Innovative Food Science and Emerging Technologies xxx (2012) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Innovative Food Science and Emerging Technologies

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

Effect of pulsed light combined with an antibrowning pretreatment on quality of fresh cut apple

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

[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
[c] Consejo Nacional de Investigaciones Científicas y Técnicas de la República, Argentina

ARTICLE INFO

Article history:
Received 23 January 2012
Accepted 2 May 2012
Available online xxxx

Keywords:
Pulsed light
Antibrowning treatment
Cut apple
Native flora
Color
Texture
Rheology

ABSTRACT

The aim of this study was to evaluate the effect of pulsed light (PL) combined with an anti-browning dipping (AD) (ascorbic acid plus $CaCl_2$ solution) and refrigerated storage on native microflora survival, color, rheological properties (oscillatory shear, creep/recovery and double-compression tests), texture, micro and ultrastructure of cut apple. The anti-browning dipping was effective in inhibiting browning on apple surface exposed up to a PL dose of 71.6 J/cm^2. Native microflora counts in stored samples treated with AD + PL were lower than in non-treated apples. Changes in rheological properties due to treatments and/or storage were detected. They were mainly associated with a decrease in G′ and G″ and an increase in compliances J_0, J_1 and J_2 and modifications of TPA parameters. The assessors only evidenced a slight decrease in juiciness and crispness in stored and/or AD + PL treated apples. Changes in rheological properties and texture were partially correlated with structure features.

Industrial relevance: During the last few decades, research on food preservation has focused on meeting consumer demands for more natural and healthier food, with the interest moving from conventional thermal treatments toward "non-thermal" preservation techniques. Pulsed light is an emerging preservation factor that is being studied as an alternative process to decontaminate foods. This study contributes to evaluate the feasibility of pulsed light treatment to extend the shelf life of cut apple.

1. Introduction

During the last decades, research on food preservation has focused on meeting consumer demands for more natural and healthier food, with the interest moving from conventional thermal treatments toward "non-thermal" preservation techniques. Pulsed light (PL) is one of the emerging preservation factors that are being studied as a feasible alternative to conventional processes. It involves the use of intense and short-duration (1 μs–0.1 s) pulses of broad spectrum light of wavelength ranging from UV to near-infrared (200–1100 nm). Power is magnified by storing electricity in a capacitor over relatively long times (fractions of a second) and releasing it in a short time (millionths of thousandths of a second) (Gómez-López, Ragaert, Debevere, & Devlieghere, 2007). Its use has been approved by the FDA (1996) for the decontamination of food and food surfaces. The significant microbial reduction in very short treatments time, the limited energy cost, the low environmental impact and its great flexibility are some of the major benefits claimed for this technique (Oms-Oliu, Martín-Belloso, & Soliva-Fortuny, 2010).

PL technology is of limited efficacy for the in-depth treatment of opaque substrates due to absorption and scattering of light, and therefore is only suitable to control surface microflora (Woodling & Moraru, 2005). Various studies have demonstrated the positive effect of pulsed light on inactivation of microbial populations on food surfaces. Reductions in counts of *Escherichia coli* O157:H7 on alfalfa seeds (Sharma & Demirci, 2003), *Aspergillus niger* spores on corn meal (Jun, Irudayaraj, Demirci, & Gêiser, 2003), *Listeria monocytogenes* and *E. coli* O157:H7 on raw salmon fillets (Ozer & Demirci, 2006), *Salmonella enterica* and *E. coli* O157:H7 on raspberries and strawberries (Bialka, Demirci, & Puri, 2008) and *L. monocytogenes* on infant foods (Choi, Cheigh, Jeong, Shin, & Chung, 2010) have been reported, indicating this technology could be a powerful nonchemical (residue-free) option for decontaminating foods.

While the efficacy of pulsed light in term of inactivation of many microorganisms is well documented, its influence on other quality attributes (color, texture, taste, and aroma) during storage has not been well assessed. Recently, Gómez, Salvatori, García Loredo, and Alzamora (in press) examined the dose effect of PL irradiation on surface color, microstructure, and microbial stability of cut-apples stored under refrigeration. An increase in surface browning was observed

* Corresponding author at: Departamento de Industrias, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Ciudad Universitaria, 1428 Ciudad Autónoma de Buenos Aires, Argentina. Tel./fax: +54 11 45763495.
E-mail addresses: alzamora@di.fcen.uba.ar, smalzamora@gmail.com (S.M. Alzamora).
[1] Both authors share the first place.

1466-8564/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ifset.2012.05.011

when increasing PL doses were applied. Light microscopy observations indicated that the modifications on color of treated 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. But increases in temperature during PL irradiation at high doses could also cause non enzymatic browning. Oms-Oliu, Aguiló-Aguayo, Martín-Belloso, and Soliva-Fortuny (2010) reported an increase in browning of fresh-cut mushrooms promoted by an increase in polyphenol oxidase activity when a high dose of pulsed light was applied. Gómez-López, Devlieghere, Bonduelle, and Debevere (2005) also observed the development of browning in PL irradiated minimally processed lettuce. They recommended the application of antibrowning agents before PL flashing in order to avoid that this defect limits the shelf-life of the product.

The purpose of the present work was to evaluate the effect of pulsed light combined with an anti-browning pretreatment and refrigerated storage on some quality characteristics of fresh-cut apples. Native flora evolution as well as differences in surface color, linear viscoelastic (as derived from dynamic oscillatory and creep/recovery tests) and texture profile analysis (TPA) behavior, and sensory texture (evaluated by a trained panel) were investigated. Results of rheological techniques were compared with those obtained with the trained texture panel. It was also explored how differences in apple tissue structure (optical and transmission electronic microscopy observations) were expressed by macroscopic rheological and sensory parameters.

2. Materials and methods

2.1. Sample preparation

Raw apples (*Malus pumila*, Granny Smith var.; $a_w \cong 0.98$; 11.1–13.2 °Brix, pH 3.2–3.5) 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 with a cork borer to obtain 0.03 m in diameter and 0.006 m in thickness discs. 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 moisture loss.

2.2. Pulsed equipment and dosimetry

PL treatments were performed with a RS-3000B Steripulse-XL system (Xenon Corporation, Woburn, MA, USA), which produced polychromatic radiation in the wavelength range of 200 to 1100 nm. The system consisted of a RC-747 power/control module, a treatment chamber that houses a xenon flash lamp (non toxic, mercury free) and an air cooling system attached to the lamp housing to avoid lamp overheating during operation. The system generated high intensity pulsed light at a pulse rate of 3 pulses per second and a pulse width of 360 μs. According to the specifications supplied by the manufacturer, each pulse delivered 1.27 J/cm^2 for an input of 3800 V at 1.9 cm from the quartz window surface of the lamp. The fluence (light dose) was modified by altering the number of applied pulses. Fluence measurements were taken by a pyroelectric head model ED500 (Gentec Electro-Optics, Québec, Canada) connected to an oscilloscope model TDS 2014 (Tektronix, Beaverton, USA), with an aperture cover of 20.3 cm^2. Measurements were performed in triplicate.

2.3. Treatments

Prior to irradiation, some apple discs were subjected to an antibrowning dipping (AD) by immersion into an aqueous solution 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 (AD apple) (Ponting, Jackson, & Watters, 1972).

For irradiation, apple discs with (AD + PL apple) and without previous immersion into the antibrowning solution (PL apple) were put below the lamp and around the central point on an stainless steel shelf in the PL unit and exposed to light pulses for 2, 10, 20, 60 and 100 s at 10 cm distance from the quartz window of the xenon lamp. This sample location allowed minimized variations in PL dose according to fluence measurements.

The corresponding doses applied were 2.4, 11.9, 23.9, 71.6 and 119.4 J/cm^2. Color evaluation was performed after 2, 10, 20, 60 and 100 s irradiation, while for the other attributes assayed, apple discs were exposed to irradiation during 60 s. Treated and untreated or control samples (C apple) were then packed in closed plastic boxes permeable to air and stored in the dark at 5 °C (±1 °C).

Concomitant with fluence increase, the temperature of apple surface gradually increased with the number of flashes from 19 °C to 32 °C, 49 °C and 60 °C after 20 s, 60 s and 100 s of irradiation respectively (Gómez et al., in press).

2.4. Color measurement

Surface color of control and treated cut apples was measured at 0, 3 and 7 days of storage with a handheld tristimulus reflectance spectrocolorimeter (Minolta Co. Model CM-508-d, Japan) by using a 1.4 cm measuring aperture and a white background. The CIE color coordinates (X, Y, Z) were obtained for C illuminant and 2° observer. These numerical values were converted into "Browning Index" (BI), using the following equations:

$$BI = [100(x-0.31)]/0.172 \quad (1)$$

where:

$$x = X/(X + Y + Z). \quad (2)$$

Ten independent samples were measured for each condition and five readings were taken at different positions on the sample surface. To minimize biological variability between fruits, values were expressed as differences with respect to the corresponding average value for the fresh fruit just before undergoing irradiation.

2.5. Analysis of rheological properties

2.5.1. Texture profile analysis

An Instron Universal Testing Machine model 3345 (Canton, Massachusetts, USA), with a 5000 N-load cell interfaced with a series data acquisition software (Bluehill 2, v. 2.17, Instron, USA) was used to conduct the texture profile analysis (TPA). Tests were performed with a crosshead speed of 0.001 m/s and a 0.035 m diameter cylindrical probe. A two cycle compression was set to 70% deformation. The TPA parameters (fracturability (N), hardness (N), hardness 2 (N), area 1 (J), area 2 (J), cohesiveness, adhesiveness (J), springiness, gumminess (N), and chewiness (N)) were obtained from the force-time curves, according to the definitions of Bourne (1978). The deformability modulus (E_d) was calculated from the initial linear portion of the first compression using Eqs. (3)–(5) (Calzada & Peleg, 1978):

$$E_d = \sigma_R/\varepsilon_R \quad (3)$$

Please cite this article as: Gómez, P.L., et al., Effect of pulsed light combined with an antibrowning pretreatment on quality of fresh cut apple, *Innovative Food Science and Emerging Technologies* (2012), doi:10.1016/j.ifset.2012.05.011

$$\sigma_R = F(t)[(H_0 - \Delta H)/A_0 H_0] \quad (4)$$

$$\varepsilon_R = \ln[H_0/(H_0 - \Delta H)] \quad (5)$$

where F(t): compression force at time t; H_o: height of the sample before compression; ΔH: difference of the height of the sample before compression and during compression; A_o: cross-sectional area of the cylinder before compression. The test was replicated a minimum of 20 times and mean values for each parameter were calculated.

2.5.2. Viscoelastic properties

Viscoelastic properties were analyzed at 25 °C in a Paar Physica MCR 300 rheometer (Antor Paar GMBH, Graz, Austria) using a 0.030 m 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 (ω) of 10 s^{-1} to determine the linear viscoelastic range (LVR) with the Paar Physica US 200 software package (Anton Paar GmbhH, 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′) vs. log (ω):

$$\log(G') = n\log(\omega) + k \quad (6)$$

where n is the slope of the regression and k is log(G′) value at 1 s^{-1} of angular frequency.

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 Pa 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 & 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):

$$J(t,\tau) = (J_0) + \sum_{i=1}^{2}(J_i)\left(1 - e^{-t/\lambda_i}\right) + t/\eta_N \quad (7)$$

where J (t, τ) is the creep compliance (= γ(t)/τ with γ(t) being the strain at the time *t* and τ the constant stress applied). J_0 is the instantaneous compliance at t = 0; J_i are the retarded compliances; λ_i (= $\eta_i \times J_i$) are the retardation times and η_i are the coefficients of viscosity associated with the Kelvin–Voigt elements; η_N is the coefficient of viscosity associated with Newtonian flow and its inverse the steady-state fluidity of the material. In this model, the rheological behavior of apple tissue is 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/η_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 Origin v.7.0 software (OriginLab Corporation, Northampton, USA) was employed for nonlinear 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.

2.6. Sensory descriptive analysis

Nine panelists (three males, six females), all between the ages of 21–38, composed the sensory panel. The panelists were trained with the texture profile method following the procedures described by Civille and Szczesniak (1973) during 35–40 h (2 h/week) to recognize texture attributes of hardness (HS), fracturability (FS), juiciness and crispness. The scales used to train the panel were the same appointed by Garcia Loredo, Guerrero, Gómez, and Alzamora (in press).

Samples (tempered at room temperature for around 30 min) were individually presented to the panelists in glasses of white plastic identified by numbers of 3 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 panelists's palates. As differences in sample color could influence texture perception by the panelists (Gómez et al., in press; Meilgaard, Civille, & Carr, 1999), sensory evaluation was performed only in irradiated samples with previous dipping into the antibrowning 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 day 5, when the changes in color were not relevant. The descriptive analysis was replicated two times.

2.7. Microscopic observations

For light microscopy (LM) 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. Sections (1–2 μm thick) of the Spurr-embedded tissue were cut on a Sorvall MT2- B Ultracut microtome and stained with toluidine blue (1 g/100 g) and basic fuchsin (1 g/100 g) solutions. Samples were then examined in a Zeiss AxiosKop 2 microscope (Carl Zeiss AG, Jena, Germany). For transmission electron microscopy (TEM), samples embedded in Spurr resin were cut in ultrathin sections (1 μm thick) using a glass knife with a the 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).

2.8. Microbiological analysis

The effect of PL and the antibrowning pretreatment on native flora of apple discs was evaluated. Apples discs were obtained as described in Section 2.1 but sample processing was not performed in sterile conditions in order to increase the initial level of native flora. Apple discs (with and without antibrowning dipping) were exposed to irradiation on both sides during 60 s at 10 cm from the lamp, stored in plastic boxes at 4–5 °C in the dark and analyzed at 0 and 7 day storage. For enumeration, samples were put into stomacher bags (Whirl-Pak, Nasco, USA) containing 20 mL of sterile peptone water and were pummeled in a Laboratory blender (AES Laboratories, France) at high speed for 3 min. Tenfold dilutions of homogenates were made in 0.1% w/v peptone water, and 0.1 mL sample suspension was surface plated using Plate Count Agar (PCA, Britania S.A, Argentina) for aerobic

Please cite this article as: Gómez, P.L., et al., Effect of pulsed light combined with an antibrowning pretreatment on quality of fresh cut apple, *Innovative Food Science and Emerging Technologies* (2012), doi:10.1016/j.ifset.2012.05.011

microorganisms count and Yeast Glucose Chloramphenicol Agar (YGC, Britania S.A., Argentina) for mold and yeast count. Plates were incubated for 72 h at 37 °C ± 1 °C (PCA) for bacteria or 27 °C ± 1 °C (YGC) for molds and yeasts. Three replicates were examined for each condition and experiments were made in duplicate. Results were expressed as N (where N is the number of CFU/g).

2.9. Weight loss measurement

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. (8):

$$PP(\%) = 100 \times (p_t - p_0)/p_0 \quad (8)$$

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

2.10. Statistical analysis

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) was performed on microbiological results according to the factors "treatment" and "time". A two-way ANOVA with repeated measures was performed on Browning Index and weight loss values. Sensory data were analyzed by a two-way ANOVA according to the factors "assessor" and "treatment". In case of significant interactions between factors, single effects were examined (i.e. effects of one factor holding the other fixed). Significant level was set at $p<0.05$ and multiple comparisons were performed using the Tukey test.

Multivariate analysis of variance (MANOVA) was used to analyze rheological data. Significance level was set at $\alpha<0.05$. Hotelling corrected for Bonferroni test was performed in case of finding significant differences. Principal analysis component (PCA) of mean ratings for each attribute was used to illustrate the relationship among variables and samples.

Linear Partial Least Squares Regression Analysis (PLS) was used to analyze the relationships between sensory and rheological properties matrices, using the GenStat statistical language (GenStat discovery edition 3, Oxford, UK). Both sensory and instrumental variables were standardized previously to the PLS analysis.

3. Results and discussion

3.1. Brown Index

In a previous study, Gómez et al. (in press) found that exposure of cut apples to PL increased surface browning throughout storage as compared with non irradiated apples. The authors also showed that Browning Index function (BI) was a good indicator of browning development and reported BI values (expressed as difference with the BI value for fresh apple discs, $BI–BI_0$) after 7 days of refrigerated storage equal to 14.1 (± 5.8), 7.2 (± 3.6), 18.0 (± 4.6), 24.7 (± 7.7) and 29.8 (± 5.3) for untreated apples and apples exposed to PL at 10 cm from the xenon lamp during 2, 20, 60 and 100 s respectively. The evolution of BI during storage in apple samples irradiated at different PL doses but previously treated with the antibrowning solution analyzed in the present work can be observed in Table 1. A significant interaction between treatment and storage time was found ($F_{10,\ 108} = 9.26$; $p<0.001$). $BI–BI_0$ values of non irradiated cut-apples (with and without AD) increased during storage, but variations were greater in apples without antibrowning pretreatment. In samples treated with AD and exposed to PL, only those irradiated at the highest fluence (100 s) showed a significant difference in $BI–BI_0$ values as compared with fresh sample ($p<0.05$) just after irradiation. This fact could be attributed not only to the huge energy exposure but to the high temperature reached by the apple samples (60 °C). During storage, $BI–BI_0$ values of samples exposed to PL during 2, 20 and 60 s did not change significantly ($p>0.05$). Apples exposed to PL during 100 s showed BI variations similar to control samples (without AD) after 7 day storage. These results demonstrated the effectiveness of ascorbic acid/calcium chloride solution to minimize browning on PL irradiated apple surfaces. In subsequent analysis apples were irradiated during 60 s (71.6 J/cm^2), the maximum fluence tested where browning development was negligible. The large standard deviations associated with BI values could be attributed to the non uniform color within each irradiated apple disc and the variability in the response of different samples.

Table 1
Effect of antibrowning and pulsed light treatments at different PL doses on Browning Index difference ($BI–BI_0$) of cut apple discs during storage at 5 °C.

Treatment	$BI–BI_0$		
	Storage time (day)		
	0	3	7
0 (fresh)	0^{aA}	0.2 ± 2.4^{aA}	7.3 ± 2.9^{bA}
AD	0^{aA}	4.4 ± 3.1^{bB}	2.7 ± 1.6^{bB}
AD + 2 s PL	0.8 ± 1.7^{aA}	1.7 ± 2.6^{aC}	2.1 ± 2.1^{aB}
AD + 20 s PL	0.9 ± 1.3^{aA}	0.9 ± 2.3^{aA}	2.2 ± 2.1^{aB}
AD + 60 s PL	0.6 ± 3.4^{aA}	2.1 ± 2.2^{aC}	2.7 ± 3.6^{aB}
AD + 100 s PL	4.4 ± 1.9^{aB}	$6.2 \pm 2.3^{a,bD}$	6.4 ± 3.8^{bA}

AD: antibrowning dipping. PL: pulsed light.
Results were expressed as mean ± standard deviation.
For each storage time, means at different irradiation times followed by same uppercase letter were not significantly different at $p<0.05$. For each irradiation time, means at different storage time followed by same lowercase letter were not significantly different at $p<0.05$.

3.2. Native flora

Table 2 shows the survival of native flora during refrigerated storage in apples exposed to PL with and without previous antibrowning dipping. The interaction between the factors treatment and storage time was significant ($F_{2,\ 11} = 284.2$ for aerobic mesophilic; $F_{2,\ 11} = 339.5$ for molds and yeast). The irradiation of apples immersed or not in the antibrowning solution provoked a significant reduction ($p<0.001$) in the initial counts of native flora (~0.8–0.9 log cycles). After 7 day storage, aerobic mesophilic population increased in untreated samples to about 3.2 log cycles, while the proliferation of yeast and molds was about 3.3 log cycle. Stored samples treated with AD + PL showed greater population levels than apples only irradiated (2.3 vs 1.6 log cycles for

Table 2
Effect of 60 s PL irradiation on native flora of cut-apple discs with (AD + PL) and without antibrowning pretreatment (PL) after storage at 5 °C in the dark.

N (CFU/g)				
Microorganism	Storage time (day)	Control	PL	AD + PL
Aerobic mesophilic	0	89 ± 19^{aA}	15 ± 4^{aB}	12 ± 3^{aB}
	7	1456 ± 119^{bA}	41 ± 12^{bB}	184 ± 6^{bC}
Molds and yeasts	0	147 ± 20^{aA}	14 ± 3^{aB}	18 ± 8^{aB}
	7	2144 ± 155^{bA}	97 ± 18^{bB}	402 ± 17^{bC}

Results were expressed as mean ± standard deviation. AD: antibrowning dipping. PL: pulsed light.
For each type of microorganism and storage time, means followed by same uppercase letter were not significantly different at $p<0.05$. For each type of microorganism and treatment, means followed by same lowercase letter were not significantly different at $p<0.05$.

Please cite this article as: Gómez, P.L., et al., Effect of pulsed light combined with an antibrowning pretreatment on quality of fresh cut apple, *Innovative Food Science and Emerging Technologies* (2012), doi:10.1016/j.ifset.2012.05.011

aerobic mesophilic and 2.6 vs 2.0 log cycles for molds and yeasts respectively). The greater microbial growth observed in these samples could be due to the important tissue structure damage (as it will shown later in Fig. 5H) and/or the antioxidant capacity of ascorbic acid that could in part diminish the damage caused by PL on microorganisms. A similar protective effect of the antibrowning solution was also reported by Gómez, Alzamora, Castro, and Salvatori (2010) in cut apples irradiated with continuous UV-C light. In spite of this, microbial populations in AD + PL treated apples remained lower than in control samples (~0.9 and 0.7 log cycles in aerobic mesophilic and in yeast respectively) at the end of the storage period. According to these results, PL treatment would increase the shelf-life of cut apple discs mainly due to the reduction in the initial microbial load. It is to be noticed that temperature gradually rose with irradiation time but only for few seconds the samples were exposed to temperatures higher than 40 °C until reaching 49 °C at the end of the treatment (Gómez et al., in press). Thus the effect of 60 s PL treatment on microorganisms' inactivation would be mainly provoked by the irradiation per se.

3.3. Viscoelastic properties

3.3.1. Dynamic spectra

Fig. 1 shows the average dynamic mechanical spectra of apple discs exposed to AD and/or PL with and without previous dipping into the antibrowning solution. G′ was much higher than G″ at any given frequency, indicative of clearly dominant solid characteristics (tan $\delta \approx 0.11$–0.19). The solid-like character was also evidenced in the slight linear increase in G′ values with increasing angular frequency, demonstrating a behavior similar to a flocculated gel with a three-dimensional network structure for untreated and treated apple tissues. The frequency dependence of G″ consisted of one small negative slope at low frequencies and a positive slope at high frequencies. The observed pattern of dynamic spectra was in agreement with those previously reported for apple (Martínez, Nieto, Castro, & Alzamora, 2007), potato (Alvarez & Canet, 1998), melon (Martínez, Nieto, Viollaz, & Alzamora, 2005) and Korla pear (Wu & Guo, 2010).

Significant differences were found in the parameters of the linear regression represented by Eq. (6) among different samples (MANOVA, $F_{6,144} = 12.4$; $p < 0.0001$). Just after treatments (day 0), treated apple discs showed a decrease in G′ values and, curiously, a slighter dependence with frequency (n values were 0.06; 0.030; 0.04 and 0.04 for C, AD, PL, and AD + PL samples respectively) as compared with fresh tissues. This "more solid" behavior of just treated apples was also confirmed by lower values of tan δ (data not shown). The decline in G′ of AD samples was about 20–28% depending on the angular frequency, while in PL apples (with and without AD) the reduction was about 40–57%. After storage, treated samples showed a slight increase in n, while in untreated apples this parameter slightly decreased (n values were 0.040; 0.050; 0.050 and 0.060 for C, AD, PL, and AD + PL samples respectively). Storage modulus at 1 s^{-1} of angular frequency (i.e. k value) declined in all apple samples due to storage. However, G′ values in irradiated tissues remained lower than in the untreated apples and in samples treated only with AD. G′ spectrum showed significant differences ($p < 0.05$) between fresh and treated samples but there were not significant differences between PL and AD + PL apples and between AD and AD + PL apples at day 0 and between PL and AD + PL samples and between C and AD samples at day 7. The decrease in the level of elastic modulus G′ might be correlated to a loss of rigidity in the network and consequently, apples softened due to treatments and/or storage. A similar pattern was exhibited by the loss modulus, indicating that apple tissues became less viscous.

3.3.2. Creep-recovery curves

Average creep-recovery curves for treated and untreated apple discs at 0 and 7 days of storage are presented in Fig. 2. Just after treatments, treated samples showed only minor changes in the deformation at the end of the creep phase as compared with fresh fruit. However, at the end of storage, the modifications in the creep/recovery pattern were notable for irradiated samples, with or without antibrowning pretreatment. For the time scale of the experiments, the creep response

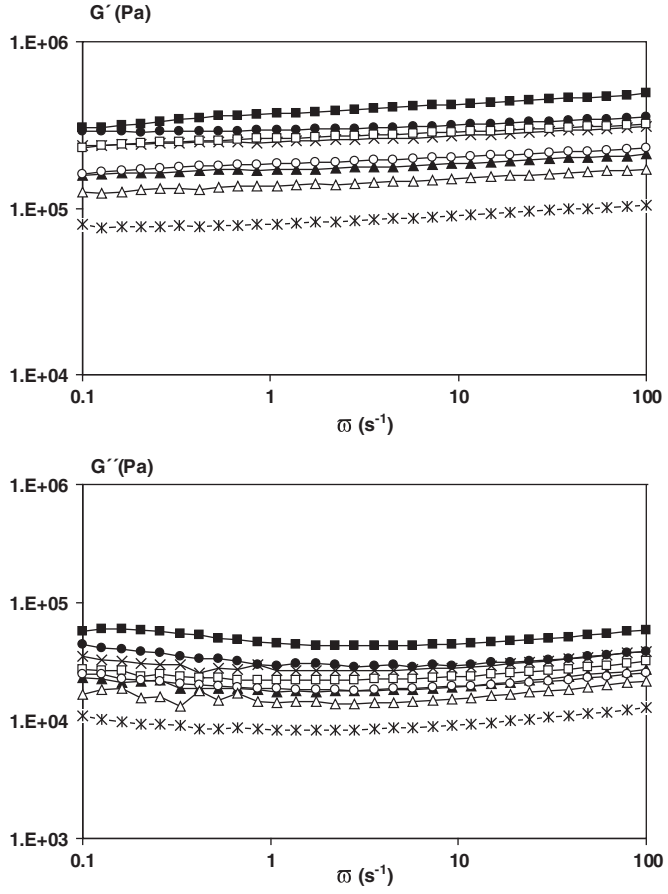

Fig. 1. Variation of storage modulus (G′) and loss modulus (G″) with frequency for apple tissue dipped into the antibrowning solution (AD) and/or irradiated 60 s with pulsed light (PL) and stored 7 days at 5 °C. Day 0: (■) Control, (●) AD apple, (▲) PL apple, (x) AD + PL apple. Day 7: (□) Control, (○) AD apple, (Δ) PL apple, (*) AD + PL apple.

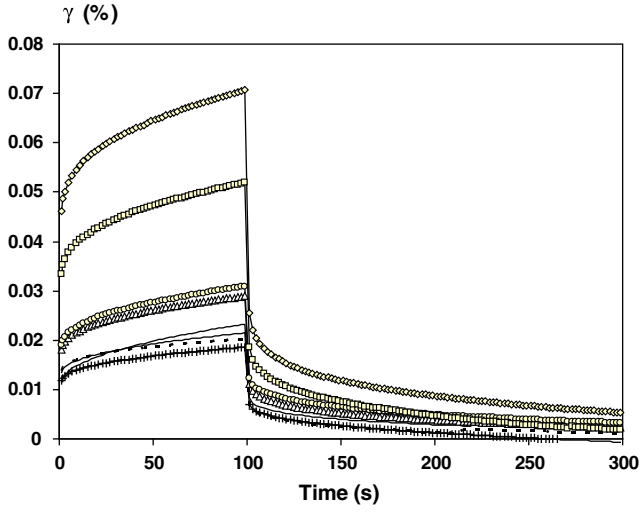

Fig. 2. Average experimental creep/recovery curves for apple tissue dipped into the anti-browning solution (AD) and/or irradiated 60 s with pulsed light (PL) and stored 7 days at 5 °C. Day 0: (—) Control, (+) AD apple, (Δ) PL apple, (—) AD + PL apple. Day 7: (- -) Control, (○) AD apple, (□) PL apple, (◊) AD + PL apple.

Please cite this article as: Gómez, P.L., et al., Effect of pulsed light combined with an antibrowning pretreatment on quality of fresh cut apple, *Innovative Food Science and Emerging Technologies* (2012), doi:10.1016/j.ifset.2012.05.011

of fresh and treated tissues was well characterized (correlation coefficient > 0.99) by the mathematical model represented by Eq. (7) and the corresponding viscoelastic parameters are supplied in Table 3. As expected, creep parameters presented great standard deviations, which had been attributed to many factors, such as no homogeneity of the tissue, stage of development, agronomic practices, etc. (Mittal & Mohsenin, 1987; Pitt, 1992; Alzamora, Viollaz, Martínez, Nieto, & Salvatori, 2008).

There were significant differences in the viscoelastic parameters between fresh and treated apples (MANOVA, $F_{18,\ 207} = 6.1$; $p < 0.0001$). In PCA analysis, 79% of total variance was explained by the first two components (PC1 50.1% and PC2 29.2%). PC1 was defined positively by λ_1 and η_N, and negatively by J_0 and J_2. PC2 was defined positively by J_1 and λ_2. Just after treatment with AD, apples showed a decrease in the steady-state viscous compliance ($1/\eta_N$) and an increase in the viscoelastic compliance J_1 and the retardation times λ_1 and λ_2. On the other hand, PL apples showed an increase in the instantaneous compliance (J_0) and the viscoelastic compliance J_2. AD + PL apples presented lower values of the $1/\eta_N$ compliance and higher values of retardation time λ_1 than C samples but they did not significantly differ from apples only irradiated. Changes during storage in PL apples were reflected mainly in an increase in J_0, J_1 and J_2, denoting that these tissues became more deformed. Furthermore, an increase in compliance $1/\eta_N$ and a decrease in retardation time λ_1 were also detected. AD + PL apples did not differ significantly from slices only irradiated. An increase in J_0 was observed in stored C and AD samples but in a lesser extent than in irradiated tissues. C sample also showed a notorious decrease in compliance $1/\eta_N$ as compared with the fresh fruit without storage.

The increase in the overall compliance at the end of the creep phase in stored treated samples as compared to fresh tissue was 130% for AD apples, and 200–300% for PL apples and AD + PL apples. For all samples, the relative contribution of each type of compliance was in the range 37–62% for instantaneous elastic; 14–41% for the slow-rate viscoelastic; 10–25% for the fast-rate viscoelastic and 8–21% for the steady-state viscous compliance (Table 3). In general, the major contribution to overall compliance for treated and untreated apples was given by J_0, both at the beginning and at the end of storage. All samples exhibited plastic strain which remained unrecovered after test. Plasticity values (the ratio of unrecoverable or permanent deformation, t/η_N, to the total deformation at the end of the creep phase, $J(t,\tau)$) of treated samples were slightly lower than those of untreated ones at day 0 (21%, 12%, 15%, and 11% for C, AD, PL, and AD + PL samples respectively). But at day 7, the control fruit maintained a lower degree of strain or compliance than treated apples (8%, 15%, 13%, and 12% for C, AD, PL, and AD + PL samples respectively).

3.4. Texture profile analysis (TPA)

Instrumental texture profiles obtained by uniaxial compression for fresh and treated apples are shown in Fig. 3. All curves exhibited an initial sharp peak and then a molder peak at the end of the first compression, denoting that samples were hard and fracturable. TPA parameters were obtained from the experimental curves for each sample (Table 4). Significant differences among fresh, treated and/or stored apples were found ($F_{40,\ 396} = 10{,}6$; $p < 0{,}0001$). In PCA analysis, 94% of variance was explained by the first two components. PC1 (49.9% of variance) was defined negatively by fracturability, hardness 1, hardness 2, area 1 and E_d and positively by springiness. PC2 (43.9% of variance) was defined positively by area 2, cohesiveness, gumminess and chewiness (biplot not shown). Control and AD samples stored 5 days showed an increase in fracturability, hardness (1 and 2) and area 1, and a decrease in springiness compared to fresh control without storage. Apples exposed to PL (with and without AD) presented minor changes in the parameters mentioned above and a decrease in cohesiveness and chewiness. Moreover, apples with AD + PL and stored control showed higher values of E_d as compare to fresh control. On the contrary, a decline in E_d was observed in samples irradiated without AD. Apples treated only with AD showed higher values of area 2 and gumminess. The increase in gumminess in these samples was expected as they showed high values of hardness and cohesiveness.

3.5. Sensory texture evaluation

The results of the sensory analysis can be observed in Table 5. The judgments made by the panel for hardness, juiciness and crispness were consistent and homogeneous. Instead, the differences in fracturability between samples were not easy for the panel to discern and the judgments were not homogeneous ($F_{7,\ 21} = 195$, $p < 0.0001$). Thybo and Martens (1998) and Garcia Loredo et al. (in press) reported also that trained assessors had difficulty in detecting differences in fracturability of cooked potatoes and osmotically dehydrated apples respectively.

Panelists did not find significant changes in fracturability ($F_{3,21} = 0.21$; $p = 0.88$) and hardness ($F_{3,12} = 0.96$; $p = 0.43$) of cut-apples due to treatments and/or to storage. On the contrary, significant differences in crispness and juiciness were observed. Juiciness decreased ($F_{3,15} = 11.1$; $p < 0.0001$) in stored samples (treated and non treated), while crispness ($F_{3,21} = 3.70$; $p = 0.02$) decreased in samples treated with AD and exposed to PL.

As observed, TPA, creep and G′ and G″ measurements were more sensitive techniques than trained panel analysis, and significant differences provoked by treatments/storage could be ascertained instrumentally, although they were not as apparent during mastication. Partial Least Squares regression analysis (PLS) was performed to correlate sensory (y-variables) and instrumental measurements (x-variables). About 72% of the variability in sensory attributes could be explained by mechanical parameters using a PLS regression model with 4 PLS-factors. According to this model, juiciness and sensory hardness were the best explained properties (approximately 20.7% and 19.7% of the variance explained, respectively), while crispness and fracturability were less

Table 3
Effect of antibrowning dipping and 60 s PL irradiation on the viscoelastic parameters of cut-apple derived from creep test.

Time (day)	Treatment	J_0 (1/Pa) ($\times 10^6$)	J_1 (1/Pa) ($\times 10^6$)	J_2 (1/Pa) ($\times 10^6$)	λ_1 (s)	λ_2 (s)	η_N (Pa.s) ($\times 10^{-8}$)	
0	Control	3.1 ± 0.9	1.4 ± 0.7	0.7 ± 0.3	26.4 ± 3.9	2.6 ± 0.5	0.7 ± 0.5	A
	AD	3.1 ± 0.8	4.3 ± 3.2	0.5 ± 0.2	32.9 ± 12.2	3.1 ± 1.1	1.9 ± 1.2	B
	PL	4.91 ± 1.1	1.4 ± 0.3	0.9 ± 0.2	26.2 ± 8.1	2.4 ± 0.6	0.8 ± 0.3	CD
	AD + PL	3.5 ± 0.5	1.2 ± 0.5	0.6 ± 0.1	35.0 ± 19.1	2.1 ± 0.6	1.5 ± 0.8	D
7	Control	4.1 ± 0.9	1.1 ± 0.4	1.9 ± 1.8	30.3 ± 13.4	2.6 ± 0.6	1.7 ± 0.8	D
	AD	5.2 ± 1.4	1.4 ± 0.7	0.9 ± 0.3	19.1 ± 5.7	1.9 ± 0.7	0.8 ± 0.6	C
	PL	8.2 ± 4.4	2 ± 1	2 ± 1	22.8 ± 3.8	2.1 ± 0.6	0.6 ± 0.2	CE
	AD + PL	13 ± 5.2	3.1 ± 1.8	2.2 ± 0.9	21.3 ± 3.9	2.6 ± 0.9	0.4 ± 0.2	E

Results were expressed as mean followed by the standard deviation.
PL: pulsed light; AD: antibrowning dipping.
Parameters derived by fitting Eq. (7) to compliance data from the creep phase.
Different letters indicate significant differences between treatments ($p < 0.05$).

Please cite this article as: Gómez, P.L., et al., Effect of pulsed light combined with an antibrowning pretreatment on quality of fresh cut apple, *Innovative Food Science and Emerging Technologies* (2012), doi:10.1016/j.ifset.2012.05.011

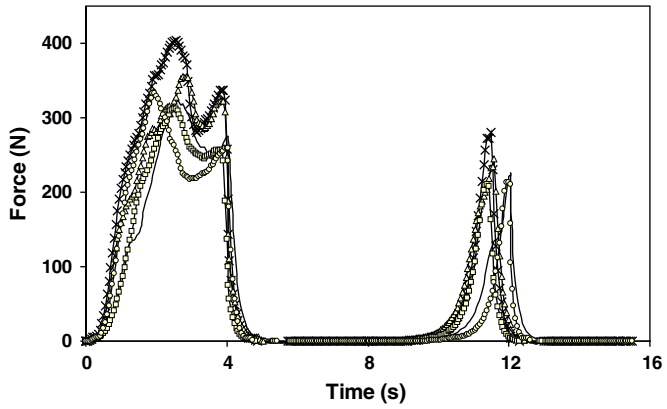

Fig. 3. Typical TPA responses for fresh apple and for apple dipped into the antibrowning solution (AD) and/or irradiated 60 s with pulsed light (PL) stored 5 days at 5 °C. (—) Control (fresh fruit at day 0), (X) Control stored 5 days, (Δ) AD apple, (□) PL apple, (○) AD + PL apple.

explained (approximately 14.5% and 14.7% of the variance explained, respectively). The relationships between TPA parameters and sensory attributes are shown in Fig. 4A. Fracturability, hardness 1, hardness 2 and area 1 were positively related to sensory fracturability and hardness and negatively correlated to juiciness. Deformability modulus had a small contribution to variability in sensory properties because of its small loadings for both PLS-factors 1 and 2.

Creep parameters could explained 82% of the variance of sensory attributes using four PLS factors. Crispness and juiciness were the best explained sensory properties (approximately 18% and 17% of the variance explained, respectively) and sensory hardness and fracturability were less explained (approximately 10% and 4.6% of the variance explained, respectively). Fig. 4B shows that crispness was negatively correlated to instantaneous and retarded compliances (J_0, J_1 and J_2). The steady-state viscosity (η_N) was negatively correlated to juiciness and the second retarded time (λ_2) was positively correlated to juiciness and negatively related to sensory hardness. The first retarded time (λ_1) had a small contribution to variability in sensory properties compared with other parameters because of its small loadings for both PLS-factors 1 and 2.

The values of G′ modulus at 0.1 s^{-1}, 1 s^{-1}, 10 s^{-1}, and 100 s^{-1} were shown to be positively related to crispness. On contrary, the viscous modulus G″ at the same frequencies appeared to be positively correlated to juiciness and negatively correlated to crispness. In both analyses, approximately 68–69% of the variance was explained using two PLS factors (data not shown).

It is to be noticed that measurement in the linear viscoelastic region involve probing the structure of the apple tissue in a non-destructive manner, while in the mouth and in the TPA, irreversible deformations take place (Kealy, 2006). But viscoelastic measurements give an indication of the initial experience of a consumer, as confirmed by the high degree of correlation between crispness and juiciness with creep and dynamic parameters. Instead, TPA fracture properties evaluated using large strain methodology proved to be more correlated with sensory hardness and fracturability.

Table 5
Sensory texture parameters for fresh apple, apple dipped into the antibrowning solution (AD) and apple dipped into the antibrowning solution and irradiated 60 s with pulsed light (AD + PL) stored 5 days at 5 °C.

Treatment	Hardness	Fracturability	Crispness	Juiciness
Control (day 0)	6.5 ± 0.4[a]	5.9 ± 2.9[a]	7.3 ± 0.7[a]	6.2 ± 0.6[a]
Control (day 5)	6.6 ± 0.6[a]	6.0 ± 2.9[a]	6.9 ± 0.7[ab]	4.8 ± 0.7[b]
AD	6.5 ± 0.4[a]	5.9 ± 2.9[a]	7.2 ± 0.8[a]	5.2 ± 0.8[b]
AD + PL	6.3 ± 0.6[a]	5.9 ± 2.9[a]	6.4 ± 0.9[b]	5.0 ± 0.9[b]

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

3.6. Water loss

The weight loss (associated with the loss of water) along refrigerated storage for fresh and PL irradiated apples (with and without AD) is presented in Table 6. Interaction between the factors time and treatment was not significant ($F_{4,81}=0.7$; $p=0.59$). All samples (treated and control) showed a significant decrease in weight during storage, but the decrease was higher in AD + PL apples. After 7 days of storage, weight loss for control and slices treated only with AD were approximately 12%, while for apple exposed to PL was about 16%.

Fresh-cut fruits and vegetables demonstrate increased respiration rates and wound induce ethylene production, thus exacerbating water loss (Toivonen & Deell, 2002). The exposure to irradiation would provoke an additional injury to apple tissue than generated during peeling and cutting, which would be translated in an increase in respiration and transpiration rates.

3.7. Microscopic observations

Light and transmission electron microscopy observations were performed to evaluate micro and ultrastructural changes produced by treatments. Parenchyma apple tissues localized at the irradiated surface (with and without previous anti-browning dipping) at day 0 and day 7 are visualized in Figs. 5 and 6. In C and AD tissues, cells, more or less regular in shape, appeared moderately turgid, with stained walls and in general parietal cytoplasm. In few cells, membranes appeared broken or with an incipient plasmolysis, probably due to a cutting effect (Fig. 5A,C). Intercellular spaces exhibited various shapes and sizes. In TEM images of fresh tissues, cell walls showed a slightly stained middle lamella, and a longitudinal fibrillar or an intermixed fibrillar pattern according to the region (Fig. 6A). Samples treated with AD showed cell walls with a darker staining compared with untreated tissues (Fig. 6B). In opposite, cell walls of PL tissues appeared less electronically dense, indicating a PL-induced degradation of biopolymers. In some areas, cytoplasm was visualized separately

Table 4
TPA parameters for fresh apple and apple dipped into the antibrowning solution and/or irradiated 60 s with pulsed light and stored 5 days at 5 °C.

Treatment	Fracturability (N)	Hardness 1 (N)	Hardness 2 (N)	Area 1 (J)	Area 2 (J)	Springiness (–)	Cohesiveness (–)	Gumminess (N)	Chewiness (N)	Ed (mPa)	
C (day 0)	334.7 ± 22.3	340.2 ± 20.6	235.5 ± 23.7	0.8 ± 0.1	0.13 ± 0.01	0.67 ± 0.04	0.16 ± 0.02	54.8 ± 6.9	36.6 ± 5.7	1.52 ± 0.25	A
C (day 5)	362.1 ± 31.8	392.7 ± 38.2	276.8 ± 32.3	1.0 ± 0.1	0.11 ± 0.01	0.61 ± 0.05	0.12 ± 0.01	46.1 ± 5.1	27.6 ± 4.5	1.95 ± 0.27	B
AD	345.1 ± 47.2	385 ± 45	264.2 ± 37.8	0.9 ± 0.1	0.15 ± 0.01	0.64 ± 0.04	0.16 ± 0.01	61.3 ± 7.5	39.6 ± 6.5	1.4 ± 0.2	C
PL	337.7 ± 27.8	342.6 ± 28.5	242.9 ± 24.1	0.8 ± 0.1	0.09 ± 0.01	0.63 ± 0.04	0.11 ± 0.01	38.2 ± 5.4	24.2 ± 4.3	1.29 ± 0.23	D
AD + PL	339.2 ± 33.6	350.9 ± 34.4	250.6 ± 30.6	0.9 ± 0.1	0.11 ± 0.02	0.62 ± 0.05	0.11 ± 0.02	40.5 ± 8.1	25.3 ± 6.3	1.78 ± 0.28	E

Results were expressed as mean ± standard deviation.
Different letters indicate significant differences ($p<0.05$) between treatments.

Please cite this article as: Gómez, P.L., et al., Effect of pulsed light combined with an antibrowning pretreatment on quality of fresh cut apple, *Innovative Food Science and Emerging Technologies* (2012), doi:10.1016/j.ifset.2012.05.011

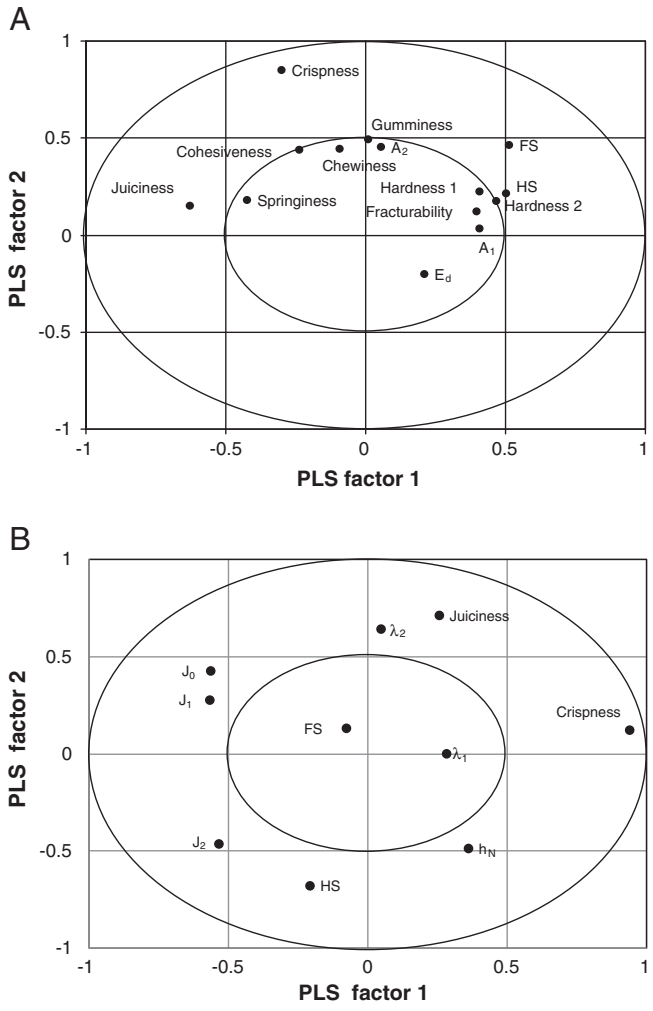

Fig. 4. Plot of X-loadings and Y-loadings for (A) TPA parameters and (B) creep curve parameters of fresh and treated apple tissues.

from the cell wall or forming vesicles due to rupture of membranes (Fig. 6C). In LM observations, extensive breakage of membranes (plasmalemma and tonoplast) and cells more rounded that those of fresh fruit or AD apples were also observed (Fig. 5B). Tissues exposed to PL with previous AD showed better stained cell walls than tissues only irradiated (Fig. 6D), although some walls appeared broken (Fig. 5D). Cells were also visualized rounded as in PL tissues (Fig. 5D).

After storage, cell walls in the untreated sample appeared with some degree of folding (Fig. 5E) but much more stained than before storage, with a very tightly fibrillar arrangement (Figs. 5E, 6E). This much reinforced cell walls of C apple tissue stored in refrigeration was also visualized in previous studies (Gómez, García Loredo, Salvatori, Guerrero, & Alzamora, 2011). AD apples exhibited cell walls with lesser electronic density than at day 0 (Fig. 6G). In stored PL and AD + PL apples, cells appeared collapsed, with broken membranes and a greater folding of walls than control and AD apples (Fig. 5F,H). This extensive folding could be due in part to the loss of turgor and in part to some alteration of wall components. Tissues only irradiated presented cell walls less stained in the central zone of the middle lamella but with a greater intensity toward the margin than at day 0 (Fig. 6F). On the other hand, AD + PL apples showed much undulated cell walls with lesser electronic density than before storage but with a more homogeneous density distribution than PL apples (Fig. 6H and I).

Table 6
Weight loss (%) for fresh and treated apple discs throughout storage at 5 °C.

Storage time (day)	Control	AD	AD + PL
0	–	0.4 ± 0.2	3.7 ± 0.4
3	4.5 ± 0.9	5.2 ± 1.3	10.1 ± 3.2
7	12.4 ± 3.5	12.5 ± 2.5	15.8 ± 3.9

Results were expressed as men ± standard deviation.
AD: anti-browning dipping. PL: pulsed light.

Changes found in rheological properties and sensory texture perception due to treatments and/or storage could be partially supported by microscopic observations. It has been suggested that rheological parameters are associated with some structural components of the fruit tissue, reflecting changes that occur at cellular level (Jackman & Stanley, 1995; Martínez et al., 2005, 2007; Alzamora et al., 2008). At the cellular level, the three major structural aspects that contribute to textural properties of plant-based foods are turgor (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. The elastic response of plant tissues has been attributed to: 1) cellulose, the main component of the cell wall, which provides individual cells with rigidity and resistance to rupture (John & Dey, 1986; Pitt, 1992); 2) the occluded air in the porous matrix; and 3) the turgor pressure (Bourne, 1976; Alzamora, Castro, Nieto, Vidales, & Salvatori, 2000; Alzamora et al., 2008). These structure elements would mainly influence G′, J_0 and E_d values. On the other hand, according to the interpretation proposed for Jackman and Stanley (1995) to explain creep behavior in tomato fruits, 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, and 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. This interpretation has been successfully used for explaining cooked potato and osmotically dehydrated melon and apple creep behavior (Alvarez & Canet, 1998; Martínez et al., 2005, 2007).

Before building associations between rheological studies and microscopic observations, it is important to be noticed, that due to the low penetration of PL irradiation, changes in structure would be given mainly in surface of irradiated samples. Thus rheological changes provoked by the treatments were not of great magnitude, although the differences in instrumental parameters were in general significant. In this case, the relationship between structure and instrumental values is not easy to be determined since each rheological parameter is influenced by more of one structure element. The modifications in these are mainly at surface level, many times influencing rheological behavior in a different sense, and could affect none linearly rheological properties.

All assayed instrumental tests (instrumental texture profile analysis, oscillatory and creep-recovery tests) were sensitive distinguishing structure differences among treatments/storage in a different degree. TPA allowed discriminating between the structure of C at day 0 and C, AD and AD + PL stored day 5 days, but G′ and G″ modules and creep parameters did not differentiate the PL treatments (with or without AD) at each storage time.

The decline in G′ and the increase in J_0 in irradiated tissues (with and without AD) would be mainly associated with the loss of turgor pressure due to membrane rupture and vacuole burst, as well as the modification in wall polymers (mainly cellulose pattern) caused by pulsed light. This loss of turgor, evidenced in extensive folding of walls and cell collapse (Fig. 5F,H), would be accentuated during storage as result of greater water loss, resulting in even lower G′ and J_0 values after storage. Furthermore, the PL-induced degradation of biopolymers of cell wall observed in tissues just after only irradiation or in PL and PL + AD stored tissues would be traduced in higher values of compliance J_2. At day 0, the AD treatment previous to irradiation

Please cite this article as: Gómez, P.L., et al., Effect of pulsed light combined with an antibrowning pretreatment on quality of fresh cut apple, *Innovative Food Science and Emerging Technologies* (2012), doi:10.1016/j.ifset.2012.05.011

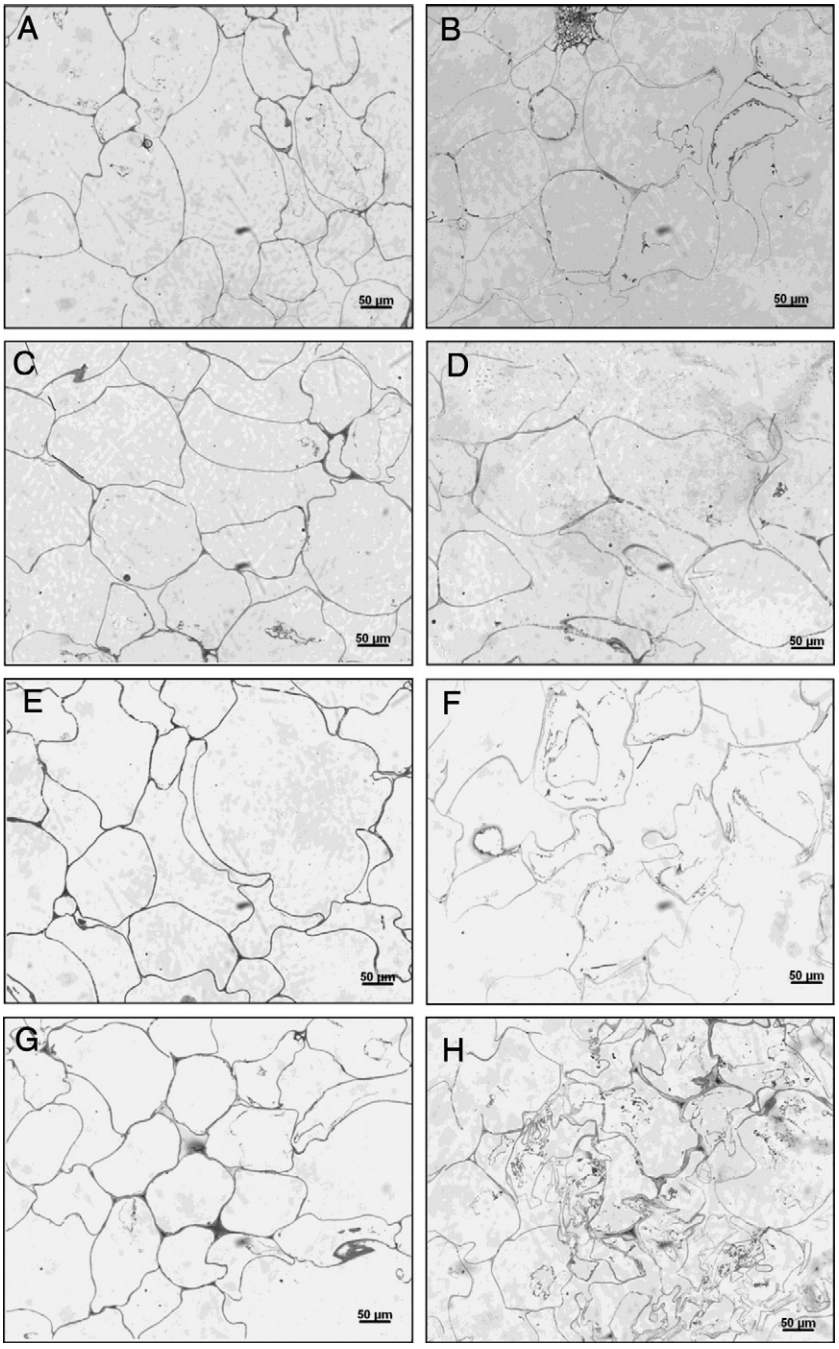

Fig. 5. Light microscopy images from apple surface irradiated 60 s with and without antibrowning dipping at 0 and 7 days of storage. Day 0: (A) Control, (B) PL apple, (C) AD apple, (D) AD + PL apple. Day 7: (E) Control, (F) PL apple, (G) AD apple, (H) AD + PL apple.
A, B, E and F adapted from Gómez et al. (in press).

probably contrarrested the effect of PL exposure, as shown by the micrograph in Fig. 6D., resulting in lower J_1 and J_2 values compared with those of fresh fruit. On the other hand, the decrease in compliance $1/\eta_N$ after AD and AD + PL treatments at day 0 or in the control stored 5 days would be in concordance with the reinforcement observed in cell walls, and the consequent decrease in fluidity.

In stored control samples, the reinforcing of cell walls observed after refrigerated storage would be associated with the increase in the parameters fracturability, hardness and E_d, and the decrease in compliance $1/\eta_N$.

On the other hand, changes detected by the sensory panel in crispness and juiciness could be ascribed to structure modifications and water loss. Factors that are prerequisites to juiciness have reported to be high water content, organized cellular network with proper turgor and integrity, cell walls mechanically weaker than middle lamella, low viscosity and/or little suspended solids in the expressed liquid (Szczesniak & Ilker, 1988). According to our results, the decrease in juiciness in stored treated samples would be mainly associated with the water loss, favored in the case of irradiated samples by the rupture of membranes, and in the case of non treated stored apples, the reinforced walls. The decrease in crispness perceived by the panel in the 5 day stored AD + PL apples would be related to the greater loss of turgidity and the weakening of the cell walls that was observed in these tissues.

It is important to remark that the slight increase in temperature after 60 s PL exposure would not be expected to affect rheological

Please cite this article as: Gómez, P.L., et al., Effect of pulsed light combined with an antibrowning pretreatment on quality of fresh cut apple, *Innovative Food Science and Emerging Technologies* (2012), doi:10.1016/j.ifset.2012.05.011

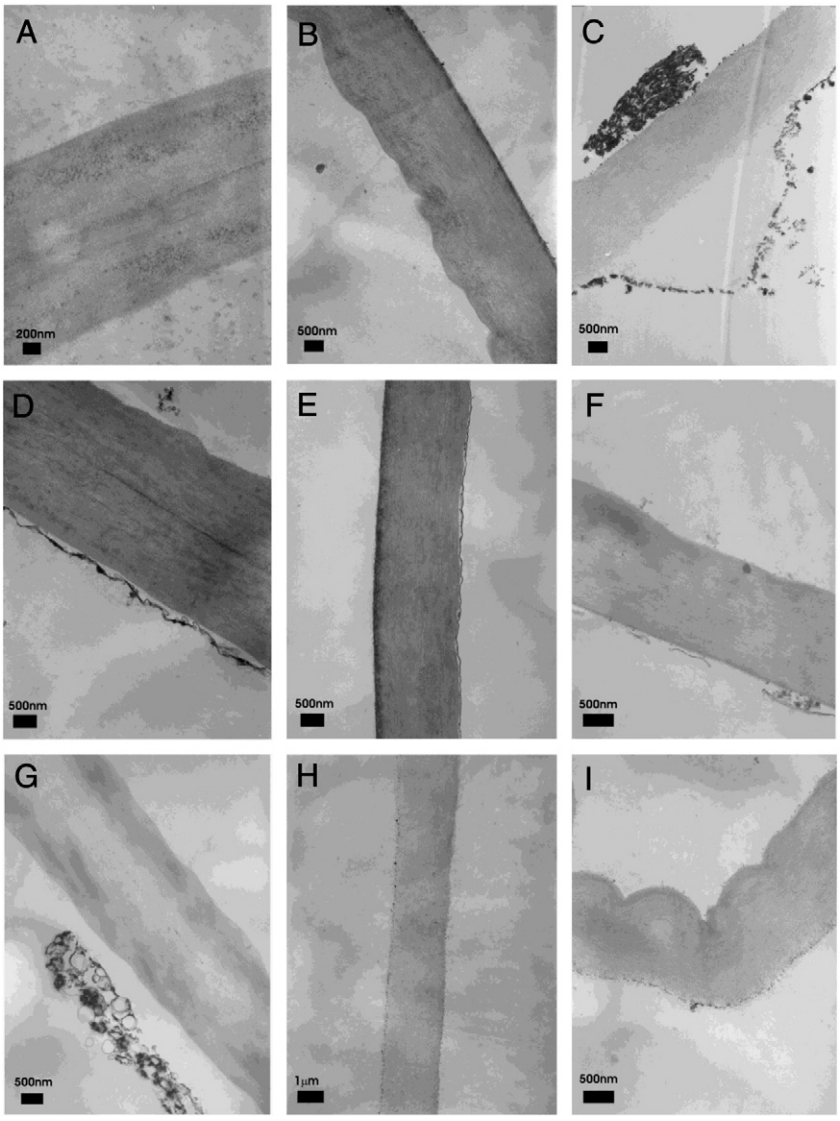

Fig. 6. TEM micrographs from apple surface irradiated 60 s with and without antibrowning dipping at 0 and 7 days of storage. Day 0: (A) Control, (B) AD apple, (C) PL apple, (D) AD + PL apple. Day 7: (E) Control, (F) AD apple, (G) PL apple, (H and I) AD + PL apple.

properties and texture perception. Regarding viscoelastic properties, we studied in a previous work (Martínez, Nieto, Viollaz, & Alzamora, 2002) the evolution of G′ and G″ when apple tissues were heated from 20 °C to 100 °C at different heating rates. We found that both modules remained constant until temperature was approximately 70 °C, where a drastic fall in the storage and loss modules was observed. This would indicate that until 70 °C there were not important structure changes in apple tissues.

4. Conclusions

Dipping in the ascorbic acid/calcium chloride solution was effective to minimize browning on irradiated apple surfaces up to a PL dose of 71.6 J/cm^2. PL and AD + PL treatments reduced native microflora counts. After storage, microbial population was lower in PL and AD + PL apples than in untreated ones. Changes in TPA, dynamic and creep behavior were evidenced due to treatments and/or storage. However, the trained texture panel only differentiated significantly between the juiciness of stored untreated, AD and AD + PL apple samples and the fresh fruit, and between the crispness of AD + PL apples and the fresh fruit. Sensory differences detected in hardness and fracturability were not significant, though discernable. PLS analysis allowed correlating some rheological parameters with panel results; in general, viscoelastic measurements with crispness and juiciness, and TPA parameters with sensory hardness and fracturability. Rheological properties and texture were partially ascribed to microstructure and ultrastructure features.

Acknowledgments

The authors acknowledge the financial support from the University of Buenos Aires, CONICET, and ANPCyT of Argentina and from BID.

References

Alvarez, M. D., & Canet, W. (1998). Rheological characterization of fresh and cooked potato tissues (cv. Monalisa). *Zeitschrift für Lebensmittel-Untersuchung und -Forschung, 207*, 55–65.

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 S. M. Alzamora, M. S. Tapia, & A. López-Malo (Eds.), *Minimally processed fruits and vegetables* (pp. 153–171). Maryland: Aspen Publishers Inc.

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 G. E. Gutiérrez-López, G. V. Barbosa-Cánovas, J. Welti-Chanes, & E. Parada-Arias (Eds.), *Food engineering: Integrated approaches* (pp. 133–214). New York: Springer.

Bialka, K. L., Demirci, A., & Puri, V. (2008). Modeling the inactivation of *Escherichia coli* O157:H7 and *Salmonella enterica* on raspberries and strawberries resulting from exposure to ozone or pulsed UV-light. *Journal of Food Engineering*, *85*, 444–449.

Bourne, M. C. (1976). Texture of fruits and vegetables. In J. M. DeMan, P. W. Voisey, V. F. Rasper, & D. W. Stanley (Eds.), *Rheology and texture in food quality* (pp. 275–307). New York: Van Nostrand Reinhold/AVI.

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

Calzada, J. F., & Peleg, M. (1978). Mechanical interpretation of compressive stress–strain relationships of solids foods. *Journal of Food Science*, *43*, 1087–1092.

Choi, M. S., Cheigh, C. I., Jeong, E. A., Shin, J. K., & Chung, M. S. (2010). Nonthermal sterilization of *Listeria monocytogenes* in infant foods by intense pulsed-light treatment. *Journal of Food Engineering*, *97*, 504–509.

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

FDA (1996). *Code of Federal Regulations.* 21CFR179.41.

Garcia Loredo, A. B., Guerrero, S. N., Gómez, P. L., & Alzamora, S. M. (in press). *Relationship between rheological properties, texture and structure of apple (Granny Smith var.) affected by blanching and/or osmotic dehydration.* Food Bioprocess and Technology, http://dx.doi.org/10.1007/s11947-011-0701-9.

Gómez, P., Alzamora, S., Castro, M., & Salvatori, D. (2010). Effect of ultraviolet-C light dose on quality of cut-apple: Microorganism, color and compression behaviour. *Journal of Food Engineering*, *98*, 60–70.

Gómez, P., García Loredo, A., Salvatori, D., Guerrero, S., & Alzamora, S. M. (2011). Viscoelasticity, texture and ultrastructure of cut apple as affected by sequential anti-browning and ultraviolet-C light treatments. *Journal of Food Engineering*, *107*, 214–225.

Gómez, P., Salvatori, D., García Loredo, A., & Alzamora, S. M. (in press). *Pulsed light treatment of cut apple: dose effect on color, structure and microbiological stability*, Food and Bioprocess Technology, http://dx.doi.org/10.1007/s11947-011-0598-3.

Gómez-López, V. M., Devlieghere, F., Bonduelle, V., & Debevere, J. (2005). Factor affecting the inactivation of micro-organisms by intense light pulses. *Journal of Applied Microbiology*, *99*, 460–470.

Gómez-López, V. M., Ragaert, P., Debevere, J., & Devlieghere, F. (2007). Pulsed light for food decontamination: A review. *Trends in Food Science & Technology*, *18*, 464–473.

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.

John, M. A., & Dey, P. M. (1986). Postharvest changes in fruit cell walls. *Advances in Food Research*, *30*, 139–193.

Jun, S., Irudayaraj, J., Demirci, A., & Gêiser, D. (2003). Pulsed UV-light treatment of corn meal for inactivation of *Aspergillus niger* spores. *International Journal of Food Science and Technology*, *38*, 883–888.

Kealy, T. (2006). Application of liquid and solid rheological technologies to the textural characterization of semi-solid foods. *Food Research International*, *39*, 265–276.

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.

Martínez, V. Y., Nieto, A. B., Viollaz, P. E., & Alzamora, S. M. (2002). Viscoelastic properties of fresh and thermally treated apple tissue. *Institute of Food Technologists—Annual Meeting. Anaheim, California, USA, June 15–19*.

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.

Meilgaard, M., Civille, G. V., & Carr, B. T. (1999). *Sensory evaluation techniques* (3rd ed.). Florida: CRC Press.

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

Oms-Oliu, G., Aguiló-Aguayo, I., Martín-Belloso, O., & Soliva-Fortuny, R. (2010a). Effects of pulsed light treatments on quality and antioxidant properties of fresh-cut mushrooms (*Agaricus bisporus*). *Postharvest Biology and Technology*, *56*, 216–222.

Oms-Oliu, G., Martín-Belloso, O., & Soliva-Fortuny, R. (2010b). Pulsed light treatments for food preservation. A review. *Food and Bioprocess Technology*, *3*, 13–23.

Ozer, N. P., & Demirci, A. (2006). Inactivation of *Escherichia coli* O157:H7 and *Listeria monocytogenes* inoculated on raw salmon fillets by pulsed UV-light treatment. *International Journal of Food Science and Technology*, *41*, 354–360.

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

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.

Sharma, R. R., & Demirci, A. (2003). Inactivation of *Escherichia coli* O157:H7 on inoculated alfalfa seeds with pulsed ultraviolet light and response surface modeling. *Journal of Food Science*, *68*, 1448–1453.

Sherman, P. (1970). *Industrial rheology.* New York: Academic Press.

Szczesniak, A. S., & Ilker, R. (1988). The meaning of texture characteristics—Juiciness in plant foodstuffs. *Journal of Texture Studies*, *19*, 66–78.

Thybo, A. K., & Martens, M. (1998). Development of a sensory texture profile of cooked potatoes by multivariate data analysis. *Journal of Texture Studies*, *29*, 453–468.

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

Woodling, S. E., & Moraru, C. I. (2005). Influence of surface topography on the effectiveness of pulsed light treatment for the inactivation of *Listeria innocua* on stainless-steel surfaces. *Journal of Food Science*, *70*, M345–M351.

Wu, J., & Guo, K. G. (2010). Dynamic viscoelastic behavior and microstructural changes of Korla pear (*Pyrus bretschneideri rehd*) under varying turgor levels. *Biosystem Engineering*, *106*(4), 485–492.

Please cite this article as: Gómez, P.L., et al., Effect of pulsed light combined with an antibrowning pretreatment on quality of fresh cut apple, *Innovative Food Science and Emerging Technologies* (2012), doi:10.1016/j.ifset.2012.05.011