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# Preservation of fresh-cut apple quality attributes by pulsed light in combination with gellan gum-based prebiotic edible coatings



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## ABSTRACT

Pulsed light (PL) has received considerable attention during the last years as a non-thermal method for the superficial decontamination of fresh foods. The aim of the present study was to evaluate the quality attributes of fresh-cut 'Golden Delicious' apples as affected by the combined application of a pulsed light treatment (12 J/cm<sup>2</sup>) and a gellan-gum based (0.5% w/v) edible coating enriched with apple fiber. Changes in color, firmness, antioxidant capacity, microbial growth and sensory attributes were determined during 14 days of storage at 4 °C. The combined application of coating and PL treatment retarded the microbiological deterioration of fresh-cut apples and maintained the sensory attribute scores above the rejection limits after prolonged storage. Incorporation of fiber in the coating formulation did not curb the sensory acceptability of apple cubes. Results show that the use of a gellan-gum based coating incorporating apple fiber followed by the application of a PL treatment significantly reduced softening and browning of apple pieces through storage.

Our results reveal that PL treatments applied to gellan-coated fresh-cut apples can be used to decontaminate the cut fruit surface without dramatically affecting its fresh-like quality attributes, thus conferring prebiotic potential and contributing to their shelf-life extension.

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## 1. Introduction

Minimal processing is emerging as an alternative for the provision fresh-like, highly nutritious, convenient and healthful commodities. However, mechanical bruises caused during processing and handling may compromise the safety and appearance of fresh-cut produce, leading to an increase in the respiratory rates and triggering multiple biochemical reactions that underlie microbiological spoilage and quality deterioration (Moreira, Roura, & Ponce, 2011; Oms-Oliu, Soliva-Fortuny, & Martín Belloso, 2008; Ramos, Miller, Brandao, Teixeira, & Silva, 2013; Rico, Martín-Diana, Barat, & Barry-Ryan, 2007).

Different technologies are currently investigated with the aim of decontaminating fresh-cut produce avoiding physical and chemical changes associated to processing. Pulsed light (PL) is a non-thermal technology based on the application of intense pulses of short

duration to effectively inactivate microorganisms contained either in light-transmitting media or on opaque surfaces (Gómez-López, Ragaert, Debevere, & Devlieghere, 2007; Marquenie, Michiels, Van Impe, & Nicolai, 2003). The treatment has been demonstrated to be cost effective and feasible for the microbial inactivation of both solid and liquid food products (Ramos-Villarreal, Aron-Maftei, Martín-Belloso, & Soliva-Fortuny, 2014). On the other hand, the use of edible coatings is another alternative under investigation to extend the shelf-life of fresh-cut products (Alvarez, Ponce, & Moreira, 2013; Tharanathan, 2003). Gellan gum, a microbial polysaccharide secreted by the bacterium *Pseudomonas elodea*, exhibits unique colloidal and gelling properties and, therefore, good ability to form coatings. These coatings may also serve as carriers of food additives such as antibrowning and antimicrobial agents, colorants, flavors, nutrients, spices and nutraceuticals (Oms-Oliu et al., 2008; Oms-Oliu, Martín-Belloso, & Soliva-Fortuny, 2010; Robles-Sanchez, Rojas-Gratü, Odriozola-Serrano, González-Aguilar, & Martín-Belloso, 2013). Among these last compounds, fiber was one of the first ingredients associated with health and has been used in food industry since 1980s (MoraesCrizel, Jablonski, Oliveira, Rios, & Rech, 2013). However, the fiber intake in most developed countries falls

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below the levels recommended by health authorities, which usually suggest amounts of total dietary fiber above 25 g/day for adults, of whom one third should be soluble fiber. Fiber incorporation into edible coating formulations may help to meet the daily intakes lagging far below the recommended dietary allowances. Apple dietary fiber, as those obtained from most fruit and vegetable products, possesses a higher soluble portion and better antioxidant properties than fibers from cereal sources (Marín, Soler-Rivas, Benavente-Garcíental, Castillo, & Pérez-Alvarez, 2007; O'Shea, Arendt, & Gallagher, 2012).

Both PL and edible coatings have been applied to fresh-cut produce with the objectives of reducing the incidence of food-borne pathogens, extending the produce shelf-life, and reducing food quality losses along the distribution chain (Oms-Oliu, Aguiló-Aguayó, Martín-Belloso, & Soliva-Fortuny, 2010; Ramos-Villaruel, Martín-Belloso, & Soliva-Fortuny, 2011). Gellan gum-based edible coatings have been shown to be effective in maintaining the fresh-like quality attributes of fresh-cut fruits such as apples, melons, and pears (Oms-Oliu et al., 2008; Pérez-Gago, Alonso, Mateos, & del Río, 2005; Rojas-Graü, Tapia, & Martín-Belloso, 2008). As well, the ability of PL treatments to inactivate microorganisms on fresh-cut fruit surfaces has been demonstrated in several published studies (Gómez, Salvatori, García-Loredo, & Alzamora, 2012; Izquier & Gómez-López, 2011; Oms-Oliu, Martín-Belloso, et al., 2010; Ramos-Villaruel et al., 2014). However, so far the combined effect of PL treatments and the use of edible coatings to inhibit microbial growth and to extend the shelf-life of fresh-cut fruits has not been evaluated. Furthermore, the addition of prebiotics for the promotion of health-related properties in such products has been scarcely studied. The main objective of this research was to evaluate the combined application of PL treatments with gellan-gum edible coatings incorporating apple fiber on the quality of fresh-cut apples.

## 2. Materials and methods

### 2.1. Materials

'Golden delicious' apples were purchased in a local wholesale distributor (Lleida, Spain) at commercial maturity and stored at  $4 \pm 1$  °C until processing. Food grade gellan gum (Kelcogel<sup>®</sup>, CPKelco, Chicago, IL, USA) was used as the carbohydrate film-forming biopolymer in coating formulations. Glycerol (Merck, Whitehouse Station, NJ, USA) was added to the coatings as plasticizer. Calcium chloride (Sigma–Aldrich Chemic, Steinheim, Germany) was used to induce crosslinking between the polymer chains. Ascorbic acid (Sigma–Aldrich Chemic, Steinheim, Germany) was added to prevent oxidation of the fruit surface. Dietary fiber concentrate from apple was kindly supplied by the factory Induleida S. L. (Alguaire, Lleida, Spain). This apple dietary fiber concentrate was the result of drying the washed apple bagasse remaining after apple juice extraction.

### 2.2. Preparation of film forming and crosslinking solutions

Film-forming solutions were prepared by dissolving gellan (5 g/L water) powders in distilled water and heating at 70 °C while stirring until the solution became clear. Gellan solutions were prepared with and without apple fiber addition (2 g/L). Glycerol was incorporated to the gellan solutions at a concentration of 0.6 g/100 mL. On the other hand, a crosslinking solution was prepared by adding calcium chloride (20 g/L) to an aqueous solution containing 10 g/L ascorbic acid. The concentrations of all ingredients used in these formulations were set up according to previous studies (Rojas-Graü et al., 2008).

### 2.3. Fruit coating

Apples were gently washed, rinsed and dried prior to the cutting operations. Subsequently, each fruit was peeled, cored and diced into 1 cm-thick cubes. A maximum of four fruits were processed at the same time to avoid oxidation before treatments. Apple dices were first dipped for 2 min into a gellan gum film-forming solution, either with or without added apple fiber. The excess of coating solution was allowed to drip off for 1 min before submerging the fruit pieces for 2 min into the crosslinking dip containing ascorbic acid and calcium chloride. Control samples were dipped only into the crosslinking solution. Ten apple cubes (ca. 60 g) were placed into polypropylene trays of 500 cm<sup>3</sup> (Mcp Performance Plastic LTD, Kibbutz Hamaapil, Israel), which were wrap-sealed with a 64 µm-thick polypropylene film with a permeability to oxygen of 110 cm<sup>3</sup> O<sub>2</sub> m<sup>-2</sup> bar<sup>-1</sup> day<sup>-1</sup> at 23 °C and 0% RH (Tecnopack SRL, Mortara, Italy) using a horizontal thermosealing machine (IlpraFoodpack Basic V/G, Ilpra, Vigenovo, Italy). Trays were heat-sealed and stored at  $4 \pm 1$  °C during less than 30 min prior to PL-processing.

### 2.4. Pulsed light treatment

The trays containing gellan gum-coated apple cubes were exposed to PL treatments delivered by a XeMaticA-2L device (SteriBeam Systems GmbH, Germany). The system is equipped with two lamps situated at 8.5 cm above and below a quartz sample holder. Experiments were carried out at a charging voltage of 2.5 kV. Each lamp delivered 30 pulses of duration of 0.3 ms with an emitted fluence of 0.4 J/cm<sup>2</sup> at the sample level, thus resulting in an accumulated energy of 12 J/cm<sup>2</sup>. The emitted spectrum wavelengths ( $\lambda$ ) ranged from 180 to 1100 nm with 15–20% of the light in the UV region. Energy calculations were carried out according to the calibration of the equipment with a standard light source estimated by photodiode readings and following manufacturer's directions. Furthermore, transparency of the polypropylene film in the UV region was found to be above a 97% of the total emitted energy. Reduction of light transmission was negligible for visible wavelengths and increased for shorter wavelengths. However, only a 15% of the incident energy corresponding to wavelengths between 200 and 320 nm was blocked by the packaging material. Furthermore, spectroscopic measurements of the film-forming solution were carried out to optically characterize the gellan gum coating. The transmittance of the coating was calculated considering a film thickness of 155.75 µm, as reported in previous studies (Rojas-Graü, Tapia, Rodríguez, Carmona, & Martín-Belloso, 2007).

Temperature increase during the treatments was prevented by coupling a lab vacuum air extractor device to the treatment chamber. Temperature was measured with a thermocouple attached to the package surface and never exceeded 30 °C. Measurements were also taken at the surface of unpackaged fruit pieces over the PL treatment to guarantee that abusive temperatures were not reached. Untreated coated apple cubes and PL-treated uncoated apple cubes were used as reference treatments. Immediately after processing, the samples were stored at 4 °C in the absence of light. Analyses were carried out periodically through 14 days for randomly sampled pairs of trays.

### 2.5. Microbiological analysis

Mesophilic aerobic, psychrophilic and yeast and mold counts on fresh-cut apples subjected to the different treatments were evaluated throughout storage. A portion of 10 g of apple, obtained from eight different apple pieces, was aseptically removed from each tray and transferred into sterile plastic bags. Samples were diluted with 90 mL of saline peptone water (0.1 g peptone/100 mL water,

Biokar Diagnostics, Beauvais, France) and homogenized for 1 min in a stomacher blender (IUL Instruments, Barcelona, Spain). Serial dilutions were made and then pour-plated onto plate count agar (PCA) and chloramphenicol glucose agar (GCA) (Biokar Diagnostics, Beauvais, France). Plates were incubated for 48 h at 30 °C to determine mesophilic, 5–7 days at 5 °C for psychrophilic counts and 3–5 days at 25 °C for yeast and mold counts (Alvarez et al., 2013). Colonies were counted and the results expressed as CFU/g of apples. Analyses were carried out periodically during 14 days in randomly sampled pairs of trays. Two replicate counts were performed for each tray.

## 2.6. Antioxidant capacity

The antioxidant capacity of the fruit samples was evaluated using the method described by Odrizola-Serrano, Soliva-Fortuny, and Martín-Belloso (2008), which determines the free radical-scavenging effect of a sample extract on the 1,1-diphenyl-2-picrylhydrazyl (DPPH) radical. The DPPH assay provides an estimate of the overall antioxidant capacity of a sample, since it is not specific to any particular antioxidant compound. Apple cubes were crushed and centrifuged at 10,000 g for 15 min at 4 °C (Centrifuge Medigifer; Select, Barcelona, Spain). The supernatant was collected and filtered. Thereafter, 3.9 mL of methanolic DPPH solution (0.025 g/L) were added to 100 µL of the clarified extract. The homogenate was shaken vigorously and kept in darkness for 30 min. Absorbance at 515 nm was read with a spectrophotometer (CECIL CE 2021; Cecil Instruments Ltd., Cambridge, UK) against a blank of methanol without DPPH. Antioxidant capacity was calculated as the percentage inhibition of the DPPH radical with respect to the initial amount in a blank DPPH solution with 100 µL of water.

## 2.7. Color measurement

Cut apple surface color was measured with a Minolta chroma meter (Model CR-400, Minolta, Tokyo, Japan). The equipment was set up for illuminant D75 and 10° observer angle and calibrated using a standard white reflector plate ( $Y = 94.00$ ,  $x = 0.3158$ ,  $y = 0.3322$ ). Five replicates were evaluated for each tray and three measures of the CIE  $L^*$ ,  $a^*$  and  $b^*$  values were read per replicate by changing the position of the fruit pieces. Color modification was evaluated through changes in lightness ( $L^*$ ) and hue ( $h^*$ ). Hue was calculated from  $a^*$  (red-green) and  $b^*$  (blue-yellow) chromatic values with the following expression:  $h^* = \arctan(b^*/a^*)$ .

## 2.8. Firmness measurements

Apple firmness was evaluated using a TA-XT2 Texture Analyzer (Stable Micro Systems Ltd., England, UK) by measuring the maximum penetration force required for a 4 mm diameter probe to penetrate into apple cubes of 1 cm height to a depth of 5 mm at a rate of 5 mm/s. Ten apple cubes, randomly withdrawn from each pair of trays, were placed perpendicular to the probe so as to penetrate the center of the fruit pieces.

## 2.9. Sensory acceptability

Sensory acceptability of treated and untreated apple cubes was determined by judges who regularly consume apples. For the hedonic tests, ten individuals aged between 20 and 30 year old who like and eat apple frequently were recruited among the research personnel of the Department of Food Technology, University of Lleida, Spain and specifically trained to evaluate color, firmness, taste, and overall preference. Evaluations were performed immediately after sample withdrawal from refrigerated packages. The

order of the samples was randomized for each judge. They were asked to evaluate each of the samples attributes on non-structured linear scales with anchor points at each end, where 0 indicated extreme dislike and 5 indicated extreme like. The judges' average response was calculated for each attribute. The limit of acceptance was three; hence a score below 3 for any of the evaluated attributes was deemed to indicate end of shelf-life from a sensory point of view (Alvarez et al., 2013).

## 2.10. Statistical analysis

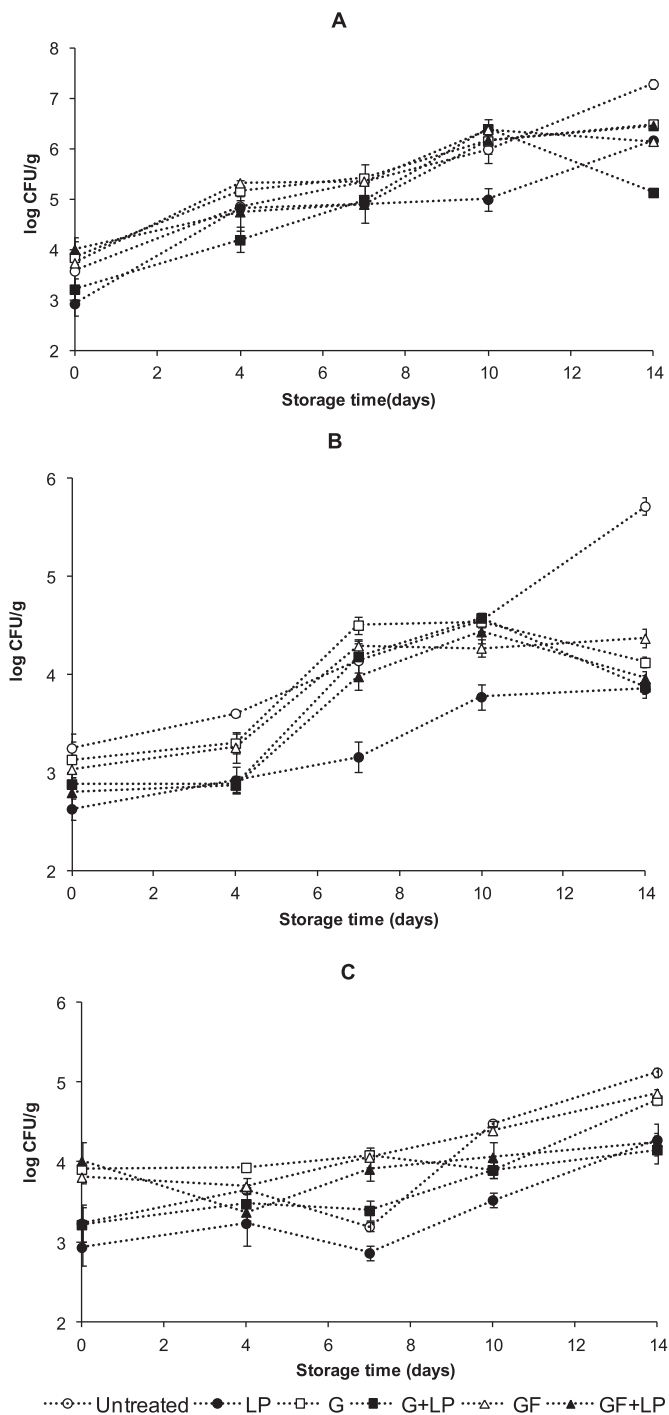
Data were analyzed using the SAS software (version 9.0, SAS Inst. Inc., Cary, NC, USA). Differences between means were determined using the LSD (least significant difference) test. PROC GLM (general linear model procedure) was used for the variance analysis (ANOVA). Differences were determined by the Tukey–Kramer multiple comparison test ( $p < 0.05$ ). PROC UNIVARIATE was used to validate the ANOVA assumptions. Each processing condition was assayed in duplicate. Each duplicate belong to a separate experimental run. Analytical determinations for each sample were assayed in triplicate.

## 3. Results and discussion

### 3.1. Microbial counts

Fig. 1 shows the growth of naturally-occurring microorganisms on either coated or uncoated apple cubes exposed to PL treatments. The proliferation of mesophilic aerobic bacteria on fresh-cut apples subjected to the different treatments is displayed in Fig. 1A. Mesophilic microorganisms provide an estimate of total viable populations and are indicative of the endogenous microbiota and the contamination undergone by the material (Ponce, Roura, & Fritz, 2002). Just after processing, the initial mesophilic counts on untreated and coated samples not subjected to PL treatment were in the range of 3.7–4.0 log CFU/g. The application of PL significantly reduced the initial mesophilic counts (3.0 log CFU/g) regardless the coating application. PL exerted a significant ( $p < 0.05$ ) inactivating effect on the initial mesophilic counts of both uncoated and coated apple cubes. Nevertheless, scarce differences ( $p < 0.05$ ) were observed between the mesophilic counts treated and untreated fresh-cut apples throughout storage. Gomez-López et al. (2007) reported that shielding of microorganisms by rough apple surface and microorganism internalization in apple tissue pores may greatly influence the inactivation patterns. Aerobic counts increased by ca. 4.0 log CFU/g on untreated apple cubes, while microbial loads on treated fruit increased by 2.0–3.0 log CFU/g throughout 2 weeks, regardless the applied treatment. Hence, untreated control apple cubes exhibited significantly higher mesophilic aerobic microbial counts ( $p < 0.05$ ) at 14 d of storage than apple pieces subjected to PL treatments and/or coated with gellan gum. At that point, the greatest inhibition of microbial growth ( $>2.0$  log CFU/g) was found for coated PL-treated apple cubes without incorporation of fiber.

The counts of psychrotrophic aerobic bacteria on fresh-cut apples as affected by the different treatments are shown in Fig. 1B. Psychrotrophic aerobes represent an important group of microorganisms in fresh-cut products. Although they usually constitute a small percentage of the initial microbiota, they could survive and eventually predominate under chill temperatures recommended for the storage of these commodities (Ponce et al., 2002). Consistently with this statement, the initial counts were low as compared with the significantly higher mesophilic aerobic counts. In addition, significant differences ( $p < 0.05$ ) between the counts of untreated and treated apple pieces were not evidenced during the first 10 days of



**Fig. 1.** Changes in the native-occurring microbiota of fresh-cut apples as affected by PL treatments, the application of gellan gum-based edible coatings enriched with apple fiber and storage at 4 °C: (A) total mesophilic bacteria; (B) psychrophilic bacteria; (C) yeast and molds counts. Bars indicate standard deviations. PL: pulsed light treated G: gellan gum-coated; GF: gellan gum-coated with apple fiber. Results are the mean of two independent experiments counted in duplicate.

storage. Nevertheless, counts of psychrophiles on untreated apple pieces increased by about 2.5 log CFU/g through 14 days, whereas for any of the evaluated treatments, the increase during the same period was in the range of 1.0 log CFU/g. Interestingly, uncoated PL-treated fresh-cut apples were the only samples to exhibit significantly lower counts ( $p < 0.05$ ) than the untreated fruit throughout

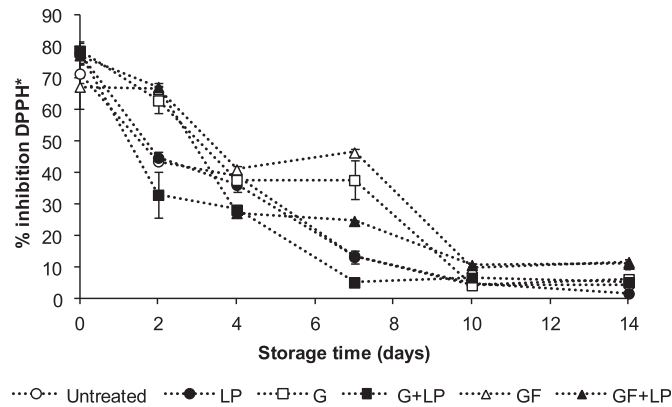
the whole storage period. This fact suggests that gellan coating layers could hinder microbial inactivation by pulsed light, which was confirmed by the spectrometric readings. Transmittance values in the UV-A, UV-B and UV-C regions were calculated to be 99.3%, 99.0% and 73.0%, respectively, thus indicating that the coating could block not all but a significant part of the incident UV-C radiation.

Regarding the effect of the PL treatment, our results are in accordance to those reported by other authors. Luksiene, Buchovec, Paskeviciute, and Viskelis (2012) reported inactivation levels of naturally distributed mesophilic bacteria in different PL-treated fruit and vegetables such as plums, cauliflowers, sweet peppers and strawberries between 1.0 and 1.3 log CFU/g, thus indicating the feasibility of such technology to reduce contamination in food products with surface irregularities. As well, Gómez-López, Devlieghere, Bonduelle, and Debevere (2005) reported significant reductions (1.0–2.0 log CFU/g) in mesophilic bacteria counts after treating minimally processed vegetables (spinach, carrot, cabbage) by PL. Similar results were reported by Aguiló-Aguayó, Charles, Renard, Page, and Carlin (2013), working with PL-treated tomatoes stored during 15 days. As well, Oms-Oliu, Aguiló-Aguayó, et al. (2010) investigated the effects of PL treatments on microbial quality of fresh-cut mushrooms and recommended the application fluencies of up to 12 J/cm<sup>2</sup> in combination with the use of anti-browning agents for extending the microbiological shelf-life of fresh-cut mushrooms without affecting their quality and antioxidant properties. However, our results seem to point out a certain antagonistic effect of the combined use of PL treatments and gellan gum edible coatings regardless the addition of dietary fiber. This could probably be attributed to a protective influence of the gellan coating layer towards microorganisms growing on the surface of the cut fruit.

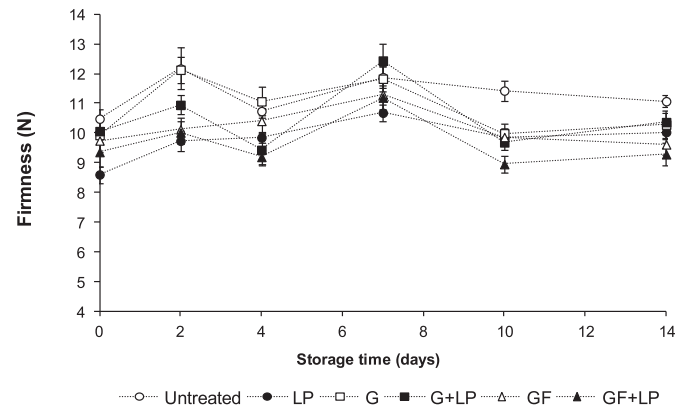
The counts of yeast and mold counts on fresh-cut apples are displayed in Fig. 1C. Yeast and molds act towards the fruit tissues sometimes as strict plant parasites and sometimes as latent parasites, depending on the plant resistance, the virulence of the strain, the competing microbiota, and the ambient conditions. They may present a dramatic change in their growth rate after harvest, when the plant resistance is diminished, and lead to rapid spoilage (Ponce et al., 2002). Initial yeast and mold counts were in the range of 3.0–4.0 log CFU/g. In addition, most treatments resulted into similar or even higher counts than those found in the untreated product. Only uncoated apples treated with PL underwent a reduction in their initial counts. These lower values were consistent through storage. Combinations of PL treatment and edible coatings, with or without incorporated apple fiber, generally resulted into scarce but significant ( $p < 0.05$ ) reductions of the mould and yeast counts with respect to their reference treatments without PL exposure. Our results regarding the effect of PL treatment are consistent with those of Aguiló-Aguayo et al. (2013), who reported that PL treatments caused a significant reduction (approximately 1 order log) in yeast and mold counts on tomatoes kept during 15 days. Other authors have reported significantly lower initial microbial counts on apple slices compared to those presented in this work (Gómez et al., 2012; Ignat, Manzocco, Maifreni, Bartolomeoli, & Nicoli, 2014; Rojas-Graü et al., 2007). In particular, Ignat et al. (2014) reported low counts of mesophilic bacteria (2.2 log CFU/g) and yeast and mold counts below the detection limits (50 CFU/g). Hence, differences when comparing their results with those presented in this work could be, at least in part, originated by the different initial microbial loads reported in each study.

### 3.2. Antioxidant activity

The antioxidant potential status of a vegetable tissue is determined by the type and amount of bioactive compounds present in



**Fig. 2.** Changes in the DPPH radical-scavenging activity of fresh-cut apples as affected by PL treatments, the application of gellan gum-based edible coatings enriched with apple fiber and storage at 4 °C. Bars indicate standard deviations. **PL:** pulsed light treated **G:** gellan gum-coated; **GF:** gellan gum-coated with apple fiber. Results are the mean of two independent experiments assayed in triplicate.



**Fig. 3.** Changes in the firmness of fresh-cut apples as affected by PL treatments, the application of gellan gum-based edible coatings enriched with apple fiber and storage at 4 °C. Bars indicate standard deviations. **PL:** pulsed light treated **G:** gellan gum-coated; **GF:** gellan gum-coated with apple fiber. Results are the mean of two independent experiments assayed in triplicate.

the product. Fig. 2 shows the changes in the DPPH radical-scavenging activity of fresh-cut apples subjected to PL treatments and the application of gellan gum-based edible coatings. No significant differences ( $p < 0.05$ ) were observed among the initial antioxidant potential of fresh-cut apple samples regardless the applied treatment. A dramatic loss of antioxidant potential was observed in both untreated and untreated fruit pieces during the first week of storage. However, apples coated with incorporation of apple fiber exhibited less evident signs of oxidation through storage. Hence, after one week, PL-treated apple cubes with added fiber had lost a 68% of their initial antioxidant value whilst samples only exposed to the PL-treatment exhibited a decrease of 83%, which was similar to that observed for the untreated fruit (81%). These results are in accordance with those reported by Oms-Oliu, Aguiló-Aguayo, et al. (2010), who did not find significant differences between the antioxidant activity of untreated and PL-treated mushrooms (4.8 and 12 J/cm<sup>2</sup>), stored at 4 °C during 15 days. In contrast, gellan-coated apple cubes not exposed to PL exhibited significantly higher antioxidant activities throughout the first week of storage. The addition of fiber was also found to exert a beneficial effect. These results are in accordance to those previously reported by Moreira, Martín-Belloso, Cassani, and Soliva-Fortuny (2015, in press), stating that a gellan gum coating enriched with apple fiber

was effective to maintain the antioxidant capacity of fresh-cut fruit. Accordingly, Robles-Sanchez et al. (2013) reported that a gellan gum-based edible coating effectively increased the antioxidant capacity of fresh-cut mangoes. Also, in recent years, studies have been conducted to demonstrate the functional properties of dietary fibers derived from orange and apple, highlighting their antioxidant properties (Figuerola, Hurtado, Estévez, Chiffelle, & Asenjo, 2005; Marin et al., 2007; MoraesCrizel, Jablonski, Oliveira, Rios, & Rech, 2013). Because of this fact, although apple fiber addition did not result into an immediate increase in the antioxidant potential of fresh-cut apples, its incorporation to the edible coatings formulation could be beneficial for the preservation the antioxidant activity potential of the fruit.

### 3.3. Color

Lightness ( $L^*$ ) is the most indicative parameter associated with the enzymatic browning of fruit and vegetables. Color parameters,  $L^*$  and hue ( $h^\circ$ ), of cut apples as affected by gellan gum-coatings and PL treatments are displayed in Table 1. Both untreated and PL-treated fresh-cut pieces exhibited slightly but significantly higher lightness ( $L^*$ ) values than gellan gum-coated apple pieces. These differences were transitory and almost disappeared during

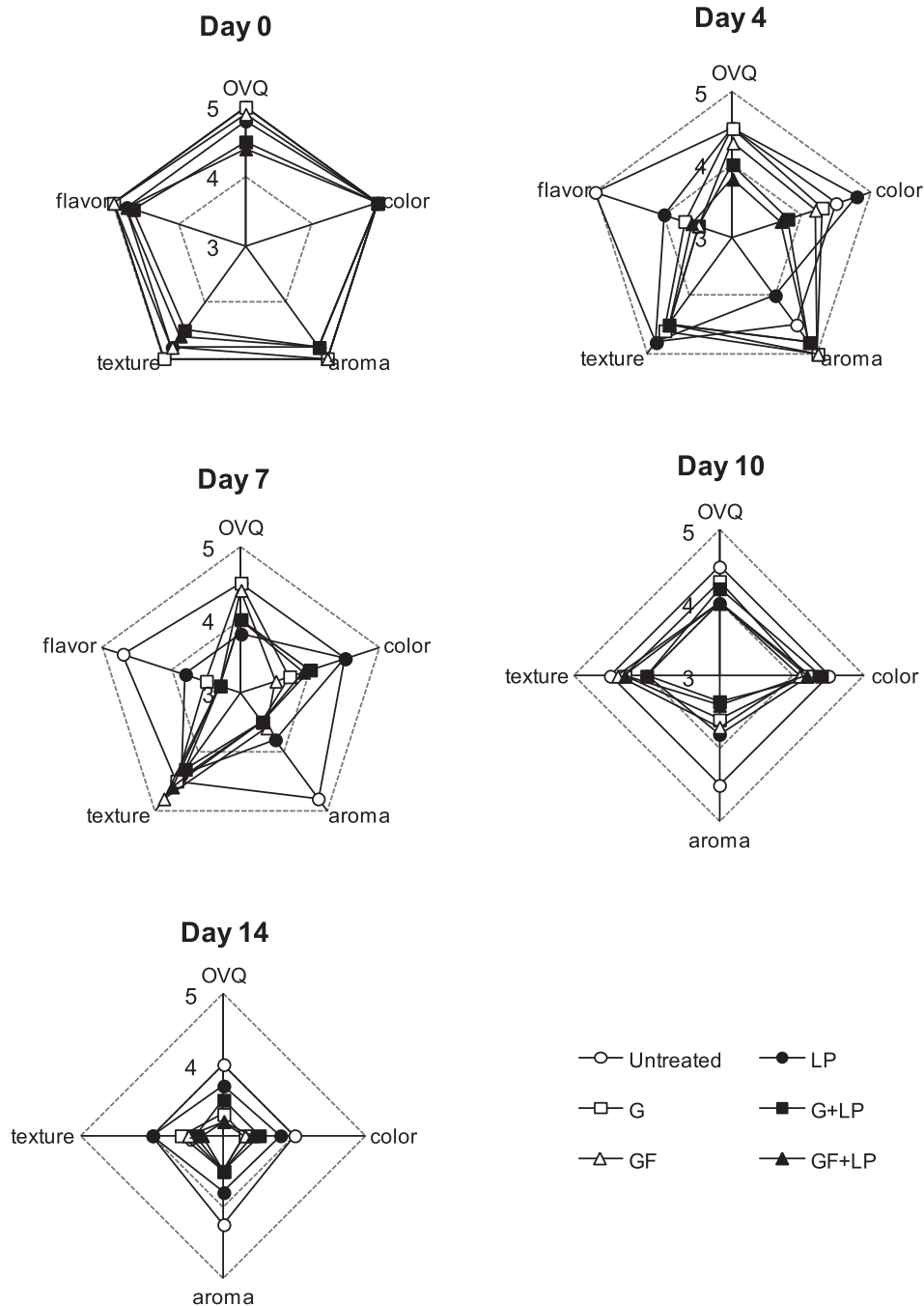
**Table 1**  
Changes in the color attributes of fresh-cut apples as affected by PL treatments, the application of gellan gum-based edible coatings enriched with apple fiber, and storage at 4 °C.

Storage time (days)	0	2	4	7	10	14
$L^*$						
Fresh	81.12 ± 0.46 <sup>aA</sup>	80.41 ± 0.83 <sup>abA</sup>	80.31 ± 0.78 <sup>aA</sup>	80.84 ± 0.34 <sup>aA</sup>	81.34 ± 0.63 <sup>aA</sup>	81.38 ± 0.40 <sup>aA</sup>
LP	79.70 ± 0.68 <sup>abA</sup>	81.63 ± 0.88 <sup>aA</sup>	80.38 ± 0.57 <sup>aA</sup>	80.47 ± 0.70 <sup>aA</sup>	79.58 ± 0.82 <sup>abA</sup>	79.31 ± 0.44 <sup>abA</sup>
G	76.46 ± 1.04 <sup>bcA</sup>	76.93 ± 0.83 <sup>bA</sup>	78.01 ± 0.70 <sup>aA</sup>	79.89 ± 0.42 <sup>abA</sup>	80.01 ± 0.74 <sup>aA</sup>	78.48 ± 1.20 <sup>abA</sup>
G + LP	75.01 ± 0.89 <sup>cb</sup>	77.17 ± 0.88 <sup>abB</sup>	78.38 ± 0.73 <sup>abB</sup>	78.00 ± 0.69 <sup>abB</sup>	79.21 ± 0.76 <sup>aA</sup>	76.62 ± 1.26 <sup>abB</sup>
GF	75.61 ± 0.72 <sup>cbA</sup>	76.93 ± 1.39 <sup>bA</sup>	78.14 ± 0.87 <sup>aA</sup>	79.13 ± 0.66 <sup>abA</sup>	79.38 ± 0.71 <sup>aA</sup>	78.24 ± 1.08 <sup>abA</sup>
GF + LP	73.07 ± 1.17 <sup>cb</sup>	79.98 ± 1.13 <sup>abA</sup>	79.25 ± 0.53 <sup>aA</sup>	80.26 ± 0.27 <sup>abA</sup>	79.27 ± 0.56 <sup>aA</sup>	76.29 ± 1.03 <sup>abB</sup>
$h^\circ$						
Fresh	104.7 ± 0.9 <sup>aA</sup>	103.4 ± 0.6 <sup>abB</sup>	103.2 ± 0.5 <sup>abAB</sup>	103.9 ± 0.4 <sup>abAB</sup>	102.3 ± 0.5 <sup>abB</sup>	101.0 ± 0.5 <sup>abB</sup>
LP	104.3 ± 0.7 <sup>aA</sup>	103.5 ± 0.4 <sup>aA</sup>	105.3 ± 1.1 <sup>abA</sup>	105.4 ± 0.6 <sup>abA</sup>	100.6 ± 0.5 <sup>ab</sup>	99.0 ± 0.6 <sup>bcB</sup>
G	103.2 ± 0.6 <sup>abB</sup>	103.1 ± 0.8 <sup>abB</sup>	104.3 ± 0.4 <sup>abA</sup>	104.5 ± 0.7 <sup>abA</sup>	102.8 ± 0.8 <sup>abB</sup>	99.7 ± 0.9 <sup>bcB</sup>
G + LP	105.5 ± 1.3 <sup>aA</sup>	103.3 ± 1.0 <sup>aA</sup>	105.6 ± 0.7 <sup>aA</sup>	106.2 ± 0.6 <sup>aA</sup>	103.8 ± 0.8 <sup>aA</sup>	103.0 ± 0.6 <sup>aA</sup>
GF	104.6 ± 0.6 <sup>aA</sup>	100.9 ± 0.6 <sup>abC</sup>	104.4 ± 0.8 <sup>abA</sup>	103.2 ± 0.5 <sup>abB</sup>	100.4 ± 0.7 <sup>abC</sup>	98.2 ± 0.6 <sup>cc</sup>
GF + LP	102.8 ± 0.7 <sup>abB</sup>	101.3 ± 0.6 <sup>abB</sup>	102.6 ± 0.7 <sup>abB</sup>	103.2 ± 0.8 <sup>ba</sup>	100.4 ± 0.5 <sup>abC</sup>	98.2 ± 0.6 <sup>cc</sup>

Data is shown as means ± standard deviations. Mean values with different lower case letters in the same column indicate significant differences ( $p < 0.05$ ) between treatments. Mean values with different capital letters in the same row indicate significant differences ( $p < 0.05$ ) with respect to storage time. **LP:** light pulses treatment; **G:** gellan edible coating; **GF:** gellan edible coating with apple fiber.

the subsequent 48 h. From then on, differences between  $L^*$  values of gellan gum-coated PL-treated and untreated apple cubes were not observed or were really scarce. Lightness values of apple pieces stored for 14 days were similar to those of the just processed products regardless the applied treatment. Similarly, no significant differences ( $p < 0.05$ ) between the  $h^\circ$  values of apple cubes subjected to the different treatments were detected and no major changes could be observed throughout storage ( $p < 0.05$ ). As all samples were dipped into an antibrowning solution containing ascorbic acid and calcium chloride, it seems that the application of

other treatments was compatible with this commercial practice, at least in what pertains to color preservation. On the other hand, no signs of browning were detected after PL application. Gómez, Salvatori, et al. (2012), Gómez, García-Loredo, et al. (2012) reported that exposure of cut apples to PL increased surface browning throughout storage as compared with untreated samples. Our results show that the use of ascorbic acid at 1% before PL application minimized browning through refrigerated storage of apple cubes. This is in agreement with the results published by Gómez-López et al. (2005); and Oms-Oliu, Rojas-Graü, et al. (2010).



**Fig. 4.** Changes in the sensory scores of fresh-cut apples as affected by PL treatments, the application of gellan gum-based edible coatings enriched with apple fiber and storage at 4 °C. Bars indicate standard deviations. **PL:** pulsed light treatment; **G:** gellan gum-coated; **GF:** gellan gum-coated with apple fiber. Results are the mean of two independent experiments assayed in triplicate.

### 3.4. Firmness

Fig. 3 depicts the changes in firmness of fresh-cut apples as affected by the application of gellan-gum coatings, the incorporation of apple fiber, PL treatments, and storage time.

Fruits are likely to soften mainly due to hydrolysis of the pectic acids found in the cell walls, with a consequent loss of fluids (Tapia et al., 2008). The protective effects of calcium chloride treatments against texture loss in fresh-cut apples have been widely reported (Gómez et al., 2012; Soliva-Fortuny, Grigelmo-Miguel, Odriozola-Serrano, Gorinstein, & Martín-Belloso, 2001). In the present work, firmness was maintained as a consequence of the applied treatment and along storage regardless of the applied treatment. This fact was as well observed for gellan gum-coated apples, where calcium chloride is used as a cross-linking agent of the polymer matrix. This is in line with the results obtained by other researchers, which underline the beneficial effects of calcium salts toward fruit firmness maintenance when these are incorporated into edible coating formulations (Olivas, Mattinson, & Barbosa-Cánovas, 2007; Rojas-Graü et al., 2008). No further deleterious or beneficial effects could be attributed to the exposure to PL or to the fiber incorporation to the edible coating formulations.

### 3.5. Sensory quality

Fig. 4 shows the changes in five relevant sensory attributes of fresh-cut apples as affected by PL treatments, edible coatings and time under refrigerated storage. The taste of PL-treated samples was determined only during the first week of storage due to microbiological criteria. The rest of the tested parameters in all treated samples were always above the rejection limit for up to 14 days. It is important to highlight that the addition of fiber itself did not entail a decrease in the sensory scores. The presence of off-odors limited the overall acceptability of the treated fruits. Thus, the combination of coatings and PL-treatments led to the lowest scores for aroma especially beyond the first storage week. The scores for this attribute fell below the threshold of acceptability beyond the first week of storage (day 10). Gómez-López et al. (2005) reported a distinctive off-odor, described as “plastic”, appearing right after the application of PL treatments. However, this immediate effect was not so evident in the current case, probably as a consequence of the differences in color, topography and surface/volume ratio among products.

## 4. Conclusions

Pulsed light (PL) is an emerging technology which has considerable potential as an alternative to thermal and chemical methods for rapid and effective inactivation of microorganisms on food surfaces. The application of gellan coatings with PL treatments may be useful to extend the shelf-life of fresh-cut apple. This study provides new data about the effect of these techniques to decontaminate fresh-cut fruits. Indeed, new information on the possible benefits and drawbacks of their combined application are highlighted. In this regard, it is important to point out that the use of edible coatings could act as a limiting factor for the surface decontamination by PL treatments. However, the combination of both treatments has been shown to favor the preservation of the antioxidant value of fresh-cut apples. The application of PL-treatments before the coating formation might avoid this problem. However, it does not allow the application of PL once the product is inside the package. On the other hand, the incorporation of fiber to the coatings was not found to have any negative implication on the quality of fresh-cut apples, thus becoming an interesting alternative for increasing the prebiotic benefits of fresh-cut

commodities.

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