Journal of Food Engineering 107 (2011) 214–225

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

# Viscoelasticity, texture and ultrastructure of cut apple as affected by sequential anti-browning and ultraviolet-C light treatments

P.L. Gómez [a,1], A. García-Loredo [a,2], D.M. Salvatori [b,2], S. Guerrero [a,2], S.M. Alzamora [a,*,2]

[a] Departamento de Industrias, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Ciudad Universitaria, 1428 Ciudad Autónoma de Buenos Aires, Argentina
[b] Departamento de Química, Facultad de Ingeniería, Universidad Nacional del Comahue, Buenos Aires 1400, 8300 Neuquén, Argentina

ARTICLE INFO

*Article history:*
Received 13 October 2010
Received in revised form 17 February 2011
Accepted 18 May 2011
Available online 28 June 2011

*Keywords:*
UV-C light
Anti-browning dipping cut apple
Texture
Structure
Viscoelastic properties

ABSTRACT

The aim of this work was to analyze the effect of UV-C radiation (fluence: 11.2 kJ/m$^2$), with or without an anti-browning pretreatment containing 1% (w/v) ascorbic acid plus 0.1% (w/v) calcium chloride, on the linear viscoelastic properties (oscillatory shear and creep/recovery), instrumental texture (TPA), sensory texture and ultrastructure (ESEM, TEM) of cut apple. Changes in structural features and viscoelastic parameters were mainly evidenced after refrigerated storage. All samples showed a viscoelastic solid behavior with the storage modulus ($G'$) dominating the viscoelastic response. Overall, both dynamic moduli decreased, and instantaneous compliance ($J_0$), decay compliances ($J_1$ and $J_2$) and fluidity significantly increased after treatments and storage at 5 °C, while retardation times were in general constant. Fracture properties proved to be the most highly correlated with sensory texture. The test panel only significantly differentiated stored untreated apple from the other samples regarding fracturability and juiciness. Mechanical spectra and creep parameters showed ability to evidence ultrastructural differences (rupture of membranes, swelling of cells, alteration of cell walls) in the surface of cut apples subjected to the different treatments.



## 1. Introduction

Physical methods for removing microorganisms from produce surfaces include ultrasound, short-wave ultraviolet radiation (UV-C), high pressure, high-intensity electric field pulses, radiofrequency and ionizing radiation (Gil et al., 2009). UV-C is a radiation in the range of 200–280 nm which cross DNA pyrimidine bases of cytosine and thymine to form crosslinks, impairing formation of hydrogen bonds with the purine base pair on the complimentary strand of DNA and thus reproduction of microorganisms (Bintsis et al., 2000; Guerrero-Beltrán and Barbosa-Cánovas, 2004; Shama, 2006). It has also been proved to cause significant damage in the cytoplasmic membrane integrity and in the cellular enzyme activity (Schenk et al., 2011). Few studies regarding the influence of UV-C disinfection on fruit quality (color, texture, taste, and aroma) during storage have been made (Shama and Alderson, 2005; Erkan et al., 2001). The reported effects are quite diverse depending on the type of produce and the dosages applied (Shama, 2006) and in most of cases the effects are restricted to whole produce. Recently, Gómez et al. (2010) examined the effect of UV-C irradiation at different doses on structure, surface color, compression properties and native flora and inoculated microorganism behavior of cut apple stored in refrigeration for 7 days. They also explored the use of some pretreatments (hot water blanching, dipping into a solution containing ascorbic acid, calcium chloride) to minimize apple browning caused by UV-C light. Color and compression parameters were found to be dependent on UV-C dose, storage time and type of pretreatment. At the end of storage, samples exposed to only UV-C light turned darker (lower $L^*$ values) and less green (higher $a^*$ value) when compared to fresh-cut apple slices or to samples on day 0 and this effect was more pronounced at the greatest UV-C dose. Both pretreatments helped in maintaining the original color of apple slices after UV-C light exposure. Light microscopy observations clearly indicated that the modifications in color of only UV-C irradiated apples could be at least partially ascribed to the breakage of cellular membranes, which would cause a loss of functional cell compartmentalization, increasing enzyme–substrate contact with the consequent increase in tissue browning. Results indicated that UV-C light must be combined with a suitable anti-browning pretreatment to be used as a tool by the minimally processed produce industry to reduce surface microbial load avoiding color deterioration of cut apple. Regarding compression behavior, this preliminary study showed that UV-C treatment applied at different doses on raw apple had not a significant effect on true rupture stress ($\sigma_R^R$) and deformability modulus ($E_d$) values on day 0. But at day 7, $\sigma_R^R$ and $E_d$ of raw apple were significantly higher than those of UV-C treated samples. Also, the decrease in $E_d$ values

* Corresponding author. Tel./fax: +54 11 45763495.
*E-mail address:* alzamora@di.fcen.uba.ar (S.M. Alzamora).
[1] Fellowship, Consejo Nacional de Investigaciones Científicas y Técnicas.
[2] Member of Consejo Nacional de Investigaciones Científicas y Técnicas.

0260-8774/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jfoodeng.2011.05.046

**Nomenclature**

| | |
|---|---|
| ESEM | environmental scanning electron microscopy |
| $G'$ | storage modulus (Pa) |
| $G''$ | loss modulus (Pa) |
| $J$ | creep compliance ($Pa^{-1}$) |
| $J_0$ | instantaneous compliance ($Pa^{-1}$), Eq. (1) |
| $J_i$ | retarded compliance associated with the $i$th-Kelvin–Voigt element, Eq. (2), ($Pa^{-1}$) |
| LM | light microscopy |
| LVR | linear viscoelastic range |
| $n$, $k$ | empirical constants, Eq. (1) |
| PP | percentage of weight loss, Eq. (3), dimensionless |
| $p$ | weight of apple sample at time $t$ (g) |
| $t$ | time (s) |
| tan ($\delta$) | ($=G''/G'$) loss tangent, dimensionless |
| TEM | transmission electron microscopy |

*Greek symbols*

| | |
|---|---|
| $\gamma$ | strain at time $t$, dimensionless |
| $\delta$ | phase angle (rad) |
| $\eta$ | coefficient of viscosity of the dashpot, Eq. (2) (Pa s) |
| $\lambda$ | retardation time, Eq. (2), (s) |
| $\tau$ | constant shear stress, Eq. (2), (Pa) |
| $\omega$ | angular frequency ($s^{-1}$) |

*Subscripts*

| | |
|---|---|
| $i$ | $i$th Kelvin–Voigt element, Eq. (2), $i = 1, 2$ |
| N | associated to Newtonian flow |
| $t$ | at time $t$ |
| 0 | initial value |

of UV-C irradiated apples previously immersed into the anti-browning solution was in general significant (although small) after the treatment as well after 7 days of storage.

Producing high quality fruit products requires understanding the factors controlling texture. One component of sensory texture is rheological properties. They are an overall manifestation of structure (micro-, ultra-, nano) features and the inter-atomic and intermolecular interactions (Peleg, 2006). The relationship between rheological properties and microscopic features of plant tissues is well known. Dynamic oscillatory shear and creep/recovery tests performed in the linear viscoelastic regimen are usually used to determine material properties, allowing characterizing microstructures in a non-destructive manner (Khan et al., 1997). This is not the case in the mouth and in the TPA analyzer, where irreversible deformation takes place. At the cellular and tissue levels, the three major structural factors that contribute to mechanical behavior of plant-based foods are turgor (i.e. the force exerted on the cell membrane by intracellular fluid), cell wall rigidity, and cell–cell adhesion, determined by the integrity of the middle lamella and the plasmodesmata (Jackman and Stanley, 1995; Waldron et al., 1997; Alzamora et al., 2000, 2008).

Because of the need to gain more information about the effect of UV-C radiation combined with an anti-browning pretreatment and refrigerated storage on apple tissues, the specific aims of this study were:

(a) To analyze the linear viscoelastic behavior as derived by from dynamic oscillatory and creep tests.
(b) To explore the texture profile analysis (TPA) attributes and their correlation with sensory texture evaluation.
(c) To evaluate the ultrastructure by transmission and environmental scanning electronic microscopy and to explore how differences in tissue structure were expressed by viscoelastic, TPA and sensory parameters.

## 2. Materials and methods

### 2.1. Sample preparation

Raw apples (*Malus pumila*, Granny Smith var.; $a_w$ 0.98; 10.4–12.2 °Brix, pH 3.3–3.4) were purchased at a local market and maintained at 4–5 °C until use. Before processing, whole fruit was washed in water, dipped in sodium hypochlorite solution (100 ppm free chlorine, 3 min) and rinsed in water. All cutting boards, tools and holding vessels were sanitized in the same way before use.

Apples were hand peeled and slices of parenchymatic tissue with tangential orientation were cut parallel to the axis through the calyx and the stem. The slices were cut out vertically with a cork borer to obtain 0.03 m in diameter and 0.006 m in thickness discs. All slices were taken from the middle part between the center and the surface of the fruit, where there were few vascular bundles. Apple discs were dipped in distilled water (4–5 °C) for 1 min to eliminate cellular fluids, dried with tissue paper and immediately subjected to the different treatments to avoid the loss of moisture.

### 2.2. UV-C equipment and dosimetry

The UV-C irradiation device consisted of one bank of two reflectors with unfiltered germicidal emitting lamps (maximal emission at 253.7 nm, TUV-15W G 13 T8 55 V, Philips, Holland) located 0.1 m above the produce tray. The UV-C lamps and the treatment area were enclosed in a wooden box covered with aluminum foil with a cover protection for the operators. A ventilation device was installed in a corner of the box to avoid temperature increase due to UV-C radiation. The mean air temperature during the treatments was 27 ± 1 °C. Prior to use, the UV-C lamps were allowed to stabilize by turning them on at least 15 min.

The UV-C intensity emitted from the lamps was determined by using the iodure/iodate chemical actinometer (Rahn, 1997). All reactive employed in UV-C dosimetry were analytical grade from Merck Química Argentina S.A. (Argentina). The test was made by cuadruplicate and the mean value was reported. Variations in radiation dose absorption were minimized by placing the samples within a uniform area of the radiation field (between the lamps and equidistant with respect to lamp extremes).

### 2.3. Treatments

Prior to irradiation, some apple discs were immersed into an anti-browning solution (anti-browning dipping, AD) containing 1% (w/v) ascorbic acid (food grade, Química Oeste S.A., Argentina) plus 0.1% (w/v) calcium chloride (food grade, Saporiti S.A., Argentina), pH 3.5, for 5 min at 4 °C (Gómez et al., 2010; Ponting et al., 1972).

Apple discs with and without previous immersion into the anti-browning solution were exposed to irradiation for 20 min (fluence: 11.2 $kJ/m^2$) on one side. The selected dose was suitable to achieve microorganism's inactivation on apple slices. The log reductions for different microorganisms inoculated and native flora varied between 1.0 and 1.9 log cycles for apple discs without previous

dipping and in the range of 0.2–0.7 log cycles for pretreated samples (Gómez et al., 2010). Treated samples were compared with untreated apple discs held at a temperature (~25 °C ± 1 °C) similar to that of treated fruit during irradiation but without exposing to UV-C light, and stored in refrigeration during the same period of time (control). After irradiation, treated and untreated samples were packed in closed plastic boxes permeable to air and stored in the dark at 5 °C (±1 °C).

### 2.4. Analysis of viscoelastic properties

Viscoelastic properties were analyzed at 25 °C in a Paar Physica MCR 300 rheometer (Antor Paar GmbH, Graz, Austria) using a 30 mm diameter parallel plate geometry with rough surface. Temperature was controlled by an external liquid bath thermostat model Viscotherm VT2 (Anton Paar, Graz, Austria).

Dynamic oscillatory test were performed in the controlled strain mode. Prior to a frequency sweep, a strain sweep was carried out at an angular frequency ($\omega$) of 10 $s^{-1}$ to determine the linear viscoelastic range (LVR). The LVR was determined with the Paar Physica US 200 software package (Anton Paar GmbH, Graz, Austria). Thereafter, storage ($G'$) and loss moduli ($G''$) were measured in the frequency range 0.1–100 $s^{-1}$ using a strain amplitude value of 0.01% (within the limits of linearity previously established). Storage moduli values were fitted using a linear regression of log ($G'$) versus log ($\omega$):

$$\log(G') = n\log(\omega) + k \quad (1)$$

where $n$ is the slope of regression and $k$ is the origin ordinate.

Creep-recovery tests of apples were conducted by applying a constant shear stress of 35 Pa for 100 s. A previous stress sweep by varying the applied stress from 1 to 100 Pa indicated that in the selected condition the deformation was proportional to the stress applied. After removal of the stress, sample recovery was registered for a period of time of 200 s. Each apple sample was subjected to three consecutive creep-recovery assays. The first two trials were conducted in order to remove any surface irregularity in the specimen (Mittal and Mohsenin, 1987).

Compliance data from creep experiments were fitted by a mechanical model consisting of a spring connected in series with two Kelvin–Voigt elements (each Kelvin–Voigt element has a spring and a dashpot in parallel) and a dashpot element described by the following equation (Sherman, 1970):

$$J(t,\tau) = (J_0) + \sum_{i=1}^{2}(J_i)\left(1 - e^{-t/\lambda_i}\right) + t/\eta_N \quad (2)$$

where $J(t,\tau)$ is the creep compliance ($=\gamma(t)/\tau$ with $\gamma(t)$ being the strain at the time $t$ and $\tau$ the constant stress applied). $J_0$ is the instantaneous compliance at $t = 0$; $J_i$ are the retarded compliances; $\lambda_i$ ($=\eta_i \times J_i$) are the retardation times and $\eta_i$ are the coefficients of viscosity associated with the Kelvin–Voigt elements; $\eta_N$ is the coefficient of viscosity associated with Newtonian flow and its inverse the steady-state fluidity of the material.

The Origin v.7.0 software (OriginLab Corporation, Northampton, USA) was use for non-linear regression analyses. The estimation method used to minimize residual sum of squares was Marquardt.

In both tests, data were obtained using 10 replicates for each condition. Measurements were made at 0 and 7 days of refrigerated storage.

### 2.5. Texture profile analysis (TPA)

An Instron Universal Testing Machine model 3345 (Canton, Massachusetts, USA), with a 5000 N compression load cell interfaced with a series data acquisition software (Bluehill 2, v. 2.17, Instron, USA) was used to conduct the texture profile analysis (Bourne, 1978; Bourne and Comstock, 1981). A two cycle compression was set to 70% deformation. Tests were performed with a crosshead speed of 0.001 m/s and a 0.035 m diameter cylindrical probe. The following 10 TPA parameters were obtained from the force–time curves, according to the definitions of Bourne (1978):

*Fracturability* (N): The force at the first significant break during the first compression.
*Hardness* (N): The maximum force during the first compression cycle.
*Hardness 2* (N): The maximum force during the second compression cycle.
*Area 1* (*J*) ($A_1$): The positive area under the first compression (the area during the decompression and the negative area of adhesiveness are excluded).
*Area 2* (*J*) ($A_2$): The positive area under the second compression.
*Cohesiveness* ($A_2/A_1$): Ratio of area 2 to area 1.
*Adhesiveness* (J): The negative force area for the first bite (i.e. the work necessary to pull the compression plunger away from the sample).
*Springiness* ($d_2/d_1$): The ratio of the duration of contact with the sample during the second compression ($d_2$) to that during the first compression ($d_1$).
*Gumminess* (N): The product of hardness and cohesiveness.
*Chewiness* (N): The product of gumminess and springiness.

TPA attributes were evaluated in control and treated apple samples after 5 days of refrigerated storage. All measurements were replicated 20 times.

### 2.6. Sensory descriptive analysis

Nine panelists (three males, six females), all between the ages of 21 and 38, composed the sensory panel. For the selection of panelists 12 persons were recruited from staff from Buenos Aires University based on their interest, availability, previous experience in sensory evaluation and familiarity in texture terminology. Different screening tests were done to evaluated sensory acuity of the panelist through basic taste test, sequential triangle test (Meilgaard et al., 1999) and an intensity ranking test using the hardness scale (Civille and Szczesniak, 1973). The panelists who passed the prescreening tests were trained with the texture profile method following the procedures described by Civille and Szczesniak (1973) during 35–40 h (2 h per week) to recognize texture attributes of hardness, fracturability, juiciness and crispness. The use of the standard rating scales (Chauvin et al., 2008; Hough et al., 1994; Szczesniak and Ilker, 1988) was explained using one scale per session. Each standard rating scale was worked on until the panel fully understood the texture concepts and round-table discussions were performed to clarify any possible large discrepancies and to arrive at a general consensus between the panelists. The definitions for sensory texture parameters used to train the panel were those from Chauvin et al. (2008), Szczesniak et al. (1963), Szczesniak and Ilker (1988):

*Hardness*: The force required to compress a substance between the molars.
*Fracturability*: The force with which a sample crumbles, cracks or shatters.
*Juiciness*: The amount of juice released on the first three chews.
*Crispness*: The amount of sound produced on the first chew between incisors teeth.

Sensory studies were carried out with the same size of sample used in instrumental tests to allow a better comparison between

both measurements. Previous work made in our laboratory has shown that differences (<3.5%) in the texture attributes (fracturability, juiciness, crispness) evaluated in fresh apple slices of 0.006 and 0.01 m of thickness were not significant. On the other hand, the reference foods for the texture scales employed during the training had thicknesses of approximately 0.01 ± 0.003 m.

Samples (tempered at room temperature for around 30 min) were individually presented to the panelists in glasses of white plastic identified by numbers of three digits chosen at random during the evening in individual booths under white light. Mineral water and unsalted crackers were provided in between samples for cleansing the panelist's palates. As differences in sample color could influence texture perception by the panelists (Gómez et al., 2010; Meilgaard et al., 1999), sensory evaluation was performed only in irradiated samples with previous dipping into the anti-browning solution. Furthermore, as the panelists reported that color developed in the control after 7 day storage would influence their assessments, it was decided by consensus in round-table to evaluate the samples at five day where the changes in color were not relevant. Texture profile analysis also was performed at 5 days of storage in order to better compare with the human perception of the texture. The descriptive analysis was replicated two times.

### 2.7. Microscopic observations

For transmission electronic microscopy (TEM) observations, cubes (3 $mm^3$) of fresh and treated apples, including the exposed or irradiated cut surface, were fixed in glutaraldehyde solution (3 g/100 g) and then in 0.1 M potassium phosphate buffer (pH 7.4) overnight at room temperature. Cubes were then rinsed three times with distilled water, postfixed in $OsO_4$ solution (1.5 g/100 g) at room temperature and dehydrated in a graded acetone series prior to be embedded in low viscosity Spurr resin. Samples embedded in Spurr resin were then cut in ultrathin sections (1 μm thick) using a glass knife with a Sorvall MT 2-B ultracut microtome, collected on copper grids and double stained with uranyl acetate and Reynolds lead-citrate. Sections were examined using a JEOL JEM-1200 EX II (Japan) transmission electron microscope at an accelerating voltage of 80 kV. All reagents were from Merck Química Argentina S.A. (Argentina).

For environmental scanning electronic microscopy (ESEM) observations, apple specimens were cut in sections (about 105 $mm^3$) including the irradiated surface, mounted directly on a metal support and observed in a PHILIPS XL 30 ESEM (Philips, Holland) using 20 kV voltage acceleration and 1.1–3.5 torr.

All microscopic observations were performed at 0 and 7 day refrigerated storage.

### 2.8. Weight loss

Weight loss along storage of treated and untreated apple discs was recorded in a balance (Precisa 180 A, Switzerland) with a precision of ±0.0001 g at 0, 3 and 7 day storage. Measurements were replicated 10 times. Results were expressed as percentage change in weight with respect to fresh sample without treatment or storage, according to Eq. (3):

$$\mathrm{PP}\ (\%) = 100 \times (p_t - p_0)/p_0 \quad (3)$$

where PP, percentage of weight loss; $p_0$, initial weight of fresh apple sample; $p_t$, weight of apple sample at time $t$.

### 2.9. Statistical analysis

All statistical analyses were carried out using the Infostat v. 2009 software (Universidad Nacional de Córdoba, Argentina). Results were expressed as mean ± standard deviation of the mean (mean ± SD). Two-way analysis of variance (ANOVA) with repeated measures was performed on weight loss values according to the factors "treatment" and "time". Dynamic oscillatory and compliance data were also analyzed by a two-way ANOVA ("treatment" and "time"). In case of significant interactions between factors in those data, single effects were examined (i.e. effects of one factor holding the other fixed). Sensory data were analyzed by a two-way ANOVA according to the factors "assessor" and "treatment" and TPA data were subjected to a one-way ANOVA ("treatment"). In all cases significant level was set at $p < 0.05$ and multiple comparisons were performed using the Tukey test (Zar, 1999). The correlation between texture determinations was determined using Pearson's correlation. Principal component analyses (PCA) of means for TPA and sensory data were used to illustrate the relationship between attributes and samples.

## 3. Results and discussion

### 3.1. Viscoelastic properties

#### 3.1.1. Dynamic spectra

LVR was determined on fresh and treated samples from the strain region at which $G'$ was independent of the amplitude of the strain function. Linear viscoelastic limits ranged between 0.001% and 0.01% for control and treated samples at day 0 and between 0.001% and 0.1% for samples at day 7. Accordingly, a strain value equal to 0.01% was selected to assure linearity during subsequent frequency sweep test for all samples assayed.

Fig. 1 shows the mechanical spectrum of apple slices irradiated with UV-C light with and without previous dipping into the anti-browning solution. All samples displayed a clearly dominant solid behavior, with $G'$ exceeding $G''$ over the entire frequency range ($\tan\delta \approx 0.09$–$0.17$). The storage modulus $G'$ presented a slight linear increase with increasing angular frequency ($n$ ranging between 0.045 and 0.060) evidencing a solid-like character, with greater slope of the $G'$-frequency lines for treated samples. The frequency dependence of $G''$ was more complex: $\log G''$–$\log \omega$ curves consisted of one small negative slope at low frequencies and a positive slope at high frequencies. The pattern found for dynamic spectra were in agreement with those previously reported for apple (Martínez et al., 2007), potato (Alvarez et al., 1998), melon (Martínez et al., 2005) and Korla pear (Wu and Guo, 2010).

Not significant interaction between treatment and time was found for $G'$ values at different frequencies (with $F$ values ranging between 0.08 and 0.81). After exposure to UV-C light (day 0), as compared with fresh tissue, apple slices showed a decreased in $G'$ value (≈30%), indicating a loss of rigidity. At the end of storage (day 7), both irradiated and non-treated apples showed a significant decrease in $G'$ values, but the decrease was greater in irradiated ones (≈75%) (Fig. 1A). There were not significant differences ($p > 0.05$) in the storage modulus values between samples dipped into the anti-browning solution (with or without UV-C irradiation) and the control at day 0. On the contrary, apple tissue with anti-browning dipping showed lower $G'$ values than the control after storage, this decrease being more accentuated in apple samples also exposed to UV-C light (Fig. 1 B). A similar pattern was exhibited by the loss modulus, denoting that the relative contribution of elastic and viscous components remained approximately constant. The treated apples softened and became less viscous and less elastic than the untreated fruit after storage.

Dynamic spectra appeared to represent rather well systems with a network-type microstructure although the different dynamic mechanical spectra among stored untreated and irradiated samples, with or without previous AD, indicated a change in the microstructure of the material (Khan et al., 1997).

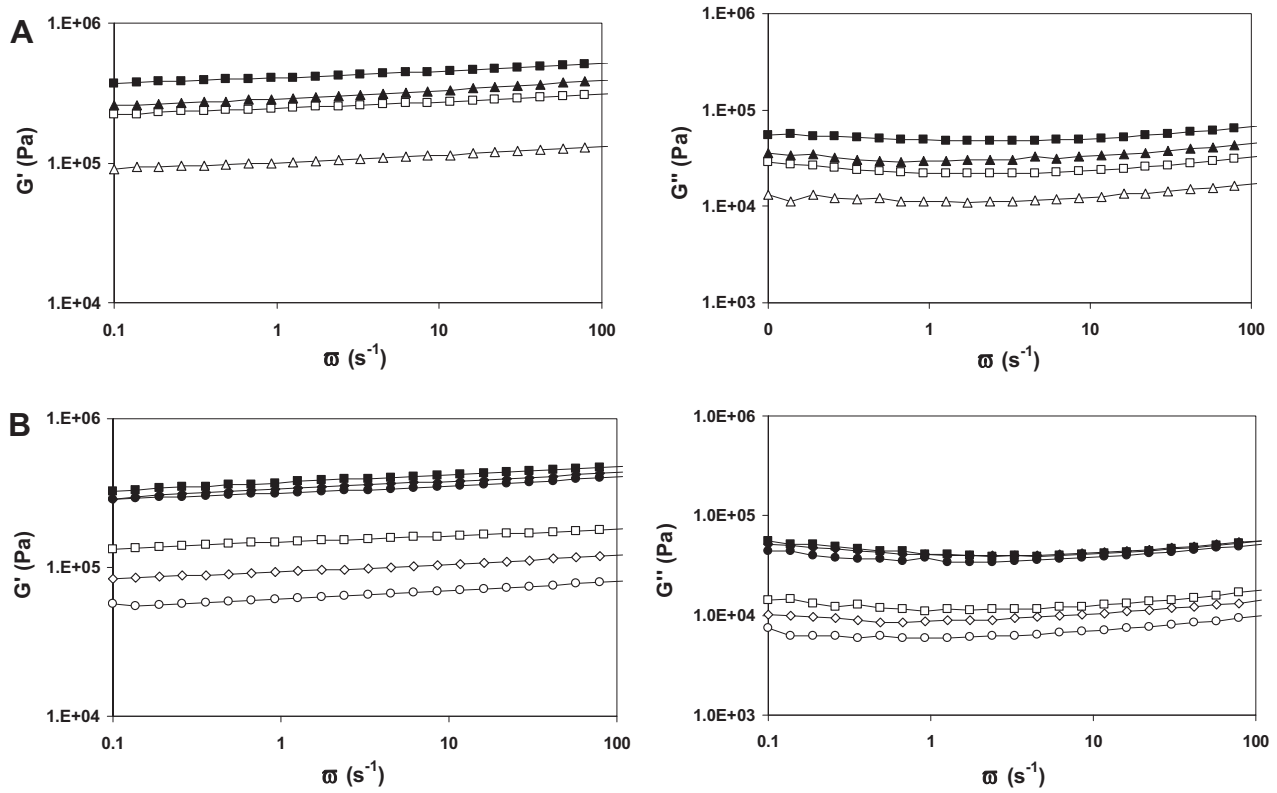


**Fig. 1.** Variation of storage modulus ($G'$) and loss modulus ($G''$) with frequency for apple tissue dipped into the anti-browning solution (AD) and/or irradiated with UV-C light and stored 7 days at 5 °C. (A) Samples irradiated without AD; (B) samples irradiated with previous AD. Day 0: (■) control (fresh); (▲) irradiated apple; (♦) apple with AD; (●) irradiated apple with previous AD. Day 7: (□) control; (△) irradiated apple; (◇) apple with AD; (○) irradiated apple with previous AD.

### 3.1.2. Creep/recovery curves

Creep-recovery curves for apple discs exposed to UV-C light with or without previous anti-browning dipping at different storage days are presented in Fig. 2. At the beginning of storage (immediately after the treatments), apple samples did not show major changes in the shape of creep curves as compared with fresh fruit. However, at the end of storage the changes were notable, especially in the creep phase. The compliance versus time curves of fresh and treated fruit during the creep phase were well characterized (correlation coefficients >0.99) by the mathematical model represented by Eq. (2) and the corresponding rheological parameters are supplied in Tables 1 and 2. The mechanical model applied provided excellent approximation of the creep data in the time range of the experiment. The rheological behavior of the apple tissue was defined in terms of four separate compliances. $J_0$ would be related to those bonds of structural units that are stretched elastically when the stress is applied and show instantaneous and complete recovery when the stress is removed. $J_i$ parameters would be related to bonds that break and reform at different rates, the weaker bonds breaking at smaller values of time than the stronger ones. They show retarded elastic recovery. The linear region of Newtonian compliance $t/\eta_N$ would be related to those bonds that are ruptured during the shear creep step and the time required for them to reform is longer than the creep-recovery period; the released units will flow and part of the structure is not recovered (Sherman, 1970).

The great variability associated with creep parameters (see the great standard deviations) are not uncommon for measured viscoelastic properties of plant tissues. It can be attributed to many factors, such as no homogeneity of the tissue, stage of development, agronomic practices, etc. (Mittal and Mohsenin, 1987; Pitt, 1992; Alzamora et al., 2008). Therefore not only a sufficient number of

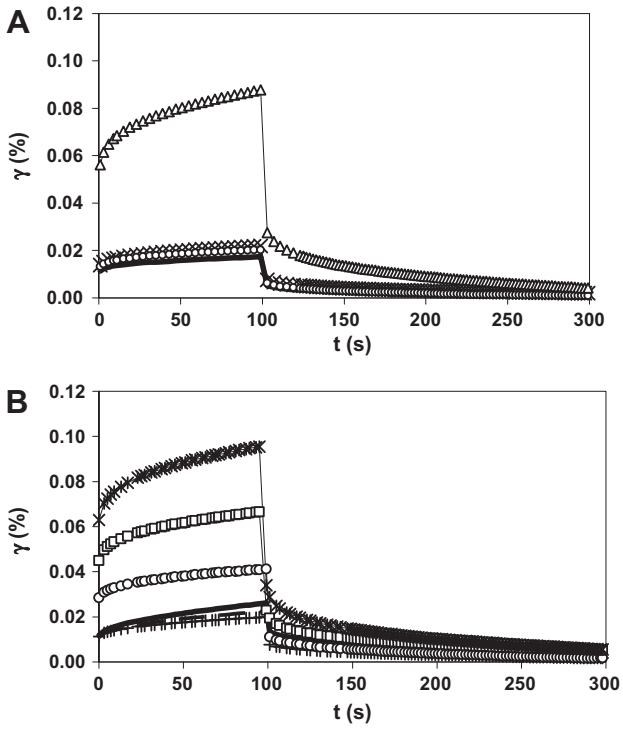


**Fig. 2.** Average experimental creep/recovery curves for apple tissue dipped into the anti-browning solution (AD) and/or irradiated with UV-C light and stored 7 days at 5 °C. (A) Samples irradiated without AD); (B) Samples irradiated with previous AD. Day 0: (—) control; (×) irradiated apple; (- -) Apple with AD; (+) irradiated apple with previous AD. Day 7: (○) control; (△) irradiated apple; (□) apple with AD; (Ж) irradiated apple with previous AD.

**Table 1**
Viscoelastic parameters* for fresh and UV-C irradiated apple tissues stored at 5 °C.

| Time (day) | Treatment | $J_0$ (1/Pa) ($\times 10^6$) | $J_1$ (1/Pa) ($\times 10^6$) | $J_2$ (1/Pa) ($\times 10^6$) | $\lambda_1$ (s) | $\lambda_2$ (s) | $\eta_N$ (Pa s) ($\times 10^{-8}$) |
|---|---|---|---|---|---|---|---|
| 0 | Control | 2.6 (0.7)$^{aA}$<br>66%** | 0.8 (0.5)$^{aA}$<br>19%** | 0.5 (0.1)$^{aA}$<br>13%** | 35.1 (22.1) | 2.3 (0.5) | 14.7 (22.9)<br>2%** |
| | UV-C | 3.7 (0.9)$^{aA}$<br>59%** | 1.10 (0.3)$^{aA}$<br>17%** | 0.7 (0.2)$^{aA}$<br>11%** | 26.7 (8.1) | 2.4 (0.6) | 1.2 (0.6)<br>13%** |
| 7 | Control | 3.7 (1.0)$^{aA}$<br>64%** | 1.1 (0.3)$^{aA}$<br>18%** | 0.7 (0.2)$^{aA}$<br>12%** | 30.7 (5.6) | 2.8 (0.6) | 2.7 (2.7)<br>6%** |
| | UV-C | 14.1 (7.1)$^{bB}$<br>60%** | 3.72 (1.3)$^{bB}$<br>16%** | 2.75 (1.1)$^{bB}$<br>12%** | 23.4 (5.6) | 2.4 (0.6) | 0.4 (0.2)<br>12%** |

Results were expressed as mean followed by the standard deviation into brackets.
In case of significant time × treatment interaction, for each storage time, means in same column with same uppercase letter were not significantly different ($p < 0.05$). For each treatment, means in same column with same lowercase letter were not significantly different ($p < 0.05$).
* Parameters derived by fitting Eq. (2) to average compliance data from the creep phase.
** Relative contribution of each type of compliance to overall compliance.

**Table 2**
Viscoelastic parameters* for fresh apple, apple dipped into the anti-browning solution (AD) and apple dipped into the anti-browning solution and irradiated with UV-C light (AD + UV-C) (storage at 5 °C).

| Time (day) | Treatment | $J_0$ (1/Pa) ($\times 10^6$) | $J_1$ (1/Pa) ($\times 10^6$) | $J_2$ (1/Pa) ($\times 10^6$) | $\lambda_1$ (s) | $\lambda_2$ (s) | $\eta_N$ (Pa s) ($\times 10^{-8}$) |
|---|---|---|---|---|---|---|---|
| 0 | Control | 3.4 (1.2)$^{aA}$<br>40%** | 1.8 (1.2)$^{aA}$<br>21%** | 0.9 (0.4)$^{aA}$<br>11% | 27.1(6.1) | 3.0 (1.1)$^{aA}$ | 0.4 (0.3)$^{aA}$<br>28% |
| | AD | 2.9 (0.7)$^{aA}$<br>44%** | 1.5 (0.5)$^{aA}$<br>23%** | 0.9 (0.8)$^{aA}$<br>15%** | 21.6(4.5) | 1.4 (0.6)$^{aB}$ | 0.8 (0.5)$^{aA}$<br>18%** |
| | AD + UV-C | 3.0 (0.4)$^{aA}$<br>51%** | 1.6 (1.4)$^{aA}$<br>27%** | 0.7 (0.1)$^{aA}$<br>12%** | 29.4(16.1) | 2.5 (0.8)$^{aA}$ | 1.7 (0.7)$^{aB}$<br>10%** |
| 7 | Control | 7.5 (2.1)$^{bA}$<br>64%** | 1.7 (0.5)$^{aA}$<br>14%** | 1.2 (0.5)$^{aA}$<br>11%** | 22.8 (6.5) | 1.9 (0.8)$^{aA}$ | 0.8 (0.5)$^{aA}$<br>11%** |
| | AD | 11.8 (4.4)$^{bB}$<br>63%** | 2.6 (0.8)$^{aAB}$<br>14%** | 2.1 (0.6)$^{bB}$<br>11%** | 21.2 (2.8) | 2.2 (0.2)$^{bA}$ | 0.4 (0.2)$^{aA,B}$<br>12%** |
| | AD + UV-C | 15.6 (4.9)$^{bB}$<br>61%** | 3.7 (0.5)$^{aB}$<br>14%** | 2.9 (0.4)$^{bB}$<br>11%** | 21.9 (2.8) | 2.3 (0.4)$^{aA}$ | 0.30(0.06)$^{bB}$<br>13%** |

Results were expressed as mean followed by the standard deviation into brackets.
AD, anti-browning dipping.
In case of significant time × treatment interaction, for each storage time, means in same column with same uppercase letter were not significantly different ($p < 0.05$). For each treatment, means in same column with same lowercase letter were not significantly different ($p < 0.05$).
* Parameters derived by fitting Eq. (2) to average compliance data from the creep phase.
** Relative contribution of each type of compliance to overall compliance.

replicates is necessary to obtain an acceptable level of confidence in creep parameters determined by instrumental tests but the same lot of fruit must be used for evaluating control and processed samples to assess the effect of treatments.

For apples that had undergone only UV-C irradiation, a significant interaction ($F_{1,36} \sim 4$–16; $p < 0.0001$) between treatment and time was found for $J_0$, $J_1$ and $J_2$, while not significant interaction ($F_{1,36} \sim 0.1$–0.9; $p > 0.1$) was found for $\lambda_1$, $\lambda_2$ and $\eta_N$ (Table 1). For apples subjected to UV-C light with previous AD, significant interaction ($F_{2,54} \sim 8$–21; $p < 0.01$) between factors was found for all parameters except for $\lambda_1$ ($F_{2,54} = 0.99$; $p = 0.38$) (Table 2).

Upon UV-C irradiation, insignificant differences between the instantaneous elastic compliance ($J_0$) and the viscoelastic compliances, $J_1$ and $J_2$, of irradiated and fresh apples were observed at day 0. But after storage, a statistically significant increase ($p < 0.05$) in $J_0$, $J_1$ and $J_2$ compliances of UV-C treated apples was detected, reflecting lower elasticity or stiffness provoked by this process (Table 1).

When both springs of the Voigt units are completely displaced, the constant increase of deformation is associated with the steady-state viscosity. The large errors associated with $\eta_N$ values of the raw fruit did not allow concluding about the behavior of this parameter after irradiation and along storage.

Retardation times of both Voigt units differed approximately in one order of magnitude for all apple samples. Because these parameters represent the time required for the strain on structural elements associated with viscoelastic behavior to reach 63% of their maximum strain, the structural elements of this 2nd Voigt unit would reach equilibrium faster than those contributing to the 1st Voigt unit (Jackman and Stanley, 1995). Response rate of viscoelastic elements was not affected neither due to irradiation nor due to storage time since retardation times ($\lambda_1$ and $\lambda_2$) did not differ significantly ($p > 0.05$) between control and irradiated samples at both storage times (Table 1).

Apple slices previously treated with ascorbic acid and calcium chloride solution (with and without irradiation) also showed higher values of $J_0$ and $J_2$ than control samples at 7 days of storage. $J_1$ slightly increased only in apples also exposed to UV-C light (Table 2). Curiously, $\eta_N$ value increased in samples after AD + UV-C treatment, but a significant increase in the steady-state viscous compliance ($1/\eta_N$) occurred at the end of storage (the value of $\eta_N$ was 37% of the value of raw apple). That is, the treated tissue exhibited a lower fluidity after processing (day 0), and a higher fluidity (associated with a greater permanent strain) after storage. Sequential AD and UV-C irradiation did not significantly affect retardation times, while apples undergone only AD showed slightly lower values of $\lambda_2$ at day 0 (Table 2).

Comparing the compliance curves of untreated and treated tissues after storage, one obvious difference between then is the increase of the overall compliance at the end of the creep phase. Regarding the compliance of raw apple at day 0, this value increased between 400% and 500% in irradiated samples with or without previous AD (Fig. 2). For all samples, the relative contribution of each type of compliance was in the range 40–66% for

**Table 3**
TPA parameters for fresh apple, apple dipped into the anti-browning solution (AD), apple irradiated with UV-C light (UV-C) and apple dipped into the anti-browning solution and irradiated with UV-C light (AD + UV-C) (5 day storage at 5 °C).

| Treatment | Fracturability (N) | Hardness (N) | Hardness 2 (N) | Area 1 (*J*) | Springiness (−) | Cohesiveness (−) | Gumminess (N) | Chewiness (N) |
|---|---|---|---|---|---|---|---|---|
| Control (day 0) | 335.4 (22.5)$^{a}$ | 341.2 (22.6)$^{a}$ | 236.3 (23.9)$^{a}$ | 0.8 (0.1)$^{a}$ | 0.67 (0.03)$^{a}$ | 0.16 (0.02)$^{a}$ | 55 (7)$^{a}$ | 36.9 (5.6)$^{a}$ |
| Control (day 5) | 359.6 (30.5)$^{a}$ | 389.8 (36.5)$^{b}$ | 273.8 (29.9)$^{b}$ | 0.97 (0.11)$^{b}$ | 0.6 (0.05)$^{b}$ | 0.12 (0.01)$^{b}$ | 45.7 (4.9)$^{b}$ | 27.2 (4.3)$^{b}$ |
| UV -C | 358.3 (33.5)$^{a}$ | 364.4 (34.5)$^{a,b}$ | 261 (27)$^{a,b}$ | 0.94 (0.1)$^{b}$ | 0.66 (0.02)$^{a}$ | 0.11 (0.01)$^{b}$ | 39.6 (5.1)$^{c}$ | 26.2 (3.7)$^{b}$ |
| AD | 345.2 (48.4)$^{a}$ | 383 (45)$^{b}$ | 262 (37)$^{a,b}$ | 0.94 (0.1)$^{b}$ | 0.64 (0.04)$^{a}$ | 0.16 (0.01)$^{a}$ | 61.1 (7.6)$^{a}$ | 39.4 (6.6)$^{a}$ |
| AD + UV-C | 335.9 (45.1)$^{a}$ | 339.9 (46.7)$^{a}$ | 254 (30)$^{a,b}$ | 0.9 (0.1)$^{a,b}$ | 0.61 (0.02)$^{b}$ | 0.14 (0.01)$^{c}$ | 46.6 (6.5)$^{b}$ | 28.5 (4.3)$^{b}$ |

Results were expressed as mean followed by the standard deviation into brackets.
Different superscripts in the same column indicate significant differences ($p < 0.05$) between the mean values of different treatment.

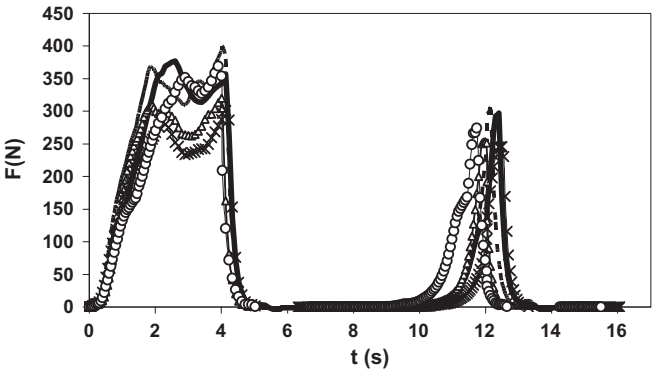


**Fig. 3.** Typical TPA responses for fresh apple and for apple dipped into the anti-browning solution (AD) and irradiated with UV-C light stored 5 days at 5 °C. (—) Control (fresh fruit at day 0); (- - -) control (fresh fruit stored during 5 days); (Δ) irradiated apple; (○) apple with AD; (×) irradiated apple with previous AD.

instantaneous elastic; 14–27% for the slow-rate viscoelastic; 11–15% for the fast-rate viscoelastic and 2–28% for the steady-state viscous compliance (Tables 2 and 3). As can be observed, the major contribution to overall compliance in treated and untreated apple tissue was given by $J_0$ component, both at the beginning or at the end of storage.

### 3.2. Texture profile analysis

Sensory and instrumental texture studies were performed on stored apple samples since major differences in viscoelastic (as determined in this study) and compression (Gómez et al., 2010) properties were not evidenced just after processing but after refrigerated storage.

Typical compression–decompression curves for fresh tissue (control at day 0) and for untreated (control at day 5) and irradiated tissues (with and without AD) stored 5 days, were displayed in Fig. 3. They exhibited the typical shape of hard materials with abrupt rupture peaks for all the samples studied. TPA parameters are presented in Table 3.

Not significant differences were found in hardness between control at day 0 and irradiated apples (with and without AD). On contrary, hardness of control at day 5 and apple treated with AD significantly increased ($F_{4,100} = 7.81$, $p < 0.0001$) after 5 days of storage. No differences within the statistical error were observed in fracturability ($F_{4,100} = 2.07$, $p > 0.05$). Overall the values of area 1 significantly increased ($F_{4,100} = 6.97$, $p < 0.05$) in stored samples with respect to fresh apple at day 0, with no significant differences among treated or untreated tissues. Springiness values of control at day 5 and of apple subjected to AD and irradiation decreased ($F_{4,100} = 16.23$, $p < 0.0001$). On the other hand, both non-treated and irradiated apple (with and without AD) showed a slightly decrease in cohesiveness ($F_{4,100} = 76.74$, $p < 0.0001$), gumminess ($F_{4,100} = 37.84$, $p < 0.0001$) and chewiness ($F_{4,100} = 30.69$, $p < 0.0001$) after storage (Table 3).

A multivariate approach to data analysis by principal components (PCA) showed the spatial relationships of the instrumental texture attributes for each sample. The first two principal components explained 61.3% and 26.7% of the variance, respectively (Fig. 4). The first axis was defined positively by fracturability, hardness 2 and area 1, and negatively by springiness, cohesiveness and chewiness. The second one contrasted hardness and gumminess positively. Control at day 5 showed an increase in fracturability, hardness, hardness 2 and area 1 with respect to control at day 0. Apple subjected to UV-C showed higher values in fracturability, hardness 2 and area 1 and lower values in chewiness and cohesiveness than AD + UV-C treated samples. Tissue treated only with AD presented higher values in hardness and gumminess with respect to samples subjected to UV-C and AD + UV-C.

### 3.3. Sensory texture evaluation

The results of the sensory analysis are presented in Table 4. Assessors and sample * assessor interactions were not significant for each evaluated attribute, indicating that the panel performance was consistent.

Sensory hardness and crispness did not show significant differences ($F_{3,12} = 2.21$, $p = 0.12$ and $F_{3,15} = 0.28$, $p > 0.05$, respectively) between all apple samples evaluated. Higher fracturability ($F_{3,9} = 3.5$, $p < 0.002$) and lower juiciness ($F_{3,12} = 5.6$, $p = 0.006$) were observed in untreated apples stored 5 days, while treated apples did not show significant differences in these attributes as compared to fresh fruit (Table 4).

Variation in data for the TPA and sensory descriptive tests was in general high (the standard deviations were in the region of 6–14% and 8–21% for TPA and sensory analysis, respectively). These values revealed the difficulty there was in the panelists in discriminating between four samples very similar in texture. The panel found small and overall insignificant differences.

Principal component analysis of sensory results showed that 98.1% of the total variation among the samples could be explained by two principal components (Fig. 5). The first component was defined positively by fracturability and hardness, and negatively by juiciness. The second axis contrasted crispness positively. Untreated apple sample at day 5 showed an increase in fracturability and hardness, and a decrease in juiciness with respect to fresh fruit. Treated samples were similar in fracturability, hardness and juiciness between them; however a decrease in crispness was observed with respect to control samples.

Pearson's correlation coefficients indicated that a highly significant correlation was found between instrumental and sensory fracturability ($r = 0.99$, $p < 0.001$). Sensory hardness was highly correlated with sensory fracturability ($r = 0.93$, $p < 0.05$), instrumental fracturability ($r = 0.97$, $p < 0.05$), instrumental hardness ($r = 0.9$, $p < 0.05$), hardness 2 ($r = 0.97$, $p < 0.05$) and area 1 ($r = 0.98$, $p < 0.05$). The correlations between juiciness and springiness ($r = 0.98$,

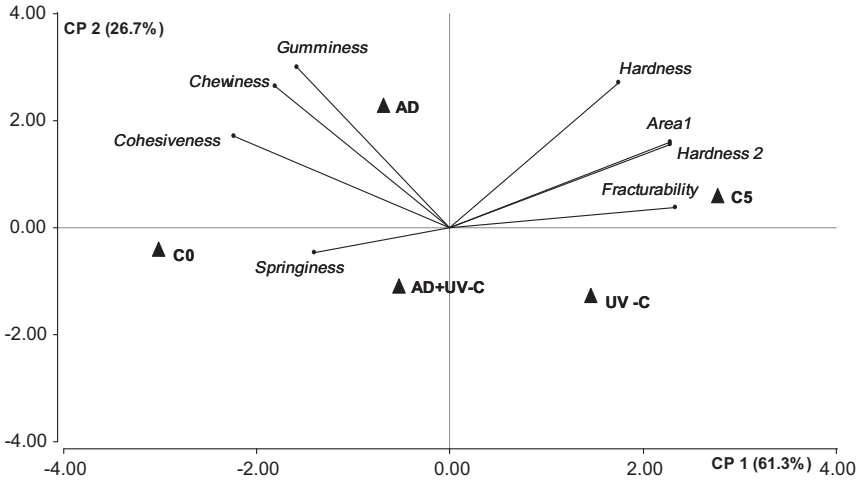


**Fig. 4.** Principal component analysis (PCA) bi-plot of instrumental parameters used to differentiate fresh (control) and treated apple tissues. C0, fresh apple; C5, untreated apple stored 5 days.

**Table 4**
Sensory texture parameters for fresh apple, apple dipped into the anti-browning solution (AD) and apple dipped into the anti-browning solution and irradiated with UV-C light (AD + UV-C) stored 5 days at 5 °C.

| Treatment | Hardness | Fracturability | Crispness | Juiciness |
|---|---|---|---|---|
| Control (day 0) | 6.06(0.58)[a] | 6.75(0.79)[a] | 7.47(0.49)[a] | 5.68(0.41)[a] |
| Control (day 5) | 6.47(0.52)[a] | 8.21(1.33)[b] | 7.39(1.42)[a] | 4.81(1.01)[b] |
| AD | 6.22(0.44)[a] | 7.29(0.73)[a] | 7.13(1.26)[a] | 5.53(0.31)[a] |
| AD + UV-C | 6.39(0.35)[a] | 7.03(0.55)[a] | 7.23(0.86)[a] | 5.27 (0.56)[a,b] |

Results were expressed as mean followed by the standard deviation into brackets. Different superscripts in the same column indicate significant differences ($p < 0.05$) between the mean values of different treatments.

$p < 0.05$), and juiciness and cohesiveness ($r = 0.93$, $p < 0.05$) were significant. Juiciness was negatively correlated with hardness 2 ($r = -0.92$, $p < 0.05$). Some instrumental parameters showed correlation between them. For instead hardness 2 was correlated with area 1 ($r = 0.99$, $p < 0.05$), springiness with cohesiveness ($r = 0.97$, $p < 0.05$) and gumminess with chewiness ($r = 0.99$, $p < 0.05$). On the other hand, juiciness was negatively correlated with sensory hardness ($r = -0.89$, $p < 0.05$).

### 3.4. Water loss

Although water is the most abundant (80–90% of the fresh weight) component of fruit tissues, even small changes in the water content of fruit are detrimental to quality. Water loss in fruits and vegetables is determined by many factors, probably the most important being the resistance of outer periderm or cuticle to transpirational movement of water vapor. In fresh-cut products the removal of skin or rind and cutting lead to exposure of a large surface as seen in fruit slices, cubes and wedges, which are prone to great water loss. Surface dehydration can have a negative impact not only on product appearance (less gloss, greater wrinkling, wilting) but also in perceived textural characteristics (Toivonen and Deell, 2002; Garcia and Barrett, 2005).

The weight loss (associated with the loss of water) for fresh and UV-C irradiated apples (with and without AD) along refrigeration storage is presented in Table 5. Interaction between the factors analyzed was significant ($F_{6,72} = 19.8$; $p < 0.0001$). All samples (treated and control) showed a significant decrease in weight during storage, but the decrease was higher in treated ones. At the end of storage, weight loss for control was approximately 8%, while for apple treated with UV-C light was about 14%. Therefore, the exposure to irradiation would provoke an additional injury to apple

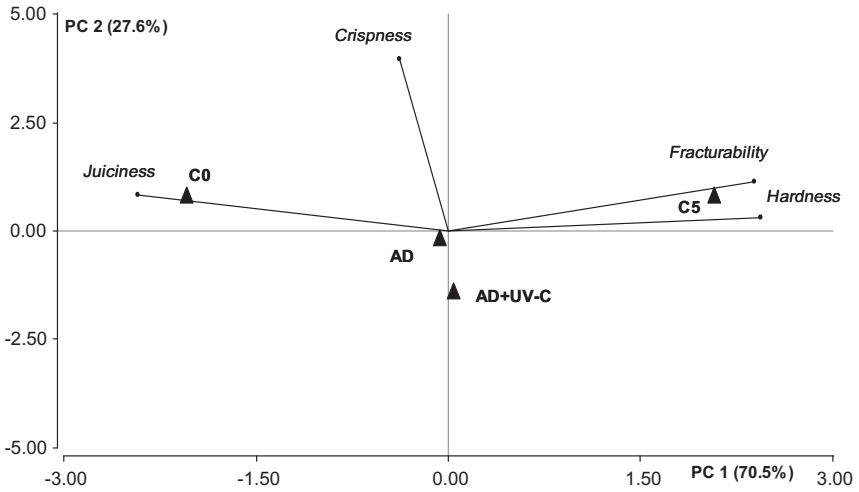


**Fig. 5.** Principal component analysis (PCA) bi-plot of texture attributes used to differentiate fresh and treated apple tissues. C0: fresh apple, C5: untreated apple stored 5 days.

**Table 5**
Weight loss (%) for fresh and treated apple discs throughout storage at 5 °C.

| Treatment | Storage time (day) | | |
|---|---|---|---|
| | 0 | 3 | 7 |
| Control | – | 4.4 (0.8)$^{aA}$ | 8.3 (0.9)$^{bA}$ |
| UV-C | 2.3 (0.9)$^{aA}$ | 7.9 (2.9)$^{bB}$ | 14.5 (1.6)$^{cB}$ |
| AD | 0.2 (0.4)$^{aB}$ | 5.0 (0.5)$^{bA}$ | 10.8 (1.3)$^{cC}$ |
| AD + UV-C | 3.1 (1.3)$^{aA}$ | 8.9 (2.9)$^{bB}$ | 15.9 (3.5)$^{cB}$ |

Results were expressed as mean (standard deviation).
AD, anti-browning dipping.
For each storage time, means with same uppercase letter were not significantly different ($p < 0.05$). For each treatment, means with same lowercase letter were not significantly different ($p < 0.05$).

tissue than generated during peeling and cutting, which would be translated in an increase in respiration and transpiration rates. Irradiated apple slices previously immersed into the anti-browning solution showed a similar evolution of weight loss to the samples that were only irradiated.

### 3.5. Microscopic observations

Typical ESEM and TEM images of parenchyma apple tissue localized at the irradiated surface (with or without previous anti-browning dipping) at day 0 and day 7 are illustrated in Figs. 6–8. In fresh tissues, cells, more or less regular in shape, appeared turgid with dense cell walls (Fig. 6A). Some intercellular spaces with different shapes and sizes could be seen. With TEM, heterogeneously stained cell walls, in some zones with a clear longitudinal fibrilar pattern (Fig. 7A), and in others with a greater intensity toward the margin and in the central zone of the middle lamella (Fig. 7B), were observed. The arrangement of cytoplasm was marginal, with some invaginations of the cytoplasm membrane (Fig. 7B, arrow). Tonoplast and plasmalemma appeared intact. UV-C irradiation provoked rupture of cellular membranes (Fig. 7D, arrow) but cell walls appeared electronically dense (Fig. 7C and D) and in some areas with a visible middle lamella (Fig. 7C). With ESEM, cells looked more polyhedral and swollen than in the control, with smoothed walls (Fig. 6C). After the anti-browning treatment, tissue arrangement and wall electronic density were observed to be similar to those of the untreated apple (Figs. 6E and 7E, F), although some walls appeared broken probably due to a cutting effect (Fig. 6E, arrow). Cells exhibited intact membranes and in general parietal cytoplasm. Again, further exposure of cells with AD to 20 min UV-C light caused disruption of membranes (Fig. 7G, arrow, and Fig. 7H) and cells looked even more swollen than non-irradiated ones (Fig. 6G).

Tissue and cell structure appeared clearly affected by storage (Figs. 6 and 8). Cell walls in the untreated sample appeared much more stained than in the tissue before storage, with a middle lamella very well defined and thick (Fig. 8A, arrow) or with a tightly fibrillar packing irregularly stained (Fig. 8B). Broken membranes, severe folding of cell walls (Fig. 8C, arrow) and tissue shrinkage were seen in irradiated apple surface (Fig. 6D and H). In non-treated tissues or tissues with only anti-browning dipping, folding was slighter (Fig. 6B and F). This folding pattern put on evidence the important impact on walls caused by the UV-C induced breaking of membranes and the consequent loss of turgor. Cell in treated apples showed undulated wall edges, densely stained walls and a intermixed fibrillar pattern (Fig. 8C–H). Enlargements in walls (as seen in Fig. 8D, arrow) were visualized in all stored cut-apples.

### 3.6. Link between structure, viscoelastic properties and texture perception

Due to the low penetration of UV-C irradiation, changes in viscoelasticity after treatment would be given mainly in surface of irradiated sample. Both viscoelastic tests employed, oscillatory and creep recovery, were sensitive to changes in ultrastructure of tissues exposed to UV-C light (with and without AD) mainly after storage.

It has been suggested that creep model parameters and $G'$ values are associated with some structural components of the fruit tissue, reflecting changes that occur at cellular level (Jackman and Stanley, 1995; Martínez et al., 2005, 2007; Alzamora et al., 2008). Various structural modifications may contribute to disassembly and loosening of primary cell walls and cell turgidity of fruits during processing, affecting creep response and storage modulus: degree of tissue turgidity, cellulose microfibrils slipping through the amorphous matrix of the wall, matrix flow, molecular regrouping of constituents (especially cellulose) or a combination of these (Alzamora et al., 2008). Cellulose (the main component of the cell wall), the turgor pressure exerted by the content of the cell on the wall and the air occluded in the matrix have been suggested as responsible of the elastic behavior of plant tissues and would influence $G'$ values. Cellulose provides individual cells with rigidity and resistance to rupture while the turgor pressure leads to the rigidity of plant cells and tissues, and together with the cell wall, provides the mechanical support for maintaining cell and tissue shape (Carpita and Gibeaut, 1993). On other hand, Jackman and Stanley (1995) proposed an interpretation of a six-element creep mechanical model to analyze the multiple softening mechanisms in tomato pericarp tissue during ripening. This interpretation has been successfully used for explaining cooked potato and osmotically dehydrated melon and apple creep behavior (Alvarez et al., 1998; Martínez et al., 2005, 2007). Instantaneous elastic compliance $J_0$ would be related to the combination of turgor and primary cell wall strength as dictated by cellulose. Viscoelastic compliances $J_1$ and $J_2$ could be attributed to time-dependent changes in pectins and hemicelluloses, respectively. Steady state viscosity could be related to cell wall fluidity arising from exosmosis and/or solubilization and degradation of polymers and less water binding capacity due to treatments.

UV-C light exposure provoked membrane breakage and vacuole burst. As a consequence, turgidity was lost since water contained in the vacuole determined the turgor pressure. But just after treatment, swelling of the cells, probably due to the redistribution of apoplastic liquid and cell contents (salts and organic acids), would compensate for loss of turgor and $G'$ values were not affected or decreased in a small way as compared to fresh fruit (Fig. 1A and B). After storage, the loss of water contributed to greater turgor loss, collapse of walls and intercellular spaces and shrinkage of cells, decreasing rigidity; accordingly, $G'$ values diminished. The increase in the instantaneous compliance $J_0$ of treated samples after 7 day storage (Fig. 2A and B) could be ascribed to structure changes in a similar way than the decrease in $G'$ values, as these parameters are both influenced by the same structure elements.

As a consequence of vacuole rupture induced by UV-C, the interactions between cell walls and cellular contents (organic acids, hydrolytic enzymes, etc.) would be facilitated and could allow cell wall degradation during storage. The change in wall characteristics and the effect of the loss of turgor would be traduced in folding and collapse of cell walls and thus in greater compliances $J_1$ and $J_2$ of irradiated apple samples (Tables 1 and 2).

Regarding $\eta_N$ response, although this creep parameter is usually affected by great standard errors due to biological variability (Alzamora et al., 2008), it can be observed that, after storage, there was a decrease in $\eta_N$ values of irradiated samples (with or without AD) indicating an increase in fluidity of the cell wall matrix. This could be attributed to the greater amount of apoplastic water due to membrane breakage and to solubilization and degradation of pectins and other wall biopolymers. It is not easy to explain the unexpected behavior of $\eta_N$ in UV-C treated apple with previous

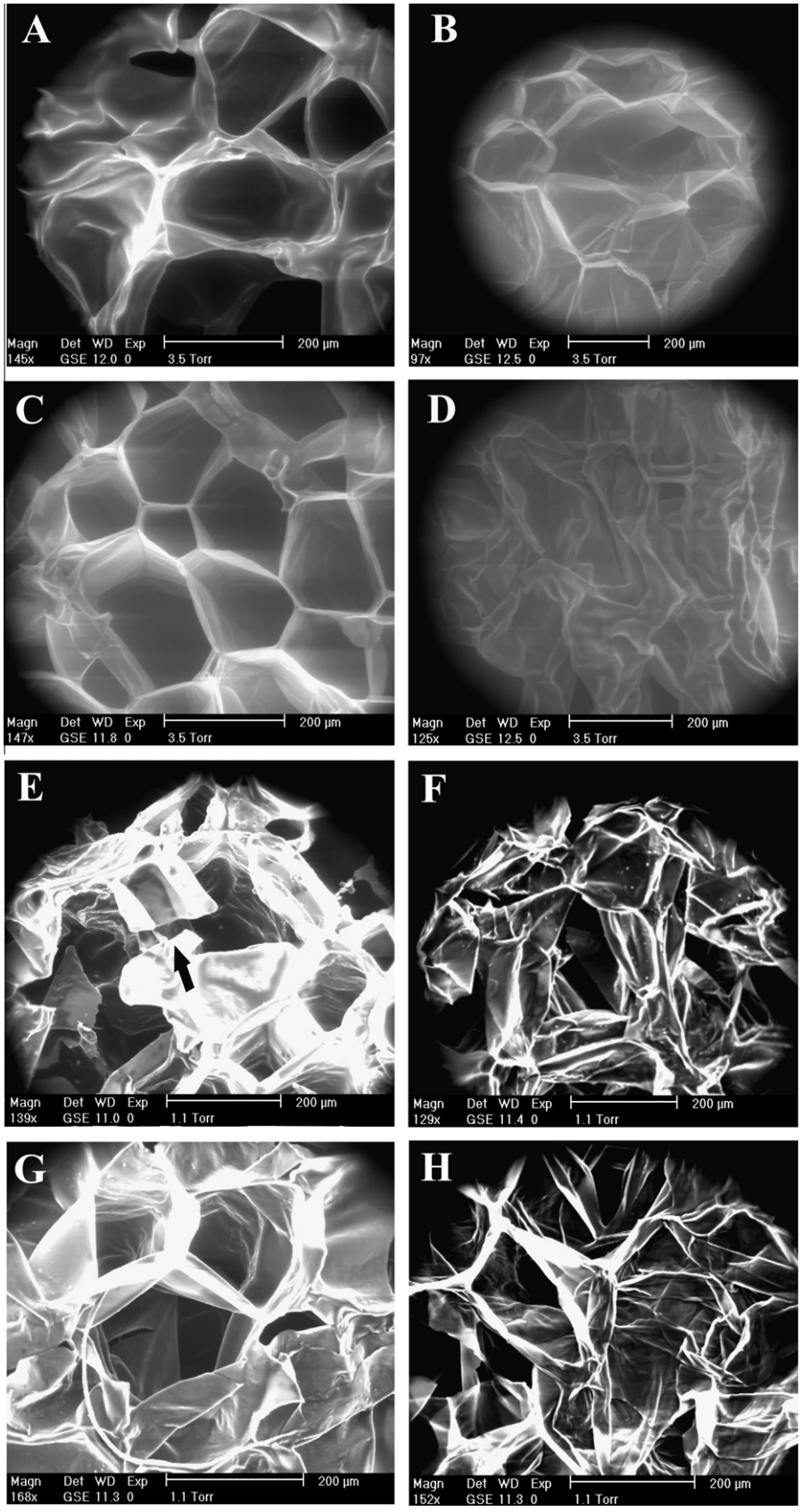


**Fig. 6.** ESEM micrographs from UV-C irradiated surface of apple tissue with and without anti-browning dipping (AD) stored a week at refrigeration. 0 day: (A) raw (control); (C) UV-C irradiated; (E) dipping into AD; (G) dipping into AD and UV-C irradiated. 7 day: (B) control; (D) UV-C irradiated; (F) dipping into AD; (H) dipping into AD and UV-C irradiated.

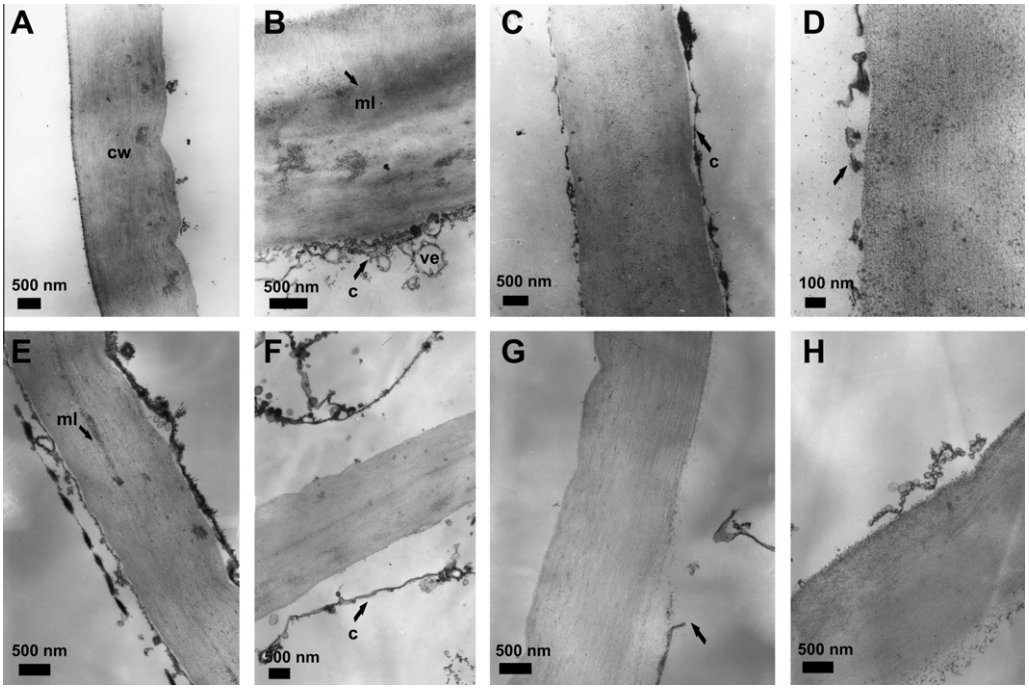


**Fig. 7.** TEM micrographs from UV-C irradiated surface of apple tissue with and without anti-browning dipping (AD) at 0 day of storage. (A and B) raw (control); (C and D) UV-C irradiated; (E and F) dipping into AD; (G and H) dipping into AD and UV-C irradiated. cw, cell wall; c, cytoplasm; ml, middle lamella; ve, vesicle.

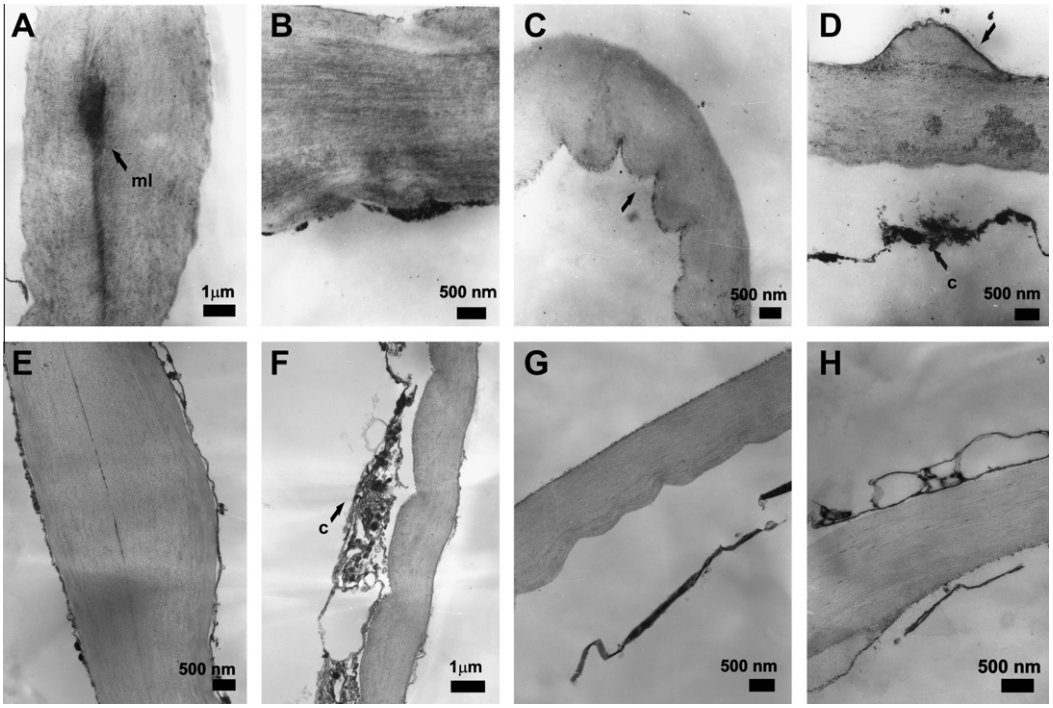


**Fig. 8.** TEM micrographs from UV-C irradiated surface of apple tissue with and without anti-browning dipping (AD) at 7 day of storage. (A and B) raw (control); (C and D) UV-C irradiated; (E and F) dipping into AD; (G and H) dipping into AD and UV-C irradiated. c, cytoplasm; ml, middle lamella.

AD at day 0 (Table 2). The decrease in fluidity would be caused due to the passage of apoplastic water to the inner of the cell to reach osmotic equilibrium; this supposition would be supported by the notorious swelling of irradiated cells observed at day 0.

Sensory juiciness is a multidimensional perception that includes: force with which the juice squirts out, total amount of juice released on chewing, flow properties of the pressed liquid and the consistency contrast between liquid and suspended cell debris (Szczesniak and Ilker, 1988). Prerequisites to juiciness include not only high water content but organized cellular network with proper turgor and integrity, low viscosity and little suspended solids in the expressed liquid and cell walls mechanically weaker than the middle lamella. In the view of the panel, the sample with the lowest juiciness was the untreated apple stored 5 days, while the first,

second and third samples most juicy were the raw apple and the stored apple samples subjected to AD and to AD + UV-C, respectively. The differences in juiciness found by the panel were insignificant in these three last samples, though discernable, and an inverse relationship was presented between sensory hardness and juiciness. The panelists ranked juiciness item in order of their water content excepting in the case of untreated apple, which exhibited the lowest PP (8.3%) but the lowest juiciness. This unexpected response could be explained if fracture would occur as a result of cell to cell debonding instead of cell wall breaking. Individual cells would not break open and release their contents. Microscopic observations confirmed that untreated stored apple samples presented reinforced cell walls and middle lamella but did not allow discerning if cell walls were mechanically stronger than the middle lamella or vice verse.

On the other hand, stored untreated apple had two dominant sensory texture characteristics: hardness and fracturability (Fig. 5). This fact was in agreement with the greatest staining of cell walls and middle lamella exhibited by this sample (Fig. 8A and B).

## 4. Conclusions

Major changes in structural features and viscoelastic parameters due to UV-C radiation with or without previous anti-browning dipping were mainly evidenced after storage. Overall, both dynamic moduli decreased, and instantaneous compliance ($J_0$), decay compliances ($J_1$ and $J_2$) and fluidity significantly increased after treatments and storage at 5 °C.

Instrumental fracture properties proved to be the most highly correlated with sensory texture. The test panel only significantly differentiated stored untreated apple from the other samples regarding fracturability and juiciness. This would indicate that apple perceived texture would not be affected by anti-browning dipping and UV-C irradiation.

Viscoelastic parameters showed ability to evidence ultrastructural differences (rupture of membranes, swelling of cells, alteration of cell walls) in the surface of cut apples subjected to the different treatments. More research is needed to explain the structure effect on juiciness.

## Acknowledgements

The authors acknowledge the financial support from University of Buenos Aires, National University of Comahue, CONICET, Agencia Nacional de Promoción Científica y Tecnológica of Argentina and BID.

## References

Alvarez, M.D., Canet, W., Cuesta, F., Lamua, M., 1998. Viscoelastic characterization of solids foods from creep compliance data: application to potato tissues. Zeitschrift für Lebensmittel-Untersuchung und -Forschung A 207, 356–362.

Alzamora, S.M., Castro, M.A., Nieto, A.B., Vidales, S.L., Salvatori, D.M., 2000. The role of tissue microstructure in the textural characteristics of minimally processed fruits. In: Alzamora, S.M., Tapia, M.S., López-Malo, A. (Eds.), Minimally Processed Fruits and Vegetables. Aspen Publishers Inc., Maryland, pp. 153–171.

Alzamora, S.M., Viollaz, P.E., Martínez, V.Y., Nieto, A.B., Salvatori, D.M., 2008. Exploring the linear viscoelastic properties structure relationship in processed fruit tissues. In: Gutiérrez-López, G.E., Barbosa-Cánovas, G.V., Welti-Chanes, J., Parada-Arias, E. (Eds.), Food Engineering: Integrated Approaches. Springer, New York, pp. 133–214.

Bintsis, T., Litopoulou-Tzanetaki, E., Robinson, R., 2000. Existing and potential applications of ultraviolet light in the food industry. A critical review. Journal of the Science of Food and Agriculture 80, 1–9.

Bourne, M.C., 1978. Texture profile analysis. Food Technology 32 (7), 62–66.

Bourne, M.C., Comstock, S.H., 1981. Effect of degree of compression on texture profile parameters. Journal of Texture Studies 12, 201–216.

Carpita, N.C., Gibeaut, D.M., 1993. Structural models of primary cell walls in flowering plants: consistency of molecular structure with the physical properties of the walls during growth. The Plant Journal 3, 1–30.

Chauvin, M.A., Younce, F., Ross, C., Swanson, B., 2008. Standard scales for crispness, crackliness and crunchiness in dry and wet foods: relationship with acoustical determinations. Journal of Texture Studies 39, 345–368.

Civille, G.V., Szczesniak, A.S., 1973. Guidelines to training a texture profile panel. Journal of Texture Studies 4, 204–223.

Erkan, M., Wang, C.Y., Krizek, D.T., 2001. UV-C irradiation reduces microbial populations and deterioration in Cucurbita pepo fruit tissue. Environmental and Experimental Botany 45, 1–9.

Garcia, E., Barrett, D.M., 2005. Fresh-cut fruits. In: Barrett, D.M., Somogyi, L., Ramaswamy, H. (Eds.), Processing Fruits. Science and Technology, second ed. CRC Press, New York, pp. 53–72.

Gil, M.I., Selma, M.V., López-Gálvez, A.A., 2009. Fresh-cut product sanitation and wash water disinfection: problems and solutions. International Journal of Food Microbiology 134, 37–45.

Gómez, P., Alzamora, S.M., Castro, M.A., Salvatori, D.M., 2010. Effect of ultraviolet-C light dose on quality of cut-apple: microorganism, color and compression behavior. Journal of Food Engineering 98, 60–70.

Guerrero-Beltrán, J.A., Barbosa-Cánovas, G.V., 2004. Review: advantages and limitations on processing foods by UV light. Food Science and Technology International 10, 137–147.

Hough, G., Contarini, A., Muñoz, A., 1994. Training a texture profile panel and constructing standard rating scales in Argentina. Journal of Texture Studies 25, 45–57.

Jackman, R.L., Stanley, D.W., 1995. Creep behaviour of tomato pericarp tissue as influenced by ambient temperature ripening and chilled storage. Journal of Texture Studies 26, 537–552.

Khan, S.A., Roger, J.R., Raghavan, S.R., 1997. Rheology: tools and methods. In: Proceedings of the National Academy of Sciences. Aviation Fuels with Improved Fire Safety, Washington, DC, pp. 39–46.

Martínez, V.Y., Nieto, A.B., Viollaz, P.E., Alzamora, S.M., 2005. Viscoelastic behaviour of melon tissue as influenced by blanching and osmotic dehydration. Journal of Food Science 70, 12–18.

Martínez, V.Y., Nieto, A.B., Castro, M.A., Alzamora, S.M., 2007. Viscoelastic characteristics of Granny Smith apple during glucose osmotic dehydration. Journal of Food Engineering 83, 394–403.

Meilgaard, M., Civille, G.V., Carr, B.T., 1999. Sensory Evaluation Techniques, third ed. CRC Press, Florida.

Mittal, J.P., Mohsenin, N.N., 1987. Rheological characterization of apple cortex. Journal of Texture Studies 18, 65–93.

Peleg, M., 2006. On fundamental issues in texture evaluation and texturization – a view. Food Hydrocolloids 20, 405–414.

Pitt, R.E., 1992. Viscoelastic properties of fruits and vegetables. In: Rao, M.A., Steffe, J.F. (Eds.), Viscoelastic Properties of Foods. Elsevier Applied Science, London and New York, pp. 3–47.

Ponting, J.D., Jackson, R., Watters, G., 1972. Refrigerated apple slices: preservative effects of ascorbic acid, calcium and sulfites. Journal of Food Science 37, 434–436.

Rahn, R.O., 1997. Potassium iodide as a chemical actinometer for 254 nm radiation: use of iodate as an electron scavenger. Photochemistry and Photobiology 66, 450–455.

Shama, G., 2006. Ultraviolet light. In: Hui, Y.H. (Ed.), Handbook of Food Science, Technology and Engineering, vol. 3. CRC/Taylor & Francis, Boca Raton, Florida, pp. 12201–12214.

Shama, G., Alderson, P., 2005. UV hormesis in fruits: a concept ripe for commercialisation. Trends in Food Science and Technology 16, 128–136.

Schenk, M., Raffellini, S., Guerrero, S., Blanco, G., Alzamora, S.M., 2011. Inactivation of *Escherichia coli*, *Listeria innocua* and *Saccharomyces cerevisiae* by UV-C light: study of cell injury by flow cytometry. LWT – Food Science and Technology 44, 191–198.

Sherman, P., 1970. Industrial Rheology. Academic Press, New York.

Szczesniak, A.S., Brandt, M.A., Friedman, H.H., 1963. Development of standard ratings scales for mechanical parameters and correlation between the objective and sensory methods of texture evaluation. Journal of Food Science 28, 397–403.

Szczesniak, A.S., Ilker, R., 1988. The meaning of texture characteristics – juiciness in plant foodstuffs. Journal of Texture Studies 19, 66–78.

Toivonen, P.M.A., Deell, J.R., 2002. Physiology of fresh-cut fruits and vegetables. In: Lamikanra, G. (Ed.), Fresh-cut Fruits and Vegetables. Science Technology and Market. CRC Press, Boca Raton, Florida, pp. 91–123.

Waldron, K.W., Smith, A.C., Parr, A.J., Ng, A., Parker, M.L., 1997. New approaches to understanding and controlling cell separation in relation to fruit and vegetable texture. Trends in Food Science and Technology 8, 213–221.

Wu, J., Guo, K.G., 2010. Dynamic viscoelastic behavior and microstructural changes of Korla pear (*Pyrus bretschneideri rehd*) under varying turgor levels. Biosystems Engineering. doi:10.1016/j.biosystemseng.2010.05.014.

Zar, J.H., 1999. Biostatistical Analysis, fourth ed. Prentice Hall, New Jersey.