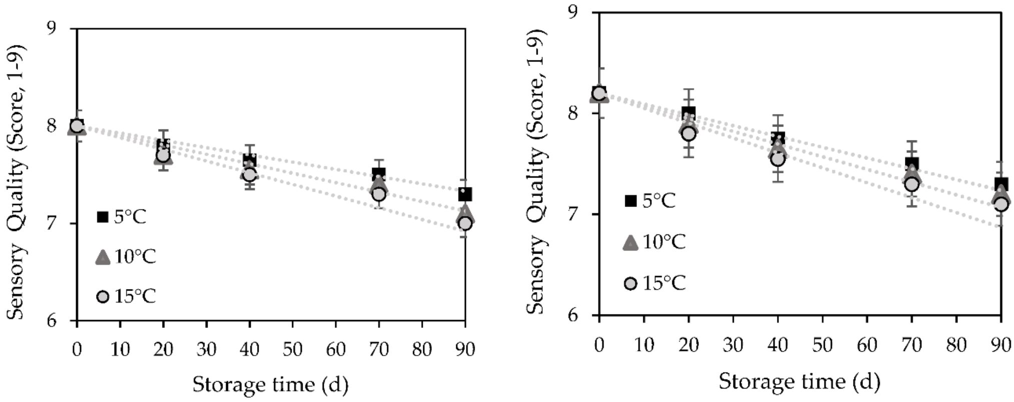


(**c**1)



(**c**2)

Figure 2. *Cont.*



(**d**1) (**d**2)

Figure 2. (**a**) Total color change (ΔE) by instrumentally measured color parameters L, a, and b, (**b**) texture measured as maximum force (hardness, F_{max}, N), (**c**) scores for total sensory quality (scale 1–9), and (**d**)% vitamin C loss of pumpkin cuts in solution of strained yoghurt whey or water (Index 1: $OD_{SY\ Whey}$ and Index 2: OD_{Water}). Experimental points correspond to isothermal temperature conditions (■) 5 °C, (▲) 10 °C, (○) 15 °C; lines represent the respective model fit.

Table 3. Estimated kinetic parameters (k_{color}, $k_{texture}$, $k_{vitaminC}$, $k_{sensory}$; E_a, k_{ref} at T_{ref} = 4 °C) used for quality deterioration of OD processed pumpkin cuts at 55 °C for 120 min ($OD_{SY\ Whey}$ and OD_{Water}), and stored at isothermal temperature (5, 10, 15 °C) conditions based on instrumental measurement of color and texture, vitamin C, and organoleptically perceived quality (sensory).

Kinetic Parameters	Temperature (°C)	$OD_{SY\ Whey}$	OD_{Water}
k_{color} (d^{-1}) ΔE_{max} t_0 (Adjusted R^2)	5	6.56 ^{aA} ± 0.53 7.12 ^{aA} ± 4.29 18.02 ^{aA} ± 3.80 (0.9582)	8.89 ^{aA} ± 0.72 12.02 ^{bA} ± 4.16 26.39 ^{bA} ± 4.71 (0.9722)
	10	7.59 ^{aA} ± 0.63 7.05 ^{aA} ± 4.35 17.65 ^{aA} ± 3.93 (0.9553)	8.98 ^{aA} ± 0.69 10.10 ^{bAB} ± 3.86 22.26 ^{aB} ± 4.25 (0.9699)
	15	10.05 ^{aB} ± 1.10 12.71 ^{aB} ± 5388 25.01 ^{aB} ± 6.53 (0.9498)	10.33 ^{aB} ± 1.62 13.80 ^{aA} ± 8.81 24.30 ^{aA} ± 9.59 (0.9061)
k_{ref} (d^{-1}) E_a (kJ/mol) (R^2)	5–15	6.07 ^{a} ± 0.34 28.36 ^{a} ± 5.47 (0.9640)	8.70 ^{a} ± 0.43 9.14 ^{b} ± 5.07 (0.7950)
$k_{texture}$ (d^{-1}) (R^2)	5 10 15	−0.0114 ^{aA} ± 0.0014 (0.9154) −0.0142 ^{aA} ± 0.0011 (0.9624) −0.0197 ^{aA} ± 0.0007 (0.9918)	−0.0223 ^{bA} ± 0.0017 (0.9638) −0.0269 ^{bAB} ± 0.0014 (0.9826) −0.0320 ^{bC} ± 0.0021 (0.9736)
k_{ref} (d^{-1}) (R^2) E_a (kJ/mol)	5–15	0.01118 ± 4.91 × 10^{-5} 36.40 ^{a} ± 4.51 (0.9848)	0.02234 ± 6.26 × 10^{-5} 24.06 ^{b} ± 0.29 (0.9998)
$k_{vitaminC}$ (d^{-1}) (R^2)	5 10 15	−0.00041 ^{aA} ± 3.75 × 10^{-5} (0.9526) −0.00065 ^{aB} ± 7.46 × 10^{-5} (0.9269) −0.00084 ^{aC} ± 8.49 × 10^{-5} (0.9419)	−0.00058 ^{bA} ± 2.39 × 10^{-5} (0.9900) −0.00079 ^{bB} ± 4.64 × 10^{-5} (0.9797) −0.00101 ^{bC} ± 6.68 × 10^{-5} (0.9743)
k_{ref} (d^{-1}) (R^2)	5–15	−0.00038 ± 2.82 × 10^{-5}	−0.00061 ± 1.22 × 10^{-5}
E_a (kJ/mol)		47.86 ^{b} ± 7.37 (0.9768)	36.98 ^{a} ± 2.05 (0.9969)
$k_{sensory}$ (d^{-1}) (R^2)	5 10 15	−0.00735 ^{aA} ± 0.00062 (0.9583) −0.00939 ^{aB} ± 0.00032 (0.9926) −0.01215 ^{aC} ± 0.00050 (0.9896)	−0.01090 ^{bA} ± 0.00036 (0.9934) −0.01252 ^{bB} ± 0.00057 (0.9874) −0.01479 ^{bC} ± 0.00083 (0.9811)
k_{ref} (d^{-1}) (R^2) E_a (kJ/mol)	5–15	0.00732 ± 5.94 × 10^{-5} 33.48 ^{a} ± 0.83 (0.9993)	0.01084 ± 1.36 × 10^{-5} 20.32 ^{b} ± 1.28 (0.9960)

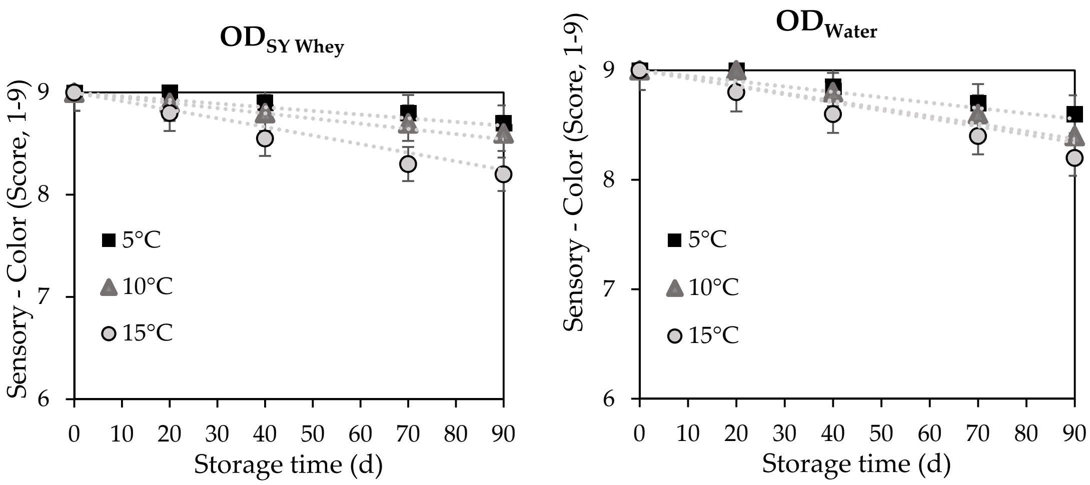
Values are mean ± standard deviation of triplicates. Values assigned with the same small letter in the same row (a,b,c) are not statistically significant; values assigned with the same capital letter in the same column (A,B,C) are not statistically significant.

The kinetic reaction rates for color change of $OD_{SY\ Whey}$ and OD_{Water} samples did not present statistically significant differences ($p < 0.05$) (Table 3). Additionally, no statistically significant differences were observed for OD_{Water} and $OD_{SY\ Whey}$ samples at 5–10 °C ($p < 0.05$; Table 3). The activation energy E_a for the color degradation of $OD_{SY\ Whey}$ and OD_{Water} samples were calculated as 28.36 and 9.14 kJ/mol, respectively. The texture degradation rates for $OD_{SY\ Whey}$ samples were significantly lower than the texture degradation rates for OD_{Water} samples ($p < 0.05$). However, the storage temperature effect on texture was not significant for $OD_{SY\ Whey}$ samples. The activation energy E_a for texture degradation of samples ranged from 24.06 (OD_{Water}) to 36.40 ($OD_{SY\ Whey}$) kJ/mol, respectively. The vitamin C loss rates for $OD_{SY\ Whey}$ samples were significantly lower (up to 40%) than the respective the vitamin C loss rates for OD_{Water} ($p < 0.05$). The storage temperature effect on vitamin content was significant for both $OD_{SY\ Whey}$ and OD_{Water} samples ($p < 0.05$). The activation energy E_a ranged from 36.98 (OD_{Water}) to 47.86 ($OD_{SY\ Whey}$) kJ/mol, respectively. Finally, the reaction rate constants for sensory quality loss of $OD_{SY\ Whey}$ and OD_{Water} samples were not significantly different at temperatures studied. E_a ranged from 20.32 ($OD_{SY\ Whey}$) to 33.48 (OD_{Water}) kJ/mol (Table 3).

In Figure 3, pictures of pumpkin, freshly cut and OD processed at the reference processing conditions (55 °C for 120 min) in solution of strained yoghurt whey or water ($OD_{SY\ Whey}$, OD_{Water}), are illustrated. In Figure 4a_1,a_2 the scores given for color, in Figure 4b_1,b_2 scores given for texture, and in Figure 4c_1,c_2 scores given for flavor of $OD_{SY\ Whey}$ (figure coding, Index 1) and of OD_{Water} (Index 2) of pumpkin cuts samples are presented.

(a) (b) (c)

Figure 3. Pictures of pumpkin cuts (**a**) fresh, (**b**) osmotically treated in SY Whey ($OD_{SY\ Whey}$), and (**c**) osmotically treated in water (OD_{Water}).



(**a**$_1$) (**a**$_2$)

Figure 4. *Cont.*

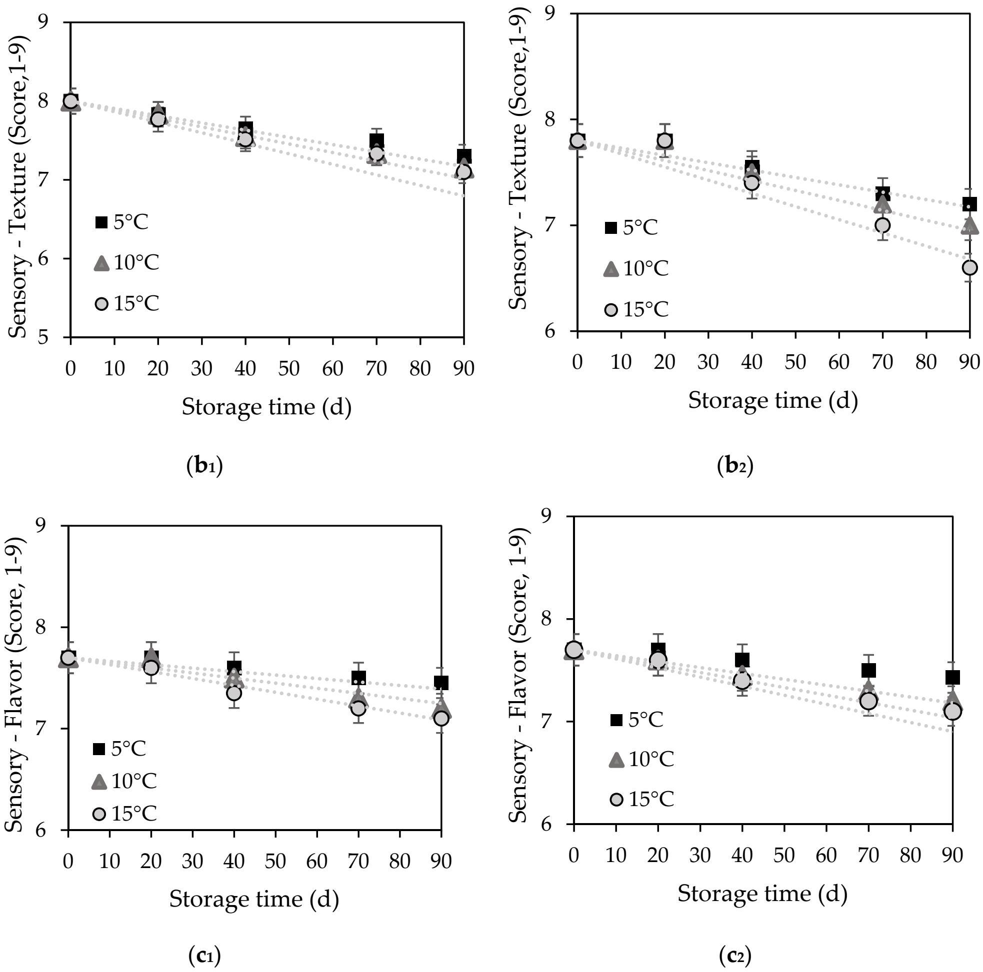


Figure 4. Scores for (**a**) color, (**b**) texture, and (**c**) flavor (scale 1–9) of pumpkin cuts (in solution of SY Whey or water) (Index 1: $OD_{SY\ Whey}$ and Index 2: OD_{Water}). Experimental points correspond to isothermal temperature conditions (■) 5 °C, (▲) 10 °C, (⊙) 15; lines represent the respective model fit.

According to sensory panelists, $OD_{SY\ Whey}$ and OD_{Water} samples had received similar scores for flavor, initially and during storage. Both OD processed samples were described to retain to a significant level, the initial, fresh-like fruit aroma, and flavor during storage. $OD_{SY\ Whey}$ samples had received significantly higher scores for texture (at the three storage temperatures) and color (at storage temperatures, 5 and 10 °C), initially and during storage. $OD_{SY\ Whey}$ samples were characterized by improved texture, initially and during storage (high scores for texture and increased hardness values) (Figure 3a–c). Both $OD_{SY\ Whey}$ and OD_{Water} samples were characterized by intense orange color (Figure 3a–c).

3.4. Microbial Growth during Cold Storage

The initial microbial counts both TVC and yeast and molds in $OD_{SY\ Whey}$ and OD_{Water} samples were at undetectable levels (<10 CFU/g). During storage (90 days), both $OD_{SY\ Whey}$ and OD_{Water} samples presented low values (up to 3–4 log cfu, the average value).

4. Discussion

4.1. Mass Transfer and Water Activity Decrease during OD Processing

The aim of the study was to investigate the effect of SY Whey (compared to Water) on *WL*, *SG*, and a_w decrease. OD caused *WL* and *SG*, up to 11.92 g w./g i.d.m. and 1.91 g s./g i.d.m., respectively, for both $OD_{SY\ Whey}$ and OD_{Water} samples (Figure 1a,b). In literature, the highest WL and SG value reported for osmotic dehydration of pumpkin was 3 g w. s./g (for both WL and SG; OS: starch syrup or glucose, 30 °C, 180 min) [42]. In the present study, the use of the multi-component osmotic solution resulted in significantly higher WL and SG values. Glycerol (40% w/w) was the main a_w lowering agent due to its low molecular weight and high humectant effect [43].

WL significantly increased with OD time at each processing temperature (35, 45, and 55 °C) (Figure 1 a_1,a_2) ($p < 0.05$). Higher WL increase was observed with OD temperature increase. Significant differences were calculated for OD processed samples at 35 and 55 °C ($OD_{SY\ Whey}$ and OD_{Water}) ($p < 0.05$). The use of SY Whey compared to water did not lead to further water loss ($p < 0.05$). However, it caused significant increase of solid gain. This increase was more pronounced with OD time and temperature ($p < 0.05$). Solid gain values were significantly higher for $OD_{SY\ Whey}$ samples at temperatures 45 and 55 °C ($p < 0.05$).

D_{ew} and D_{es} values obtained were similar to values reported in literature for osmotic pumpkin dehydration. According to Pekoslawska and Lenart [42], D_{ew} and D_{es} values were in the range of 1.12–1.85 × 10^{-9} m^2/s and 6.76–9.74 × 10^{-9} m^2/s, respectively. Mayor, Moreira, Chenlo, and Sereno [33] studied the osmotic dehydration of pumpkin in sodium chloride solution, and observed that D_{ew} and D_{es} values (linearly) increased with OD temperature increase ranging between 0.88–1.92 × 10^{-9} m^2/s and 1.88–4.22 × 10^{-9} m^2/s values, respectively. In the present study, D_{ew} and D_{es} values did not present statistically significant differences at temperatures T < 55 °C ($p < 0.05$; Table 1). To further express the processing temperature effect on water and solids diffusion, the activation energy values (Equation (5)) were calculated. The activation energy E_a for diffusion during OD ranged from 13.69 (Water) to 15.00 (SY Whey) kJ/mol for water loss and from 19.42 (Water) to 24.45 (SY Whey) kJ/mol (60% w/w) for solids gain showing similar temperature effects on water and solids diffusion for OD_{Water} and $OD_{SY\ Whey}$ samples. The obtained E_a values indicated a low processing temperature effect (in the temperature range of this study) on the diffusion during OD of pumpkin.

de Souza Silva et al. [30] reported that the diffusivity values calculated during osmotic dehydration of pumpkin for the water and sucrose were similar for 50% and 65% sucrose solutions, using samples previously blanched by both stepwise and conventional means, showing greater solute gain than water loss. An increase of D values (up to 6.2% and 40.0% for D_{ew} and D_{es}, respectively) was observed for $OD_{SY\ Whey}$ samples compared to OD_{Water} samples. D_{es} value at 55 °C was significantly higher ($p < 0.05$) for $OD_{SY\ Whey}$ sample compared to OD_{Water} sample. This could be due to the increased concentration of mono- and di-saccharides in SY Whey (that were transferred from the osmotic solution to the food sample).

Osmotic dehydration lowered water activity with the increase of time and temperature ($p < 0.05$). The mass transfer achieved by the removal of water and the solute uptake into the pumpkin tissue during OD reduced a_w. a_w decrease was significantly affected by OD temperature. Water activity exhibited similar behavior for $OD_{SY\ Whey}$ and OD_{Water} samples with $OD_{SY\ Whey}$ samples to present the lowest values for the three processing temperatures [44]. This could be related to the initial water activity of the osmotic solution. It was also observed that after 180 min at 55 °C, OD system seemed to reach equilibrium, further osmosis did not cause water activity decrease. Similarly, Mayor, Moreira, Chenlo, and Sereno [33] observed that significant changes, during OD of pumpkin, took place within 15–180 min of OD processing. The water activity of $OD_{SY\ Whey}$ and OD_{Water} samples after 180 min at 55 °C were measured as 0.81 and 0.83, respectively. It must be noted that the application of OD as a single minimal process step does not lower sufficiently water activity levels to produce a sufficiently microbiologically stable product, and an additional processing step such as drying or freezing could synergistically result in an extended shelf life product [45].

4.2. Quality and Sensory Characteristics of Osmotically Dehydrated Pumpkin

4.2.1. Color Change during Cold Storage

It has been reported that OD modifies the color of osmosed fruit samples (e.g., apple, apricot, nectarine, peach) leading to a significant decrease of lightness (lower *L* values), significant increase of redness (increase of *a* value) and yellowness (increase of *b* value) [46]. In the present study, with regard to pumpkin color, OD did not appear to significantly affect the *L* parameter in case of water, and has significant change (decrease) in case of SY Whey ($p < 0.05$). Color parameters of *a* and *b* increased after osmotic pretreatment (for both $OD_{SY\ Whey}$ and OD_{Water} samples) (Table 2). It could be concluded that both $OD_{SY\ Whey}$ and OD_{Water} samples were characterized by intense orange color (Figure 3b,c). The pumpkin color change during storage was described by the increase of the total color change value ΔE (Figure 2a_1,a_2). $OD_{SY\ Whey}$ samples presented lower ΔE values during storage at the respective storage times and temperatures showing that the use of the whey had a positive effect on color stability during storage. The temperature dependence of color degradation for $OD_{SY\ Whey}$ and OD_{Water} samples was described by the Arrhenius Equation (Equation (10), Table 3). The storage temperature had a minor effect on the rate of color change for OD_{Water} samples compared to $OD_{SY\ Whey}$ samples that presented statistically significantly higher values. Dermesonlouoglou et al. [13,16] reported that the osmotic dehydration protected the color of osmosed fruit tissues (e.g., apricot, peach, strawberry) during refrigerated storage.

4.2.2. Textural Changes during Cold Storage

Both $OD_{SY\ Whey}$ and OD_{Water} samples presented statistically significantly higher hardness values (measured as maximum force F_{max}) compared to fresh pumpkin samples (32–38% increase of hardness) showing that OD processed pumpkin samples were harder and firmer than the non-processed samples (Table 2). The increase of hardness as a result of osmotic dehydration was reported for OD processed fruit samples [15,30]. The hardness of OD processed pumpkin decreased during storage ($p < 0.05$). Osmosis in the SY Whey was found to be more effective in maintaining the hardness of samples (Figure 2b_1,b_2; Table 3). Fresh-cut fruits and vegetables preserving their initial firmness, crispness, and crunchy texture are highly desired by consumers [47].

4.2.3. Vitamin C loss during Cold Storage

Vitamin C (L-ascorbic acid) concentration significantly increased after OD processing (both $OD_{SY\ Whey}$ and OD_{Water}, $p < 0.05$) due to the increased processing temperature (55 °C) and increased ascorbic acid concentration (4% w/w) in the osmotic solution (5.5–5.8 times increase of the initial vitamin C concentration) (Table 2). Dermesonlouoglou et al. [15] reported that vitamin C concentration of kiwifruit, after immersion in osmotic agent with 2% ascorbic acid for 180 min at 45 °C, was 210 mg/100 g. In the present study, the vitamin C concentration of OD processed pumpkin samples ranged between 77 and 81 mg/100 g. For all storage temperatures, L-ascorbic acid is significantly stable in the modified matrix of pretreated samples with SY Whey compared to that pretreated samples with water samples (Figure 2c_1,c_2; Table 3).

4.2.4. Sensory Evaluation during Cold Storage

The effect of OD processing on the sensory characteristics of the final osmosed product was studied [19,40,48]. Systematic sensory evaluation was conducted in parallel to instrumental measurements, in order to correlate analytical results of texture and color with the respective sensory evaluation. Sensory panelists confirmed the analytical results of better quality retention of osmotically processed fruits and vegetables. In the present study, both OD-processed ($OD_{SY\ Whey}$, OD_{Water}) samples retained to a significant level, the initial sensory characteristics (color, texture, flavor) during storage (Figures 3 and 4). However, osmosis in whey solution resulted in OD processed pumpkin samples with improved sensory characteristics (especially texture) (compared to osmosis in water). It could be concluded that the pasteurized SY Whey could be used as an alternative osmotic solute for the partial dehydration of fruits (in this study pumpkin) not affecting the sensory characteristics of the final osmosed fruit product.

4.2.5. Microbial Growth during Cold Storage

Both $OD_{SY\ Whey}$ and OD_{Water} samples presented low values (up to 3–4 log cfu, the average value), initially and during refrigerated storage. This could be related to the low water activity (0.87) and low pH (≈3.6–3.7) of the final osmo-dehydrated pumpkin samples. Dermesonlouoglou et al. [14,40] reported similar behavior of OD processed fruit samples (apricot, peach, and strawberry). As far as the microbial growth in fresh-cut fruit samples is concerned, it is limited to 5–7 days during cold storage [44]. In this study, the fresh-cut pumpkin exceeded the 1×10^3 CFU/g for yeasts and molds and 1×10^5 CFU/g for aerobic mesophiles after 5, 4, and 2–3 days of storage at temperatures 5, 10, and 15 °C, respectively.

5. Conclusions

In the present study, the potential use of SY Whey as a novel osmotic solvent was investigated. Results support the applicability of SY Whey as an OD solvent for the production of innovative intermediate moisture products of high nutritional value and fresh-like fruit characteristics for uses such as snack foods or other food formulations (muesli, dairy products). Water and whey osmosed (reference OD conditions: 55 °C, 120 min) samples were of equivalent quality (instrumentally measured color and texture, sensorially perceived color, texture and flavor, vitamin C content) and microbiologically stable. The shelf life of both samples exceeded 90 days at temperatures 5–15 °C. The use of SY Whey vs. water as solvent enhanced the mass transfer phenomena increasing the solids uptake diffusion coefficient by 20%. It could be concluded that osmosis in SY Whey solution—compared to water—promotes the solid uptake from the OD solution and can be used for solid enrichment purposes. The reintroduction of SY Whey into the food chain (as an osmotic solvent in the proposed work) would have a positive effect on the process sustainability and consumer acceptability positively affecting costs for the dairy industry. Additionally, the use of ingredients with special characteristics such as galacto-oligosaccharides, trehalose, ascorbic acid (as osmotic solutes) could lead to products with improved nutritional properties.

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