Effect of non-thermal hurdles in extending shelf life of cut apples

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Abstract Pulsed electric fields (PEF), high pressure processing (HPP) and conventional method of heating (90 °C, 60s) were evaluated as blanching methods for fresh cut apples. The settings employed for PEF and HPP were 1.5 kV/cm, 100 pulses, 4 Hz and 600 MPa for 2 min respectively. The blanched samples were soaked in sucrose solution (60°Brix, 60 min) containing ascorbic acid, citric acid, sodium benzoate, and potassium sorbate. The treated samples were packed and pasteurized using either hot water (90 °C, 15 min) or HPP (600 MPa, 10 min). These samples were analyzed for physicochemical and microbiological attributes immediately after treatment and after 2 months of cold storage. The combination of different hurdles in all groups completely inhibited microbial growth. However, in terms of color values and texture retention, the apple cuts treated with PEF followed by hot water pasteurization were of a better quality when compared to HPP pasteurized ones ($P<0.05$).

Keywords Apple · Pulsed electric fields · High pressure processing · Hurdle · Shelf life

Introduction

Peel removal and loss of tissue integrity as a matter of cell rupture in fresh cut products fasten microbial contamination. Additionally, exposing fresh cuts to air and release of endogenous enzymes (mainly polyphenol oxidase (PPO)), due to cutting, lead to enzymatic browning. Hurdle technology not

only contributes to safety in foods but also extends their shelf life. Hurdle technology suggests that one single preservative is not effective enough to prevent food from deterioration and thus multiple preservatives in smaller quantities are required (Leistner 1995). It has been demonstrated that different hurdles in a food might act synergistically (Leistner 1978). The most important hurdles used in food preservation are temperature, water activity, redox potential and preservatives (Leistner 2007), which can hit different targets (cell membrane, pH, a_w , reduction-oxidation potential) within the microbial cells at the same time and disturb the present homeostasis in the microorganism (Leistner 1995).

Food preservatives are mainly used to maintain flavor and texture and to prevent either chemical (browning, oxidation) or biological deterioration (growth of spoilage and pathogenic organisms) in the foods (Soltoft-Jensen and Hansen 2005). One group of these preservatives is organic acids and their salts. Due to the ability of controlling pH value in foods, preventing oxidation (Eklund 1989; Soltoft-Jensen and Hansen 2005) and microbial growth in fruits and vegetables, organic acids and their salts are considered as proper food preservatives. On the other hand organic acids and their salts are also proved to be capable of controlling enzymatic browning along with application of other physical methods. Hence, in most cases both organic salts and supplementary physical methods are applied together. Thermal processing as a conventional method prevents enzymatic browning by heat inactivation of PPO. However, thermal inactivation of enzyme (blanching) may also destroy texture, flavor and cause nutritional losses. Apart from conventional methods, there are other modern processing methods namely, high pressure processing (HPP) and pulsed electric fields (PEF) (Hendricks et al. 1998; Knorr and Angersbach 1998) that can affect simultaneously microbial and enzymatic activity. Mild pressure treatments at 300–600 MPa could inactivate the pressure sensitive vegetative

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cells, molds and yeasts. Furthermore, when high pressure was combined with heat or low pH, the enzymatic browning caused by the pressure resistant enzyme of PPO was notably reduced (Eshtiaghi and Knorr 1993).

Therefore, application of different hurdles simultaneously is expected to result in optimum safety conditions in food products, which in this study was endeavored to be achieved by introducing non-thermal methods (PEF, HPP), osmotic solution, preservatives, packaging and cold storage in fresh apple cubes.

This study is an attempt to find the best combination of different hurdles in order to extend shelf life in fresh cut apples, considering the quality parameters.

Materials and methods

Electrical treatment

A pulsed electric field treatment was applied using a batch exponential decay pulse generator (Elea, Model 802 L, DIL-Germany) to generate an electric field strength of 1.5 kV cm^{-1} . A series of 100 pulses was applied at ambient temperature. A parallel plate treatment chamber consisting of stainless steel electrodes with a gap of 5 cm was used. The pulse repetition rate was 4 Hz. The time required for filling and discharging of the sample was 1 min. A sample of apple cubes (100 g) was immersed in water medium and treated with pulsed electric fields. After PEF treatment the samples were drained over a sieve.

High pressure treatment

High pressure processing (HPP) was performed with a pilot sized instrument (NC- Hyperbaric, Spain, Model Wave 6000/55) with the pressure of 600 MPa and the pressure gradient amount to 100 MPa/min. The vacuumed Polypropylene pouches containing the 100 g of fresh apple cubes were placed in the 55 L pilot-scale processing vessel, and subjected to hydrostatic pressure of 600 MPa for 2 min at 15°C . The pressure medium was tap water. The machine secured by a built-in locking device, and only then the high pressure was applied.

Thermal treatment

The samples were immersed in a water bath containing 90°C water for 60 s and 15 min in order to accomplish blanching and pasteurization respectively.

Sample preparation

Golden Delicious apples with the moisture content of 98 % were purchased from a local market in Quakenbrück,

Germany. The peeled apples were sliced in $1 \times 1 \times 1 \text{ cm}$ cubes. Also a 60 °Brix sucrose osmotic solution containing ascorbic acid (200 ppm), citric acid (200 ppm), sodium benzoate (200 ppm) and potassium sorbate (200 ppm) was prepared. The pH value in this osmotic solution was reported to be 4.5. Then 5 groups (A-E) of almost 100 g apple cubes were weighed and treated as described below:

- A) Blanching in water (at 90°C , 60s), soaking in the osmotic solution, draining over a filter, packing in polypropylene (PP) pouches, pasteurization in water (90°C , 15 min).
- B) PEF blanching (1.5 kV/cm , 100 pulses, 4 Hz) soaking in the osmotic solution, draining over a filter, packing in polypropylene (PP) pouches, pasteurization in water (90°C , 15 min).
- C) HPP blanching (600 MPa, 2 min) soaking in the osmotic solution, draining over a filter, packing in polypropylene (PP) pouches, pasteurization in water (90°C , 15 min).
- D) PEF blanching (1.5 kV/cm , 100 pulses, 4 Hz) soaking in the osmotic solution, draining over a filter, packing in polypropylene (PP) pouches, HPP pasteurization (600 MPa, 10 min).
- E) HPP blanching (600 MPa, 2 min) soaking in the osmotic solution, draining over a filter, packing in polypropylene (PP) pouches, HPP pasteurization (600 MPa, 10 min).

Then half of the samples were analyzed for texture, moisture content, color attributes and microbiological characteristics and the rest were stored at 5°C . The latter half of the samples was tested for the same parameters after 60 days of storage at 5°C subsequently.

Quality parameters evaluation

Texture evaluation

Texture measurements were performed in a Texture Analyzer (Winopal, Ahnsbeck, Germany), equipped with a razor blade. A single puncture measurement was made on each sample (10 mm depth of penetration, velocity of 2.0 mm s^{-1}) with a distance of 25 mm above the sample. Force–distance curves were recorded and firmness (maximum peak force, N) was used as indicator of textural parameters. At least 3 measurements were done for each tested condition.

Moisture content

The moisture content of the sample tissue was measured to know the approximate degree of dehydration. The apple

cubes (initial weight: W_1) were dried in an oven at 105 °C to attain an equilibrium weight, W_2 , then the water content was calculated using Eq. 1.

$$\text{Moisture Content}[\%] = (W_1 - W_2) \times 100/W_1 \quad (1)$$

Microbiological analysis

The total aerobic mesophilic counts, mold—yeast and fecal coliform of the apple samples were determined. Microbial analyses were performed after 2 months of storage at 5 °C in duplicates. Each pouch was opened under aseptic conditions. Apple samples were randomly taken from the pouch and weighed in a filtered stomacher bag. The same amount of covering solution was then added to the bag. The samples were then homogenized in a stomacher (Seward Lab Stomacher, Norfolk, UK) at 230 rpm for 2.5 min. Serial dilutions were prepared in sterilized peptone water. Then the dilutions were cultivated in duplicate on Nutrient Agar, Saborad Dextrose Agar and MacConkey Agar for detecting total count, mold—yeast and *E-Coli* respectively.

Color evaluation

The color of apple cubes was measured using a handheld tristimulus colorimeter (Minolta Chroma Meter CR-300, Osaka, Japan) to determine CIE color space co-ordinates, L^* a^* b^* values. The colorimeter was calibrated against a standard white reference tile. Lightness value, L^* , indicates how dark/light the sample is (varying from 0-black to 100- white), a^* is a measure of greenness/redness (varying from -60 to +60), and b^* is the grade of blueness/yellowness (also varying from -60 to +60). Samples were measured 10 times and the values were expressed as the mean value $\pm$ standard deviation.

Statistical analysis

The test groups were accomplished in 3 replications ($n=3$) and analysis of variance was performed using SAS Statistical software package (V 9.3.1, SAS Institute, NC, USA). Data fitting was considered significant at a probability level of 95 %. Means were separated by least significant difference (LSD) using Tukey test. All samples were analyzed in triplicates.

Results and discussion

Texture

Texture, a major quality indicator of fruits and vegetables and quality loss, is assessed by changes in firmness as an important quality criterion in fruits and vegetables. Actually the main contributor to texture in vegetables is the turgor pressure of their cells, which in its absence the texture softens (Brown 1979). Textural properties of different vegetables are predominantly governed by the physico-chemical characteristics of the cell wall, and how they change during processing. Surveying the results achieved by measuring the texture in all the samples (Table 1), it is noticeable that except for groups A and B in which the textural firmness is properly preserved, in the other groups it has declined in a similar manner ($P>0.05$).

The firming effect of low temperature blanching pretreatments has been widely accepted (Lee et al. 1979) and in the current work blanching in water for a short time (group A) confirmed the already proved fact. Additionally, in other studies heat treatments resulted in tissue softening, which may be attributed to the action of heat-activated pectin

Table 1 Physico-chemical properties of treated cut apples

Test	Treatment groups					
	Day	A	B	C	D	E
Moisture Content (%)	0	93.9 $\pm$ 0.9 ^a	94.7 $\pm$ 0.9 ^a	96.0 $\pm$ 0.9 ^b	96.9 $\pm$ 0.9 ^b	97.3 $\pm$ 0.9 ^b
	60	95.9 $\pm$ 0.9 ^a	95.7 $\pm$ 0.9 ^a	97.4 $\pm$ 0.8 ^b	97.0 $\pm$ 0.7 ^b	97.5 $\pm$ 0.9 ^b
Firmness (N)	0	37.3 $\pm$ 2.1 ^a	40.4 $\pm$ 1.1 ^a	31.6 $\pm$ 0.5 ^b	24.0 $\pm$ 1.2 ^c	29.7 $\pm$ 1.0 ^b
	60	34.2 $\pm$ 1.2 ^a	37.3 $\pm$ 2.0 ^a	20.3 $\pm$ 1.3 ^b	17.4 $\pm$ 0.5 ^b	18.3 $\pm$ 0.9 ^b
L^*	0	64.4 $\pm$ 1.4 ^a	68.3 $\pm$ 0.7 ^a	52.9 $\pm$ 1.3 ^b	50.0 $\pm$ 0.8 ^b	40.5 $\pm$ 2.1 ^c
	60	62.4 $\pm$ 1.3 ^a	65.3 $\pm$ 0.8 ^a	20.3 $\pm$ 0.9 ^b	19.3 $\pm$ 0.6 ^b	18.4 $\pm$ 1.5 ^b
b^*	0	21.7 $\pm$ 1.5 ^b	25.3 $\pm$ 2.3 ^a	20.4 $\pm$ 1.5 ^b	18.1 $\pm$ 1.5 ^c	16.0 $\pm$ 1.2 ^c
	60	16.4 $\pm$ 1.2 ^a	20.3 $\pm$ 1.3 ^a	13.8 $\pm$ 1.0 ^b	11.3 $\pm$ 0.9 ^b	10.6 $\pm$ 1.5 ^b
a^*	0	0.16 $\pm$ 1.01 ^a	0.04 $\pm$ 1.15 ^a	1.30 $\pm$ 0.51 ^a	3.42 $\pm$ 1.24 ^b	4.80 $\pm$ 1.25 ^b
	60	1.20 $\pm$ 0.87 ^a	1.43 $\pm$ 0.82 ^a	7.31 $\pm$ 0.73 ^b	8.32 $\pm$ 1.25 ^b	10.32 $\pm$ 1.49 ^b

A. water-water/ B. PEF-water /C. HPP-water /D. PEF-HPP/ E. HPP-HPP; L^* , b^* and a^* are CIE color attributes

Mean values ($n=3$) $\pm$ S.D. Different lower case letters (a, b, c ...) in the same row indicate significant difference ($P<0.05$)

methyl esterase (PME) (Bartolome and Hoff 1972; Aguilar et al. 1997).

It was also observed that the conventional blanching method, which requires heating in boiling water, was successful in preserving the rigidity in the samples. Blanching is wide known as an enzyme inactivation method in order to maintain both color and flavor in the food product. Blanching may also lead to undesirable nutrients loss (Brown 1979), which is beyond the scope of the current study. However, a mild blanching treatment of 100 °C for a few seconds has been suggested to be effective enough to preserve high organoleptic characteristics (Brown 1979).

On the other hand, minimal food processing allows consumers to have fresh-like quality fruits and vegetables, which distinguishes the result achieved by PEF application in group B. It has been proved that PEF treatment aids electroporation of cell membrane by making them more permeable (Barbosa-Canovas et al. 1998). Actually commercial application of PEF has been mainly concerning liquid products such as juices. However, some other studies have focused on PEF application in combination with other processing methods such as freezing, osmotic dehydration, etc. (Shayanfar et al. 2012; Ade-Omowaye et al. 2003; Qin et al. 1996; Rastogi et al. 1999). The moderate field strength applied (1.5 kV/cm) in this study aimed at increasing permeability and not extraction for which higher amounts of energy are required. Therefore, as it is shown in Table 1, application of PEF did not result in texture softening.

It has been claimed that mild electric field strength of PEF by itself is not sufficiently effective to soften the texture completely. A mild temperature of about 50–60 °C for at least 10 min is required to assist PEF in order to disintegrate the tissue texture to some extent, which is in accordance with the current results (Lebovka et al. 2004). Furthermore, another study stated that sufficient strength and pulse number not only result in membrane changes but also turgor pressure removal in the texture of carrots, potatoes, and apples. These findings suggest PEF effects on loss of cellular turgor pressure, rupture of cell membranes and estimable influence on the viscoelastic properties of plant tissue (Lebovka et al. 2003), which was also proved in another study (Fincan and Dejmek 2003).

Hence, the textural firmness in group B was successfully maintained and in group D and E, which were later subjected to high pressure, the texture softened. In fact it has been proved that during HP treatments there may be changes in cell biopolymers (proteins, polysaccharides, and lipids), which can affect texture/structure of plant foods (Butz and Tauscher 2002; Cano and de Ancos 2005). Textural changes in plant tissues caused by pressure treatments may occur as a result of physical disruption of the tissue. A group of researchers observed cellular structure changes and membrane folding of cauliflower and spinach leaves after HP processing

at 400 MPa with cryofracture scanning electron microscopy (Prestamo and Arroyo 1998). Microscopic studies of onion epidermis cells revealed severe damage to the vacuoles after 300 MPa treatments at 25 °C (Butz et al. 1994). Also HP treatments of 150 MPa caused irreversible cell damage, and critical changes in membrane integrity in lettuce (Schlüter et al. 2008). In other studies the effect of HP on tissue softening was reported, which all justifies tissue softening in groups C, D and E (Kato et al. 1997).

Considering firmness as the efficiency of the treatments regarding maintaining the texture, application of HPP does not seem to be helpful in case of fresh apple cubes; as it led to more texture softening in the samples.

Moisture content

Moisture removal in agricultural products, in a way that the quality is not altered, is of great importance. One of the well-known techniques to remove some water partially from fruits and vegetables is osmotic dehydration (OD) (Ade-Omowaye et al. 2003). One of the key factors in OD effectiveness is the solution concentration (Lerici et al. 1985). It is proved that OD leads to water loss and solid gain (Shi et al. 1995). It was proved that the greater the membrane permeability is the faster osmotic dehydration happens (Zhiming and Le Maguer 1997). Therefore, partial damaging of cell membrane can be beneficial in acceleration of mass transfer, which was already proved to be successful by application of PEF (Shayanfar et al. 2012; Ade-Omowaye et al. 2003; Rastogi et al. 1999). This fact was also observed in group B in which PEF was applied for both blanching and pasteurization (Table 1). However, in group D although the PEF was introduced to the samples, later application of HPP resulted in higher moisture content. The slight increase of moisture amount in group D, E and C may be due to the increased pressure on the medium and re-introduction of the moisture present in the pouches into the apple pieces.

As it is indicated in Table 1 hot water blanching also resulted in reducing moisture content in the apples, which was also reported in a study comparing the effect of hot water blanching on moisture content of potato sticks (Reis et al. 2008). Considering the results achieved in other groups, it is concluded that moisture content decreased in all groups. The greatest amount of moisture content reduction was reported in groups A and B. However, the amount of water content reduction in groups A and B was not significantly different ($P>0.05$).

Microbial study

Microorganisms apply every possible repairing mechanisms for their homeostasis to overcome the hostile environment in stable hurdle-technology. As the result of repairing mechanism, the microorganisms completely use up their energy to maintain their initial status, which results in their death or

inactivation. This leads to an autosterilization of such foods (Leistner 1995). Due to autosterilization effect of hurdle-technology, foods become safer during storage, especially at ambient temperatures. The same phenomenon was observed in a similar study with high moisture content fruit products in which the population of a variety of bacteria, yeasts and molds decreased rapidly during unrefrigerated storage as a result of the applied hurdles (pH, a_w , sorbate, sulfite) and no microbial growth was reported (Tapia de Daza et al. 1996). Likewise, in the current study all samples, disregarding how they were treated, could maintain the initial microbial population right after treatment up to 2 months of storage at 5 °C ($<1.0 \times 10^{-1}$ CFU/ml). Organic acids mechanism is preceded by the undissociated acid molecule entry into the living cell. Entry of the undissociated acid molecule into the microorganism cell makes it try to maintain its internal pH value by extruding the organic acids or proton and losing all its energy, which ends in its death. Benzoic salts are mainly effective against yeast and molds (Eklund 1989); however, sorbic acid not only acts against yeast and molds but also harnesses the growth of a wide range of bacteria (Soltoft-Jensen and Hansen 2005). Citric acid also demonstrates antimicrobial properties due to its acidulation. However, citric acid is mainly applied as an antioxidant by chelating the metal ions which catalyses oxidation (Pathanibul et al. 2009). The results achieved in this study indicated no difference ($P>0.05$) and all groups could effectively hamper microbial growth.

Additionally, in a similar work accomplished on potato cubes application of 400 MPa for 15 min at 50 °C along with immersing the potato cubes in citric acid solution of 0.5–1.0 % resulted in complete microbial inactivation (Eshtiaghi and Knorr 1993). Furthermore, *E.coli* population was decreased more than 5 log by application of more than 250 MPa in carrot juice containing Nisin, which supports the current results (Pathanibul et al. 2009). Inactivation of microorganisms by PEF is already proved to be due to the electromechanical instability of the cell membrane with irreversible pore-formation (electroporation) occurring at trans-membrane potentials in excess of 1 V (Barbosa-Cánovas et al. 2004). Electroporation may also favor the preservatives introduction into the microorganisms facilitating their inactivation.

Based on the recorded results, it was concluded that all the suggested methods were successfully effective in microbial inactivation and the microbial population of all aerobic mesophilic, coliform and mold and yeasts remained constant until the last day of storage. There was no difference perceived between all the groups in their efficiency ($P>0.05$).

Color evaluation

The CIE color attributes L^* , a^* and b^* ($\pm$ standard deviation) of treated cut apples right after processing and after 2 months of storage were displayed in Table 1.

Regarding L^* value, groups A and B showed higher values in comparison to the rest of the groups. Lower L^* value is an indicator of darkening and as it was proved in similar studies conventional blanching inactivated enzymatic browning and therefore higher values of L^* were observed (Rawson et al. 2011; Patras et al. 2011). The samples blanched and pasteurized by PEF indicated similar results and were successful in retaining the initial color, which may be due to enzyme inactivation. The subtle change of CIE color values on the 60th day of storage in both groups of A and B (Table 1) supported the idea of browning enzyme inactivation in these two groups. Enzymatic browning is one of the most limiting factors in the shelf life of fresh cut products. During processing the product undergoes various operations, which break the cell walls and as a result facilitate enzyme (mainly polyphenol oxidase) and substrate contact (Whitaker and Lee 1995). However, the rest of the groups became darker after processing and this darkening trend exacerbated until the end of storage time.

Assessing a^* values suggested Group A, B and partially C are less red-colored, which can be considered as an indicator of enzymatic browning. Actually in these samples browning was considerably less than the massive amounts observed in groups D and E. Similarly b^* values followed the same trend and the initial yellow color in apple samples was vividly higher in groups A and B.

The use of PEF is a new technology suggested to inactivate microorganisms and enzymes with minimal resultant temperature increase (Qin et al. 1996). In another alike study increasing intensity (0.9–1.9 kV/cm) and duration of PEF treatment on a culture of potato cells increased the PPO release in the medium (Knorr and Angersbach 1998). However, the initial color in the groups treated with PEF was maintained. The retention of the initial color in PEF treated samples might be because of facilitated access of anti-browning agents into the cells via electroporation. Additionally as it is indicated in Table 1, even lowering pH to 4.5 in HPP treated samples, which was suggested to minimize PPO activity (Whitaker 1994), failed to prevent browning. Nevertheless, it has also been reported that PPO in apple is quite tolerant to acidity and at pH value of 3.0 retains 40 % of its maximum activity (Nicolas et al. 1994). In fact when aiming at enzyme inactivation by applying high pressure technology, the pressure requirements vary depending on the enzyme. Some enzymes need to undergo high pressures as above 1,000 MPa to be inactivated (Hendricks et al. 1998). The findings of the current work are in accordance with the results of other studies (Asaka and Hayashi 1991; Anese et al. 1995; Gomes and Ledward 1996).

It has been reported that application of low pressure results in pressure-induced membrane damage and enzyme activation (Seyderhelm et al. 1996), which supports extensive browning in HPP treated samples. Additionally, it was also reported that application of 400 MPa for 10 min at 25 °C activated PPO in pear (Asaka and Hayashi 1991). Similarly PPO activation by

low pressures in raw carrot and apple extracts was described (Anese et al. 1995). Another set of experiments carried out on whole food products revealed the browning effect of high pressure treatment in mushrooms, apples and potatoes (Gomes and Ledward 1996). In fact PPO is introduced as the second most pressure tolerant enzyme after peroxidase (Seyderhelm et al. 1996; Valdramidis et al. 2009) and although the pressure applied in this study was higher than the amount already applied in the mentioned studies, an amount of 600 MPa is not helpful in PPO inactivation either. However, in order to inactivate 90 % of the PPO, it is suggested to apply either 900 MPa at 25 °C for 1 min or to combine ordinary pressure levels with other methods such as blanching and refrigeration in lower pH values (Anese et al. 1995), which all failed to be successful in the current work. In a similar study on potato cubes combination of 400 MPa for 15 min at 50 °C with citric acid solutions (0.5 or 1.0 %) notably reduced initial PPO activity (Eshtiaghi and Knorr 1993). This result is comparable with the results achieved in group C in which HPP blanching was followed by conventional pasteurization. Obviously application of reducing agents assisted HHP treatments to inhibit enzymatic browning, which was also declared in a similar study (Valdramidis et al. 2009).

Visual observations

The stored apple cubes were also studied for visual appearance right after processing and also on the last day of storage. In fact this observation was an evidence for accuracy of the results recorded by measuring colorimetric attributes. The visual observations also suggested although groups A and B could maintain their initial visual appearance, the other three groups failed to retain their initial color. Group E turned completely brown right after processing and groups C and D could not preserve their initial color in comparison to groups A and B. However, it is worth mentioning that visual evaluation of the samples suggested a lighter color in group C comparing with group D, which was in accordance with the results in colorimetric attribute measurements. There was no significant changes observed in visual appearance of the groups after storage when compared to their first day of storage ($p < 0.05$).

Conclusion

According to the achieved results the combination of chemical preservatives was helpful in extending the shelf life in fresh cut apples without any microbial population increase. However, visual quality parameter is of high importance in assessing the product quality, which was better maintained in samples blanched by application of PEF. In fact these results

are similar to those of achieved in the conventional method of blanching. But considering the low energy required and less temperature increase in the final product and the freshness in the pieces, PEF treatment is preferred. Additionally application of HPP either as blanching method or pasteurization not only failed to retain the initial color in the product, but also led to massive browning in the product and also texture softening. It is concluded the application of HPP under pressures of 600 MPa is not effective in PPO inactivation in fresh cut apples. In order to lessen enzymatic browning by application of HPP with higher levels of pressure, maintenance of the product firmness should also be taken into consideration, which may be applicable with the favor of texture hardening agents such as calcium ions. Application of PEF contributed to retaining color and firmness in cut apples and reduced the initial amount of water content.

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