

# COMPOSITIONAL CHANGES OF STRAWBERRY DUE TO DEHYDRATION, COLD STORAGE AND FREEZING–THAWING PROCESSES

G. MORAGA, N. MARTÍNEZ-NAVARRETE and A. CHIRALT<sup>1</sup>

*Department of Food Technology  
Universidad Politécnica de Valencia  
PO Box 22012  
46071 Valencia, Spain*

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## ABSTRACT

*Strawberry is an excellent source of food ingredients, although compositional changes might occur in improperly controlled processing, affecting product quality. In this article, changes in sugar composition (glucose, fructose and sucrose), citric acid, water and total soluble content, as induced by partial dehydration and freezing–thawing processes, were analyzed in strawberries (var. Camarosa). Osmotic dehydration (OD) with 65 °Brix sucrose solution, air drying (AD) at 45C, or combined treatments (OD–AD) were applied to reduce strawberries' water content to 70–85%. Fresh and dehydrated samples were frozen (–40C, 24 h) and stored (–18C, 30 and 180 days). All samples processed by OD and OD–AD showed a significant sugar gain, and depending on the dehydration treatment, total or partial sucrose hydrolysis was observed. Dehydration treatments caused small losses of citric acid. During the freezing–thawing process, drip loss and enzymatic action also cause changes in sugar concentration, especially in OD-treated samples.*

## INTRODUCTION

Strawberries are one of the most important seasonal fruit crops. Most of its production is destined for the fresh market, but because of the short shelf life and seasonal nature of this fruit, part of its production is processed. In this way, it is used as a food ingredient in yogurts, pies, milk shakes, jams, ice creams, etc. because of its interesting sensory attributes. The types of strawberry processing most commonly used to increase product shelf life are freezing, partial or total dehydration and other combined methods. In these cases,

<sup>1</sup> Corresponding author. TEL: 34-963879104; FAX: 34-963877915; EMAIL: dchiralt@tal.upv.es

the processed fruit undergoes changes in sensory attributes such as texture, color (Torreggiani *et al.* 1998; Moraga *et al.* 2000; Chiralt *et al.* 2001) and changes in the profile of volatile compounds (Escriche *et al.* 2000; Talens *et al.* 2002), making the product different from nontreated products. Other quality attributes, such as product taste or flavor related to fruit composition on major sugars and acidity, may also be altered during such processes (Viberg and Sjöholm 1998).

As a preservation method, freezing combines low temperature and a water activity ( $A_w$ ) reduction associated with the cryoconcentration of the fruit liquid phase during ice crystal formation. However, because of the highly freezable water content of strawberries, freezing implies important cellular damage and losses in product quality (Martínez-Navarrete *et al.* 2001). Water content reduction by dehydration treatments applied before freezing (dehydrefreezing) have been reported as a tool in fruit cryopreservation, mainly because of the reduction of freezable water content (Robbers *et al.* 1997; Chiralt *et al.* 2001; Martínez-Navarrete *et al.* 2001). In this sense, osmotic dehydration (OD) or air drying (AD) and combined treatments (OD-AD) can be used to reduce ice crystal injuries during frozen storage.

Dehydration treatments have been used to obtain strawberry products in the form of ingredients (Garrote and Bertone 1989; Álvarez *et al.* 1995; Maestrelli *et al.* 1997; Moraga *et al.* 2000; Martínez-Monzó *et al.* 2001). These treatments affect the cells of the plant tissue as a result of ruptures in cellular bonds and induced deformations (shrinkage/swelling) both in cells and intercellular spaces taking place throughout the drying process (Contreras *et al.* 2005).

During AD treatment, elimination of water involves phase changes and so, although low temperatures are used during the process, a loss of cell functionality may occur and consequently, considerable changes in sensory and nutritional quality (Spiess and Beshnilian 1998). OD of fruit into an osmotic solution implies an opposite flux of different components: water and some natural soluble substances such as sugars, vitamins, pigments, organic acids, mineral salts, etc. (García-Martínez *et al.* 2002) flow out from the fruit to the osmotic solution, and in the opposite direction, soluble solutes may be transferred from the solution to the fruit, which may change product taste and acceptability. The penetration of sugar into the fruit is quite a slow process, particularly if a high fruit particle integrity is desired in the final product (Viberg and Sjöholm 1998). This method has received considerable attention because of the low energy requirements (Taiwo *et al.* 2001) and fruit quality improvement (Heng *et al.* 1990; Panagiotou *et al.* 1998). As high temperatures are not normally used in OD processes, and no water phase changes occur, changes in sensory attributes, such as color, aroma, flavor and texture are minimized (Pinnavaia *et al.* 1988; Heng *et al.* 1990; Giangiacomo *et al.* 1994;

Raoult-Wack 1994; Escriche *et al.* 2000; Chiralt *et al.* 2001; Talens *et al.* 2002). In this sense, OD has been recommended to improve fruit quality in fruits sensitive to AD such as kiwi fruits and strawberries (Torreggiani *et al.* 1998). The operation has been used as an initial step in other processes such as AD (Moraga *et al.* 2000; Fito *et al.* 2001) and freezing (Chiralt *et al.* 2001).

However, when partial dehydration of the product is used to obtain slightly processed fruits, a section of the tissue remains alive so that cellular respiration still occurs depending on the dehydration level (Lewicki *et al.* 2001). Osmotic stress causes physiological and biochemical changes that will lead to modifications in the fruit's composition, such as changes in sugars, acids or reserve substances (Dixon and Jen 1977; Moreno *et al.* 2000). A cellular biochemical response to the osmotic stress has also been observed, resulting in the accumulation of osmolites (compatible solutes) in the cytoplasm that is induced by enzyme action (Bray 1993).

In this work, the influence of OD, AD and OD-AD applied to partially reduce moisture content and  $A_w$  on major sugars and strawberry acidity was analyzed. Likewise, the effect due to subsequent sample freezing and frozen storage was also studied.

## MATERIALS AND METHODS

### Raw Material

Strawberries (var. Camarosa) were purchased in a local market in Valencia (Spain). Six different batches were used in the study, one for each drying treatment subsequently described. In all cases, fruit pieces were selected on the basis of similar size ( $\approx 39 \pm 1.5$  mm length and  $35 \pm 1.5$  mm maximum width), degree of ripeness (ratio °Brix/acidity  $9.9 \pm 1.5$ ), apparent color and fruit firmness. After that, they were washed and cut longitudinally in halves.

### Drying Treatments

Three dehydration methods (OD, AD, OD-AD) were used to reduce the water content of strawberries to three different levels ( $w \approx 82, 78, 74\%$ ), as described in Table 1. Initial experiments were performed to establish the required time to reach the fixed dehydration levels in the fruit by periodically controlling the weight of strawberry halves during drying.

OD equipment used (Moraga 2002), made of stainless steel, consists of three sections: dehydration tank (35-mm inner diameter and 85-mm height), vacuum pump and refrigeration system by water recirculation. A control panel allows regulating pressure, temperature and osmotic solution recirculation rate. The strawberry halves were weighed and placed inside the tank supported

TABLE 1.  
SAMPLE CODES AND DEHYDRATION METHODS USED TO REACH THREE  
DEHYDRATION LEVELS IN STRAWBERRIES

Sample code	Dehydration method	Dehydration level (% water content)	Time (h)
AD 1	Air drying	82	3.0
OD 1	Osmotic dehydration	82	3.5
AD 2	Air drying	78	5.0
OD-AD 2	Osmotic dehydration	84	2.5
	Air drying	78	2.0
OD 3	Osmotic dehydration	74	8.5
OD-AD 3	Osmotic dehydration	82	3.5
	Air drying	74	3.5

1, 2 and 3: dehydration levels ( $\approx$ 82, 78, 74% water content, respectively).  
AD, air drying; OD, osmotic dehydration; OD-AD, combined treatment.

in metallic baskets with individual places for each half to identify them. OD experiments were carried out at 30C and atmospheric pressure. A 65 °Brix sucrose solution was used as osmotic agent (solution/fruit ratio 20:1), and a recirculation rate of 1 m<sup>3</sup>/h was applied to ensure a negligible external resistance to mass transfer.

AD treatments were carried out in an industrial drier, with perforated shelves (Moraga 2002). Drying conditions were 45C air temperature, 20% relative humidity and a 2-m/s air rate. The strawberry halves were also weighed and placed in an identified position before the treatment.

After dehydration treatments and before freezing or analysis, the samples were stored at 8C in sealed plastic bags for 12 h to promote the internal equilibration of water concentration.

### Freezing-Thawing Treatments

Freezing of fresh and dehydrated samples was carried out at -40C in a climatic chamber (ACR-45/87; Dycometal, S.L., Barcelona, Spain) at a 4C/min cooling rate for 24 h. Afterwards, a part of the samples corresponding to each treatment was analyzed, while another part was stored at -18C for analysis after 1 and 6 months. In all cases, thawing was carried out at 8C for 10 h before the analysis.

### Analytical Determinations

In fresh, dehydrated and frozen-thawed samples, weight was controlled (Mettler AE 100; Mettler, Zurich, Switzerland) and the following analyses were carried out.  $A_w$  was measured in a dew point hygrometer (Decagon CX-2;

Decagon, Pullman, WA). The pH was measured by a pH meter (Crison micropH 2001; Crison Instruments, Barcelona, Spain) according to Association of Official Analytical Chemist (AOAC) 981.12. Water content was analyzed by vacuum drying until constant weight was reached at 60C (AOAC 20.013). Soluble solids were determined in a refractometer (Atago, NAR T3, Atago Co. Ltd., Tokyo, Japan) at 20C (AOAC 932.12), and titrable acidity was calculated as percentage of citric acid by titrating 10 g of sample with a solution of NaOH (0.1 N) until pH 8.1 (Crison micropH 2001, Spain), according to AOAC 942.15.

Sugars (glucose, fructose and sucrose) were analyzed by high-performance liquid chromatography (HPLC) using a Waters 600E system controller (Waters Corporation, Milford, MA) along with the Waters 464 Pulsed Detecting Electrochemical Detector (Waters Corporation, Milford, MA). A 23–24C thermostated Hamilton RCX-10 column (Hamilton Company, Reno, NV) was used with a NaOH 0.15-M flow solution at a 1.0-ml/min flow rate. Sugar extraction was carried out in HPLC water in an ultrasounds bath (Ultrasons-H; J.P. Selecta, Barcelona, Spain) for 30 min at  $T < 50C$ . Lactose, used as internal standard, was added to the extract, which was clarified with the reagents Carrez I and II. After centrifugation, the extract was purified through filtration (Millex filter 0.45  $\mu\text{m}$  and cartridge Sep-Pack 0.2  $\mu\text{m}$ ).

Cryo-scanning electron microscopy (Cryo-SEM) micrographs were obtained by using a Japan Electron Optics Laboratory JSM-5410 microscope (JEOL-JSM 5410 SEM, JEOL-USA, Peabody, MA). Rectangular pieces 5 mm  $\times$  1 mm  $\times$  7 mm were cut from the epidermis of the dehydrated samples. The samples were frozen by immersion in slush nitrogen ( $-210C$ ). After that, they were freeze-fractured, etched (at  $-94.5C$ ,  $10^{-5}$  mbar for 15 min), gold coated and viewed in the cold-stage SEM. The fractured surface of the frozen sample was directly observed while it was maintained at  $-150C$  or lower.

## RESULTS AND DISCUSSION

The concentrations of water, soluble solids, glucose, fructose, sucrose and citric acid are shown in Table 2 for the batches of fresh fruit used in each different drying treatment. An analysis of variance for each component was carried out to detect differences among fresh strawberry batches used in the study. Significant differences ( $\alpha < 0.05$ ) among batches in water, soluble solids and acid contents were found, which ranged between 90.1 and 91.8, 6.8 and 9.2 and 0.74, and 1 g/100 g sample, respectively. However, the range of the values is narrow and reflects the usual variability of raw material. No significant differences ( $\alpha < 0.05$ ) were observed in glucose, fructose and sucrose in which the average content in the different batches used was  $2.3 \pm 0.2$ ,  $2.5 \pm 0.3$  and  $0.5 \pm 0.4$ , respectively. Sucrose was the minor sugar in analyzed fruit pieces, its

TABLE 2.  
CONCENTRATION (WEIGHT %) OF WATER (W), SOLUBLE SOLIDS (SS), GLUCOSE (G),  
FRUCTOSE (F), SUCROSE (S) AND CITRIC ACID (CA) IN EACH STRAWBERRY BATCH  
BEFORE THE RESPECTIVE DEHYDRATION TREATMENTS

Sample code	W	SS	G	F	S	CA
AD 1	91.8 ± 0.5	7.2 ± 0.6	2.0 ± 0.2	2.1 ± 0.2	0.3 ± 0.2	0.89 ± 0.06
OD 1	90.2 ± 0.7	8.3 ± 0.3	2.3 ± 0.4	2.6 ± 0.4	0.7 ± 0.4	0.86 ± 0.05
AD 2	90.8 ± 0.6	8.4 ± 0.6	2.5 ± 0.3	2.5 ± 0.3	0.03 ± 0.00	0.77 ± 0.01
OD-AD 2	90.1 ± 0.7	9.0 ± 0.5	2.3 ± 0.3	2.6 ± 0.4	1.2 ± 0.3	1.00 ± 0.04
OD 3	91.0 ± 0.9	6.8 ± 0.3	2.2 ± 0.3	2.4 ± 0.4	0.06 ± 0.00	0.74 ± 0.05
OD-AD 3	90.3 ± 0.2	9.2 ± 0.3	2.7 ± 0.5	3.0 ± 0.6	0.5 ± 0.3	0.75 ± 0.02
	*	**	ns	ns	ns	**

\* 95% significant differences; \*\* 99% significant differences.

1, 2 and 3: dehydration levels (≈82, 78, 74% water content, respectively).

AD, air drying; OD, osmotic dehydration; OD-AD, combined treatments; ns, nonsignificant differences.

TABLE 3.  
MEAN VALUES OF WATER ACTIVITY ( $A_w$ ) AND pH FOR EACH STRAWBERRY BATCH  
ANALYZED BEFORE AND 12 H AFTER DEHYDRATION TREATMENTS

Sample code	$A_w$		pH	
	Fresh	Treated	Fresh	Treated
AD 1	0.990 ± 0.001	0.982 ± 0.002	3.11 ± 0.06	3.33 ± 0.06
OD 1	0.990 ± 0.001	0.982 ± 0.001	3.31 ± 0.10	3.55 ± 0.08
AD 2	0.989 ± 0.001	0.977 ± 0.003	3.55 ± 0.02	3.78 ± 0.06
OD-AD 2	0.993 ± 0.002	0.979 ± 0.001	3.26 ± 0.09	3.46 ± 0.19
OD 3	0.991 ± 0.002	0.972 ± 0.002	3.65 ± 0.11	3.63 ± 0.19
OD-AD 3	0.990 ± 0.001	0.972 ± 0.001	3.44 ± 0.07	3.35 ± 0.15
	ns	**	**	*

\* 95% significant differences; \*\* 99% significant differences.

AD, air drying; OD, osmotic dehydration; OD-AD, combined treatment; ns, nonsignificant differences.

1, 2 and 3 = dehydration levels (≈82, 78, 74% water content, respectively).

content being in the limit of the method detection. This can be related with the sucrose hydrolysis described during strawberry ripening in the plant (Seymour *et al.* 1993). In all cases, fructose content was slightly higher than glucose.

Table 3 shows  $A_w$  and pH values of each strawberry batch, before and after dehydration treatment. No significant differences ( $\alpha < 0.05$ ) in  $A_w$  values from the different batches of fresh strawberries were found, the mean value being  $0.991 \pm 0.001$ . In the dehydrated samples, three homogeneous groups of samples had mean  $A_w$  values of 0.982, 0.978 and 0.972, respectively, coherent

with the three different dehydration levels reached. In almost every case, the pH increased very slightly, thus indicating small changes in the acidity of the samples as will be commented on in the following paragraphs.

Water and soluble solid contents, as well as the major sugars and citric acid of the samples processed by drying, expressed in wet basis, appear in Table 4. The expected changes observed in the different components after the drying processes were an increase in all soluble solid concentrations and a decrease in water content.

To quantify the fluxes (gain or loss) of water, soluble solids, glucose, fructose, sucrose and citric acid associated with each drying process, Eq. (1) was applied to the different components (i) in each case. The gain or loss was calculated per mass unit of fresh sample.

$$\Delta M_i = ((m_t x_{it}) - (m_o x_{io})) / m_o = \Delta M \cdot x_{it} + x_{it} - x_{io} \quad (1)$$

where:

$m_o$ : sample mass before treatment,

$m_t$ : sample mass at t treatment time,

$x_{io}$ : initial mass fraction of the compound i in the sample and

$x_{it}$ : mass fraction of the compound i at t treatment time.

$\Delta M = (m_t - m_o) / m_o$

In Fig. 1, the mass balances for changes in water, soluble solids and total mass were plotted to estimate the experimental errors. Figure 1A shows that the total weight loss of the samples during treatments, calculated from weight data of samples before and after drying, is explained by the sum of water loss and soluble solids gain (obtained by Eq. 1) from water and soluble solids content analyzed in samples before and after treatments, showing a small experimental error in the analytical methods. Likewise, Fig. 1B shows the close correlation between the total soluble solid gain (obtained from measuring the °Brix) and the sum of individual sugar and citric acid gains (Eq. 1), thus indicating no significant changes in other soluble components different from those specifically analyzed. The main deviation was observed in the OD 3 treatment, which could be attributed to the long treatment time (8.5 h), implying the lixiviation of some sample components, other than those analyzed, such as water-soluble pectin fractions that increase in line with osmodehydration (Forni *et al.* 1986; Alzamora *et al.* 1995; Torreggiani *et al.* 1998).

The gain or loss of each component calculated by Eq. (1) that occurred in each drying treatment has been plotted in Fig. 2. Figure 2A shows the weight and water losses and total soluble solid gains caused by the different treatments. Likewise, Fig. 2B shows the weight changes of the analyzed soluble solids, glucose, fructose, sucrose and citric acid. Small losses in citric acid

TABLE 4.  
CONCENTRATION (WEIGHT %) OF WATER (W), SOLUBLE SOLIDS (SS), GLUCOSE (G),  
FRUCTOSE (F), SUCROSE (S) AND CITRIC ACID (CA) IN FRESH (FS) AND DEHYDRATED  
STRAWBERRY SAMPLES, BEFORE (BF) AND AFTER FROZEN STORAGE (TIMES: 24 H, 1  
MONTH AND 6 MONTHS)

Sample		W	SS	G	F	S	CA
FS	BF	91.4 ± 0.4	6.8 ± 0.3	2.2 ± 0.3	2.4 ± 0.4	0.06 ± 0.00	0.74 ± 0.05
	24 h	90.4 ± 0.3	8.4 ± 0.1	2.5 ± 0.2	2.8 ± 0.1	0.00 ± 0.00	0.64 ± 0.03
	1 month	90.4 ± 0.2	8.2 ± 0.3	2.7 ± 0.5	3.2 ± 0.6	0.00 ± 0.00	0.68 ± 0.03
	6 months	91.1 ± 0.7	7.4 ± 0.5	2.4 ± 0.3	2.6 ± 0.4	0.00 ± 0.00	0.77 ± 0.08
		*	*	ns	ns	ns	*
AD 1	BF	83.0 ± 1.6	15.0 ± 1.4	3.8 ± 0.4	4.4 ± 0.5	1.0 ± 0.3	1.54 ± 0.06
	24 h	83.0 ± 0.7	15.0 ± 0.6	4.1 ± 0.4	4.8 ± 0.5	0.5 ± 0.1	1.59 ± 0.02
	1 month	84.7 ± 1.0	13.8 ± 1.6	4.3 ± 1.1	4.6 ± 1.0	0.5 ± 0.1	1.56 ± 0.04
	6 months	83.0 ± 1.1	14.7 ± 1.0	4.3 ± 0.6	4.8 ± 0.7	0.7 ± 0.1	1.53 ± 0.07
		ns	ns	ns	ns	(*)	ns
OD 1	BF	81.3 ± 0.4	16.5 ± 0.5	5.5 ± 0.4	6.0 ± 0.5	1.2 ± 0.1	1.17 ± 0.06
	24 h	80.2 ± 1.0	17.7 ± 0.3	4.7 ± 0.6	5.1 ± 0.6	1.7 ± 0.9	1.10 ± 0.06
	1 month	80.9 ± 0.3	17.0 ± 0.0	9.2 ± 1.1	9.3 ± 1.2	1.4 ± 0.1	1.23 ± 0.02
	6 months	81.4 ± 0.3	16.5 ± 0.1	5.6 ± 0.1	5.9 ± 0.2	1.6 ± 0.3	1.12 ± 0.09
		ns	**	**	**	ns	ns
AD 2	BF	78.7 ± 1.8	19 ± 3	4.8 ± 0.1	5.19 ± 0.2	0.3 ± 0.3	1.50 ± 0.09
	24 h	76.9 ± 1.8	21 ± 3	5.6 ± 0.6	6.3 ± 0.6	0.6 ± 0.2	1.74 ± 0.05
	1 month	75 ± 2	22 ± 3	6.2 ± 0.7	7.4 ± 0.7	0.9 ± 0.2	1.73 ± 0.07
	6 months	78.7 ± 1.0	18.9 ± 1.0	5.7 ± 0.3	6.1 ± 0.3	0.8 ± 0.2	1.80 ± 0.12
		ns	ns	ns	(*)	(*)	(*)
OD-AD 2	BF	77.0 ± 1.5	18.8 ± 0.3	5.3 ± 0.2	6.0 ± 0.2	1.9 ± 0.5	1.47 ± 0.14
	24 h	78.1 ± 0.8	20.0 ± 0.5	5.6 ± 1.1	6.3 ± 1.2	1.3 ± 1.1	1.45 ± 0.10
	1 month	78.9 ± 0.4	18.7 ± 0.3	5.5 ± 0.4	5.9 ± 0.4	2.5 ± 0.3	1.50 ± 0.10
	6 months	78.6 ± 0.8	19.3 ± 0.5	6.3 ± 0.2	6.6 ± 0.2	1.7 ± 0.4	1.45 ± 0.04
		ns	*	ns	ns	ns	ns
OD 3	BF	74.2 ± 1.2	23.8 ± 1.0	7.0 ± 0.8	7.2 ± 0.9	2.8 ± 0.5	1.32 ± 0.09
	24 h	75 ± 2	22 ± 2	6.0 ± 0.7	6.5 ± 0.9	2.7 ± 1.3	1.15 ± 0.13
	1 month	76.2 ± 0.8	22.2 ± 1.2	5.9 ± 0.3	6.2 ± 0.3	2.2 ± 1.2	1.20 ± 0.10
	6 months	74.1 ± 1.6	23.9 ± 0.8	8.9 ± 1.2	8.9 ± 1.4	1.7 ± 1.4	1.21 ± 0.02
		ns	ns	**	*	ns	ns
OD-AD 3	BF	73.4 ± 0.9	24.8 ± 0.8	5.6 ± 0.1	6.3 ± 0.1	4.9 ± 0.7	1.64 ± 0.09
	24 h	73.7 ± 1.7	22.7 ± 1.8	5.6 ± 0.2	6.3 ± 0.2	5.2 ± 1.2	1.56 ± 0.08
	1 month	73.7 ± 1.0	24.3 ± 0.3	6.6 ± 0.7	7.0 ± 0.6	4.9 ± 0.6	1.54 ± 0.08
	6 months	71.1 ± 0.9	25.7 ± 0.8	7.1 ± 0.6	7.4 ± 0.6	6.2 ± 0.7	1.53 ± 0.06
		ns	*	**	*	ns	ns

\* 95% significant differences; \*\* 99% significant differences.

AD, air drying; OD, osmotic dehydration; OD-AD, combined treatment; ns, nonsignificant differences.

1, 2 and 3: dehydration levels (≈82, 78, 74% water content, respectively).

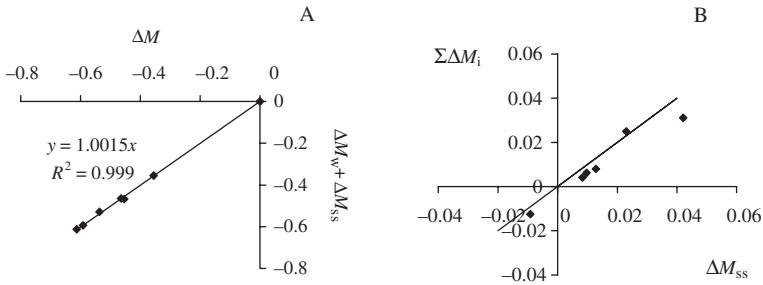


FIG. 1. MASS BALANCES (g/g initial product)

(A) Comparison between total weight loss of samples ( $\Delta M$ ) and the sum of water loss ( $\Delta M_w$ ) and soluble solids gain ( $\Delta M_{ss}$ ) during dehydration treatments. (B) Comparison between  $\Delta M_{ss}$  and the sum ( $\Sigma \Delta M_i$ ) of weight changes in glucose, fructose, sucrose and citric acid during dehydration treatments.

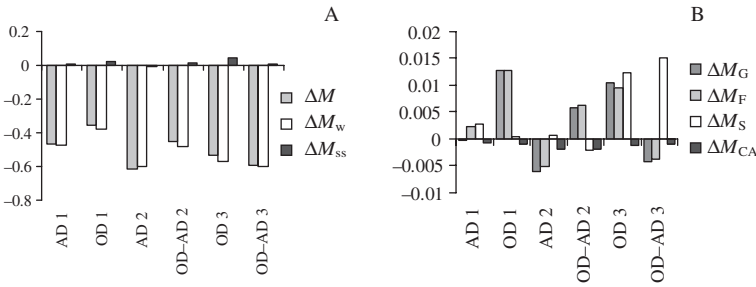


FIG. 2. (A) TOTAL WEIGHT LOSS ( $\Delta M$ ) AND WEIGHT CHANGES IN WATER ( $\Delta M_w$ ) AND SOLUBLE SOLIDS ( $M_{ss}$ ) DURING DEHYDRATION TREATMENTS (g/g initial product).

(B) WEIGHT CHANGES (g/g initial product) IN GLUCOSE ( $\Delta M_G$ ), FRUCTOSE ( $\Delta M_F$ ), SUCROSE ( $\Delta M_S$ ) AND CITRIC ACID ( $\Delta M_{CA}$ ) CAUSED BY THE DIFFERENT DEHYDRATION TREATMENTS

AD, air drying; OD, osmotic dehydration; OD-AD, combined treatment. 1, 2 and 3: dehydration levels ( $\approx 82, 78, 74\%$  water content, respectively).

(<0.2-g/100-g initial product) were observed in all applied drying treatments, coherent with the slight increase in pH observed. These losses cannot only be attributed to lixiviation of native acids to the external solution used for osmotic treatments, because they occur in AD treatments. Taking into account that during ripening of fruits, an increase in sugars and a decrease in acidity of samples occur (Seymour *et al.* 1993; Sturm *et al.* 2003), observed changes may be due to an acceleration of the fruit metabolism associated with the cellular stress caused by the dehydration (Fito *et al.* 2003). In the samples studied, the acid loss was similar in those with the lowest and highest water content reduction (0.09- and 0.11-g/100-g initial product, respectively), and

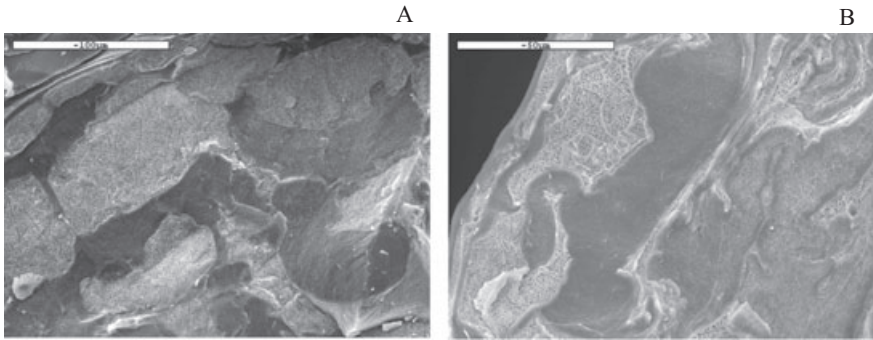


FIG. 3. CRYOSCANNING ELECTRON MICROSCOPY MICROGRAPHS OF (A) AIR-DRIED AND (B) OSMOTIC-DEHYDRATED SAMPLES WITH 78% WATER CONTENT

slightly higher for those with intermediate water content (0.19-g/100-g initial product). To analyze the results, it is important to consider that all samples were stored for 12 h at 8C in sealed polyethylene bags until analysis. During this period, only viable cells in the tissues could develop this metabolic activity, which might be responsible in part for the changes in composition. The volume fraction of active cells and the relative degree of cell alteration will vary for each treatment, in line with the different concentrations and structural profiles developed in the tissue (Albors *et al.* 1998; Salvatori *et al.* 1998). Figure 3 shows the different alteration degrees that AD and OD provoked in the most external cells of the samples dried until 0.78 overall moisture content. Most of the cells in the samples with the lowest water content would be affected, and especially, those in the external cell layers would not present biological activity (Mavroudis *et al.* 2001), explaining the obtained results. The slight cellular stress induced with AD 1 and OD 1 treatments, associated with the soft drying conditions, could also explain the lower acidity loss in this case.

Weight changes among the different sugars were affected by the kind and length of treatments; they also reflect the metabolic activity of the tissue. In all cases, treatments with OD showed an expected sugar gain. Nevertheless, this occurs not only for the external sugar (sucrose), but also for glucose and fructose. This fact can only be explained by the total or partial hydrolysis of the gained sucrose. This hydrolysis seems to occur to a total extent in the milder OD treatment, but only to some extent in the most intense OD treatment, where total sucrose gain might be greater. In AD treatments, the change in content of each sugar depended on the level of dehydration. The mild treatment causes a slight gain in fructose and sucrose (0.24- and 0.27-g/100-g initial product, respectively), while the more intense treatment causes losses in glucose and

fructose (0.61- and 0.52-g/100-g initial product, respectively). In OD-AD, the mentioned phenomena seem to occur to differing extents depending on the water content reached. The change in the sugar weight fraction in the fruits during the different treatments will be the result of different mechanisms coupled to different extents in each treatment: the sugar fluxes from or to the external medium (osmotic treatments), and the sugar generation (positive or negative) induced by cellular stress in viable cells, which will be dependent on the ratio of viable cells present in the treated fruit. Slight cellular stress in the live cells caused by mild treatments might promote the maturation processes, causing an increase in native sugars, as has been observed in other fruits such as dates (Fito *et al.* 2003). Nevertheless, a greater cellular stress promoted by more intense drying treatments can increase respiration rate and the subsequent consumption of internal sugars, especially in fruits like strawberries that have very high metabolic activity (Seymour *et al.* 1993). However, the defense of the tissue against osmotic stress seems to cause hydrolysis of the sucrose, which can be either native or introduced from the osmotic solution, to synthesize other components (glucose and fructose) that decrease the internal  $A_w$  of the cell more efficiently (Moreno *et al.* 2000; Talens *et al.* 2000). Likewise, cells will maintain their activity until a determined  $A_w$  level, below which changes in this sense are not expected (Ferrando and Spiess 2001). This could explain the amount of sucrose present in samples OD 3 and OD-AD 3 (1.22- and 1.50-g/100-g initial product, respectively).

Sample drip loss for each treatment and storage period is shown in Fig. 4. The great drip loss reduction provoked by sample dehydration can be observed in line with the considerable decrease in freezable water content, which implies less cellular cryoconcentration during freezing and less ice crystal damage in the cells. Remarkably, for a determined moisture level, the air-dried samples showed the lowest drip loss. This could be due to a smaller amount of liquid phase in the tissue, because no gain in external soluble solids occurs. Another factor explaining this behavior could be the more intense dehydration level of the external cells, which makes the tissue very compact in this zone and therefore might inhibit the loss of liquid phase from the internal cells. When OD-AD is compared with OD, at the same sample water content, the effect of the AD step on drip loss reduction was also appreciable.

Concentrations of water and total and specific soluble solids in frozen-thawed samples are shown in Table 4. In nondehydrated samples, significant differences in water and soluble solids were found between samples before and after freezing-thawing. The water content decreases and the soluble solids increase, thus indicating that drip loss implies greater losses of water than solutes. This is coherent with the extracellular ice formation and with the irreversible cellular dehydration during freezing (Grout *et al.* 1991). Throughout thawing, not all of the initial water can be absorbed by the cells, as some

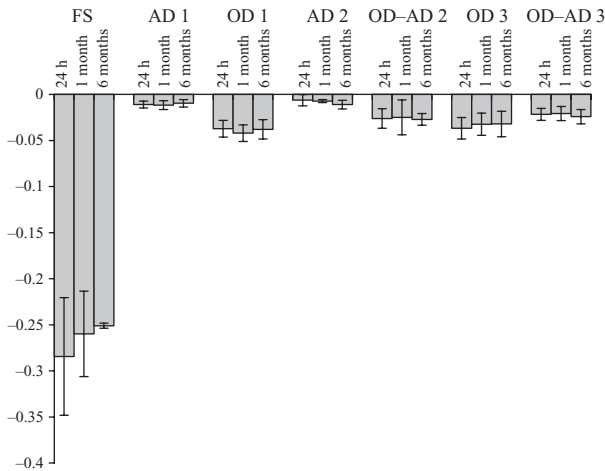


FIG. 4. MEAN DRIP LOSS VALUES (g/g product) OF FROZEN SAMPLES AFTER DIFFERENT STORAGE PERIODS (24 HOURS, 1 AND 6 MONTHS) FS, fresh sample; AD, air drying; OD, osmotic dehydration; OD-AD, combined treatment. 1, 2 and 3: dehydration levels ( $\approx 82, 78, 74\%$  water content, respectively).

is expelled from the tissue. During long storage periods, the concentration of water and solids in thawed samples becomes similar to that analyzed before freezing, which suggests that more cellular damage occurs. In this case, drip loss also involves an intracellular liquid phase, and its exudation does not provoke changes in the sample mean composition. A similar tendency, although much less marked and not as clear, was observed in partially dehydrated samples.

In the concentration of the analyzed sugars, the commented pattern for total solutes can be appreciated in AD and combined OD-AD treatments. Nevertheless, OD treatments imply a slight decrease in glucose and fructose after thawing for both moisture-reduced levels, whereas a significant increase in both sugar concentrations appeared after 1 or 6 storage months, for the less and more reduced moisture level, respectively. This behavior suggests that sucrose introduced in the tissue during the osmotic step, partially or totally hydrolyzed to glucose and fructose, flows out in drip loss probably because of its intercellular location. However, enzyme activity remains or can even be enhanced during freezing and frozen storage, as has been described by several authors for diverse fruits (Fúster *et al.* 1994; Cano *et al.* 1995; Viberg and Sjöholm 1998), in line with enzyme debonding from cell structure and its dislocation in the tissue. This can promote chemical changes in the product liquid phase. In the OD-treated samples with the highest moisture content, a glucose and fructose gain during freezing-thawing of about 3%, which can

only be attributed to enzyme action in the tissue, could be estimated by applying Eq. (1) (where  $\Delta M$  is sample drip loss in this case).

Changes in citric acid concentration during freezing–thawing seem to follow the general pattern described for total solutes. Nevertheless, their low values and natural fluctuations in raw material make the analysis of these changes difficult.

## CONCLUSIONS

The applied dehydration treatments on strawberries promote changes in the composition of sugars and citric acid other than those expected from the simple concentration of tissue. These changes reflect the cellular activity in the volume of viable cells in the tissue, which is affected by process conditions. Drying treatments seem to accelerate the metabolic activity, thus decreasing the acidity and increasing the native sugar content, but when hard drying conditions are applied, the decrease in the volume fraction of viable cells and the increase in their respiration rate seem to promote the decrease in acidity and native sugars. The sucrose gained in osmotic treatments that may be partially or totally hydrolyzed, depending on drying conditions, affects the changes previously commented on. Frozen storage conditions also affect the product composition because of the cellular damage caused by ice crystals, which increases in line with the storage time and the promotion of enzyme system dislocation in the tissue. In all cases, drying treatments promote a decrease in the drip loss of samples as a result of the reduction in the freezable water content, especially in AD treatments.

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