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Quality retention and potential shelf-life of fresh-cut lemons as affected by cut type and temperature

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Abstract

The effects of four cut types (wedges, slices, 1/2 and 1/4 slices) of 'Lisbon' lemons (*Citrus lemon* L.) and storage at four temperatures (0, 2, 5 and 10 °C) on post-cutting life were studied. Respiration rates of all cut types that were stored at 0, 2 and 5 °C up to 8 days were 2–5 times higher than those of the whole lemons, while the increase was up to 12-fold at 10 °C. Small differences among treatments were observed in the post-cutting changes of color parameters and chemical composition. Based on sensory analysis, the four cut types remained marketable for up to 7 days at all tested temperatures, but only the wedges, slices, and 1/2 slices stored at 0, 2 and 5 °C preserved their sensory attributes for up to 10 days. Good retention of vitamin C (about 85% ascorbic acid and 15% dehydroascorbic acid) and antioxidant capacity were found after 10 days at 0, 2, and 5 °C. Ethanol was the main fermentative metabolite found (88% of the total) and its concentration increased by up to three-fold in slices, 1/2 and 1/4 slices after 10 days at 10 °C. Total phenolics concentrations decreased gradually throughout the storage period in all cases.

Keywords: *Citrus lemon* L.; Citrus; Lightly processed; Nutritional quality; Vitamin C; Antioxidant capacity; Phenolic compounds; Ethanol; Acetaldehyde

1. Introduction

Citrus fruit are non-climacteric, with relatively low respiration and ethylene production rates, do not undergo any major softening or compositional changes after harvest and, therefore, can normally be stored for relatively long periods of 6–8 weeks (Kader, 2002). Citrus fruit are very important agricultural products in many countries where some times there is an over-production. In this case the presentation of these whole fruit as fresh-cut fruit will diversify and add value to the product, and avoid any decrease in prices. The fresh-cut fruit market continues to expand both for the food service and retail markets. However, expansion of fresh-cut citrus fruit has been slow due to their relatively short shelf-life and excessive juice leakage from the cut segments. The main problem is that when cells are ruptured by cutting during minimal processing, wound-induced biochemical reactions are initiated that shorten storage life (Cantwell and Suslow, 2002). While there is considerable interest in fresh-cut lemon products, there are very few published studies on post-cutting maintenance of quality of fresh-cut citrus products and to the best of our knowledge none on fresh-cut lemons.

Among fruit and vegetables, citrus fruit are reported to be a very rich source of health promoting substances (Benavente-García et al., 1997). Antioxidant activity of citrus fruit is mainly due to ascorbic acid, polyphenols and carotenoids since citrus fruit have a high content of these compounds (Peleg et al., 1991; Marlett, 1992; Marlett and Vollendorf, 1994). The ascorbic acid content of some lemons has been reported to be as high as 680 mg L^{-1} of juice and is affected by the growing area, maturity of the fruit when picked, and the length of time the fruit was kept in storage (Sinclair, 1984). The total phenolics content in peeled lemons and their peels is

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significantly higher than that in peeled oranges and grapefruit and their peels, respectively (Gorinstein et al., 2001). Lemons also produce fermentative metabolites (ethanol, acetaldehyde and ethyl acetate) under aerobic conditions and these volatiles can have an impact on sensory attributes if they are present in high amounts.

The purpose of this work was to evaluate quality maintenance of fresh-cut lemons processed into four cut types (wedges, slices, half slices and quarter slices) and stored at 0, 2, 5, and 10 °C to determine their shelf-life based on the main sensory and nutritional quality attributes.

2. Materials and methods

2.1. Plant material and sample preparation

Dark green 'Lisbon' lemons (*Citrus lemon* L.) were harvested on March 31 and were transported to the packinghouse where they were washed and stored at 11–12 °C and 90% RH until July 11 when they were degreened and packed. Packed lemons were transported to UC Davis (California, USA) where they were kept in a cold room at 5 °C and 90% RH. The next morning, fruit were processed in a clean room at 10 °C where the lemons were wiped with a wet cheesecloth before cutting into the following cut types. Wedges: eight wedges per lemon that were cut with a sharp knife; slices: 5 mm-thick crosswise slices cut with a slicing machine (Rival 1101W, Rival MFG, Co., Kansas, USA); 1/2 slices: whole slices cut with a sharp knife in two similar portions; 1/4 slices: whole slices cut with a sharp knife in four similar portions.

All cut types were washed with chlorinated water (100 μL L^{-1} NaClO) at 4–5 °C for 2 min and rinsed for 1 min in tap water at 4–5 °C. The excess surface water remaining on the products was absorbed with paper towels and then they were placed in containers as follows: wedges: eight wedges with an average weight of about 100 g were placed into 200 mL rigid plastic containers; slices: about 175 g of slices were placed into 350 mL rigid plastic containers trying to rebuild the complete lemon; 1/2 slices: approximately 100 g of 1/2 slices were placed into 200 mL rigid plastic containers trying to rebuild a half of the lemon; 1/4 slices: about 100 g of 1/4 slices were placed into 200 mL rigid plastic containers. Three replicates per treatment and storage duration (0, 4, 7, and 10 days) were prepared and stored at 0, 2, 5 and 10 °C.

In order to determine the respiration and ethylene production rates of the entire lemons and the four fresh-cut products, three replicates per treatment were kept at 0, 2, 5 and 10 °C and ventilated with a continuous flow of humidified air at 10 mL min^{-1}. About 400 g of whole lemons were placed in 2000 mL gas tight glass jars while 400 mL gas tight glass jars were used to hold about 150 g of wedges, slices, 1/2 slices and 1/4 slices. The respiration and ethylene production rates were measured daily for 8 days.

2.2. Gas analysis

Samples of 10 mL were taken from the exit flow air from the glass jars and changes in CO_2 and C_2H_4 concentrations were determined relative to known standards by an infrared gas analyzer (Horiba PIR-2000 R; Horiba Instruments Co., Irvine, CA, USA) and a gas chromatograph (Carle model 211, Carle Instruments Co., Anaheim, CA, USA) equipped with a flame ionization detector, respectively.

2.3. Physico-chemical quality analysis

On processing day and after 4, 7 and 10 days at all temperatures used, the main quality parameters of 21 pieces per treatment, distributed in three replicates of seven pieces each, were determined. Segment color was determined by a Minolta colorimeter (CR-300, New Jersey, USA), then the segments in each replicate were pressed in a manual press to extract the juice. Soluble solids contents (SSC) were determined by a temperature compensated refractometer (ABBE 10450, American Optical Co., Bufalo, NY, USA). pH and titratable acidity (TA) of the juice were monitored by an automatic titration system (Radiometer, Copenhagen, Denmark).

2.4. Sensory analysis

Dehydration, chilling injury, off-odors, albedo browning, membrane browning, segment separation and leakage were evaluated by the authors on a five-point scale of damage incidence and severity (1: none; 2: slight; 3: moderate, limit of usability; 4: severe; 5: extreme) and a mean value was obtained. Overall visual quality was evaluated using another five-point scale (1: extremely poor; 2: poor; 3: fair, limit of usability; 4: good; 5: excellent).

2.5. Extraction and analysis of vitamin C

Three samples of 30 mL juice per treatment were placed in plastic vials and frozen in liquid nitrogen and kept at −80 °C until analyzed. Procedures used to determine the vitamin C content were as described by Wright and Kader (1997) based on the method of Zapata and Dufour (1992) for the determination of ascorbic acid and dehydroascorbic acid by HPLC.

2.6. Fermentative metabolites

Three samples of 5 mL juice per treatment were placed in crimp-seal 10 mL vials containing 2 g of NaCl in three replicates per treatment. Then they were sealed and frozen at −80 °C for less than 2 months when the analysis of fermentative metabolites was conducted. The static headspace technique was used with a 37 °C sample incubating temperature for 15 min before injecting in GC as described by Pelayo et al. (2003). When the samples were ready

they were injected in a GC (HP5890) equipped with a flame ionization detector (FID) and 60/80 Carbopack B/5% Carbowax 20 M, 1.8 m × 2 mm i.d. column (supelco, bellafonte, PA). Concentrations of the fermentative metabolites were calculated by using standard aqueous solutions and by preparing the corresponding standard curves under the same conditions as those used for the fresh-cut lemon samples.

2.7. Total phenolics contents

The amount of total phenolics was determined using the Folin–Ciocalteu reagent, as described by Singlenton and Rossi (1965). A 1 mL of lemon juice was diluted with 80% aqueous methanol. Appropriately diluted extract (0.2 mL) was mixed with 1.0 mL of Folin–Ciocalteu reagent (1:10, v/v diluted with water) and incubated for 1 min before 0.8 mL sodium carbonate (7.5%, w/v) was added. The mixture was incubated for 1 h at room temperature before absorption was measured at 765 nm (Shimadzu UV-1601, UV–vis spectrophotometer, Columbia, Maryland, USA). Total phenolic content was expressed as gallic acid equivalents (GAE) in $\mu g\,mL^{-1}$ of lemon juice. All extracts were analyzed in triplicate.

2.8. Total antioxidant activity

The antioxidant activity in three replicates of intact and fresh-cut lemons was based on the evaluation of the free radical scavenging capacity of the juice according to the method described by Brand-Williams et al. (1995). DDPH is a stable free radical and the assay can accommodate a large number of samples in a short period of time and it is sensitive enough to detect active principles at low concentrations. A solution of 0.1 mM DPPH (2,2-diphenyl-2-picryl-hidrazyl) in methanol was prepared. An aliquot of 50 μL of ascorbic acid or lemon juice was added to 950 μL of this solution. Diluted samples (1:10 or 1:12) of lemon juice in 80% aqueous methanol (v/v) were used. The antioxidant activity was measured by decreasing the absorbance at 515 nm (Shimadzu UV-1601, UV–vis spectrophotometer, Columbia, Maryland, USA).The results were expressed as ascorbic acid equivalent antioxidant capacity (AEAC).

2.9. Statistical analysis

The experiment was a 4 × 4 × 4 factorial design (temperature, time and cut type) and subjected to analysis of variance using Statgraphics Plus (Version 5.1) software. For each attribute and factor (single or combined), the percentage of the sum of total squares was calculated. Mean values were subjected to the least significant difference test (LSD) at $P \leq 0.05$ according to Montgomery (2004).

3. Results and discussion

3.1. Respiration and ethylene production rates

The respiration rates (CO_2 production) reached by all cut types stored at 0, 2 and 5 °C up to 8 days were between 4.5 and 8 mg kg^{-1} h^{-1} without significant differences among treatments. These values are 2–5 times higher than the values obtained for the whole lemons stored at same temperatures (1.5–2 mg kg^{-1} h^{-1}). At 10 °C, the respiration rates of the whole lemons were a little higher (2–3 mg kg^{-1} h^{-1}), and an increase of up to 12-fold was observed for wedges and slices without differences between them (10–25 mg kg^{-1} h^{-1}). Much higher respiration rates were observed in the 1/2 and 1/4 slices, reaching 30 mg kg^{-1} h^{-1} after 4 days, 60 mg kg^{-1} h^{-1} after 5–6 days, and 100 mg CO_2 kg^{-1} h^{-1} after 8 days at 10 °C. The increase from days 4 to 8 was mostly due to microbial growth, since after 7–8 days at 10 °C the first visible symptoms of fungal attacks by *Penicillium* spp. were noticed in 1/2 and 1/4 slices of fresh-cut 'Lisbon' lemons. Our respiration rate data are in the same range as those reported by Ben-Yehoshua et al. (1979) who observed higher respiration rates in peeled than in intact citrus fruit.

The ethylene production rate at 0 °C for the whole lemons was approximately 15 nL kg^{-1} h^{-1} and was four-fold higher for all cut types stored at 0 °C from days 1 to 7 without large differences among them (40–60 nL kg^{-1} h^{-1}). However, after 8 days at 0 °C, the rates reached more than 100 nL kg^{-1} h^{-1} for 1/2 and 1/4 slices, which was probably due to microbial growth. A similar trend was found at 2 °C with ethylene production rate by the whole lemons of 35 nL kg^{-1} h^{-1} and up to four-fold higher rates by the cut products until day 7 without differences among them (100–140 nL kg^{-1} h^{-1}). Again, after 8 days at 2 °C the rates by all kinds of cuts reached 170–200 nL kg^{-1} h^{-1}.

At 5 °C the ethylene production rates by the whole lemons were 40–45 nL kg^{-1} h^{-1} and an approximately four-fold increase was measured for all cut types up to day 7 (150–210 nL kg^{-1} h^{-1}) with another small increase on day 8 in all cases.

As expected, higher ethylene production rates were obtained at 10 °C with 130–180 nL kg^{-1} h^{-1} for the whole lemons. Small differences were found among cut types kept at 10 °C. During the first 7 days approximately a 10-fold increase was recorded (1–1.5 μL kg^{-1} h^{-1}) with values of 2–3 μL kg^{-1} h^{-1} on day 8.

3.2. Physico-chemical attributes

The analysis of variance of the color parameters (Table 1) shows how the interaction of the three factors was significant for lightness (L^* value), chroma and hue angle (Table 2). The percentage of variance explanation is very low due to the extremely high residual values obtained (about 80%), which may be due to variation in the location where color measure-

Table 1
Analysis of variance of the color parameters of fresh-cut 'Lisbon' lemon products stored at 0, 2, 5, and 10 °C for up to 10 days

	d.f.	L^*	Chroma	Hue angle
Main effects				
A: temperature	3	0.2[a] NS	0.7*	0.4*
B: time	3	8.7***	2.3***	12.9***
C: cut	3	2.0***	7.8***	14.7***
Interactions				
A × B	9	0.6 NS	2.3***	1.0*
A × C	9	1.2*	0.4 NS	0.4 NS
B × C	9	2.4***	3.5***	5.3***
A × B × C	27	3.1**	2.6*	2.5**
Residual	1280	81.8	80.4	62.8
SCT (sum total squares)	1343	25014.6	6872.8	16654.8

NS: not significant. *,**,*** Significant to $P \leq 0.05$, 0.01 and 0.001, respectively.
[a] Percentage sum of total squares.

ments were done in non-homogeneous parts of the tissues at all times (membrane tissues, segments, etc).

The lightness of fresh-cut 'Lisbon' lemons on the processing day was 50 ± 3.0 (Table 2) and few changes were observed. The general trend was to slightly increase the initial value. Greater differences were observed for the smaller cut size, 1/4 slices, after 10 days where at all temperatures slight increases were found. Theses increases could be due to tissue dehydration. The chroma value was generally maintained or slightly decreased in all cases when compared to initial value (13.6 ± 1.9). A slight decrease in the color intensity after 10 days at 10 °C was noted in slices, 1/2 slices and 1/4 slices, probably due to water loss from the tissues. The hue angle recorded on processing day was 104.2 ± 1.3 and slight increases were registered during shelf life for 1/2 and 1/4 slices and also for slices after 10 days at all temperatures tested. However no changes were observed at any time for wedges when compared to the initial values.

The analysis of variance of the SSC, pH and TA (Table 3) indicates that the observed changes were mainly due to the storage time since it has the higher percentage of variance explanation. The double interactions where the storage time is present are significant and are presented in Tables 4 (temperature × time) and 5 (time × cut type). The initial SSC ($7.3 \pm 0.1\%$) did not change with time and temperature of storage (Table 4). A slight increase in pH and a slight decrease in TA were observed in almost all cases relative to the initial pH (2.64 ± 0.02) and TA ($5.76 \pm 0.50\%$) up to days 4 and 7, respectively, with no further changes between days 7 and 10.

Only small changes in SSC were noted at all sampling times when compared to initial values ($7.3 \pm 0.1\%$) for all cut types (Table 5). As the size of the fresh-cut lemon pieces became smaller, the mean pH values increased and the TA decreased after all storage durations (Table 5). This fact may be due to a higher loss of electrolytes from the smaller pieces with a larger cut surface area. Again, with longer storage time within treatments with the same type of cut, the mean TA decreased to minimum values after 7 and 10 days, without differences among them, and with significant differences from the initial TA ($5.76 \pm 0.50\%$).

Table 2
Interaction (temperature × time × cut type) in color parameters L^* chroma and hue angle of fresh-cut 'Lisbon' lemon products stored at 0, 2, 5, and 10 °C for up to 10 days

Color parameter and temperature (°C)	Time												
	Initial	Day 4				Day 7				Day 10			
		Wedges	Slices	1/2 slices	1/4 slices	Wedges	Slices	1/2 slices	1/4 slices	Wedges	Slices	1/2 slices	1/4 slices
L^*[a]													
0	50.0	51.7	55.6	51.0	51.7	52.6	55.5	50.2	51.5	55.6	52.5	51.1	54.4
2	50.0	53.3	54.6	51.9	52.2	51.5	53.4	51.0	51.6	53.5	55.4	52.4	53.3
5	50.0	53.4	56.6	53.2	52.4	51.6	50.2	53.2	51.8	51.1	52.4	53.9	54.6
10	50.0	50.7	56.2	50.8	52.6	53.4	51.5	50.5	51.6	51.8	53.7	51.2	53.2
Chroma[b]													
0	13.6	13.2	12.0	12.2	12.8	13.2	10.8	11.9	12.6	14.4	11.1	11.9	14.0
2	13.6	14.3	11.5	13.0	13.1	13.7	12.1	12.4	12.2	13.7	12.5	13.7	14.2
5	13.6	14.7	11.2	12.8	14.0	15.4	11.8	12.3	12.1	13.5	12.4	13.8	14.4
10	13.6	14.4	11.5	13.5	13.9	14.5	12.4	13.1	13.0	13.5	11.1	12.2	11.5
Hue angle[c]													
0	104.2	104.7	105.5	107.6	109.5	104.5	106.9	106.9	108.8	105.4	107.6	109.9	109.9
2	104.2	105.3	105.7	107.9	108.9	104.1	107.0	108.1	109.7	105.9	106.1	108.2	108.9
5	104.2	103.9	107.4	106.6	108.9	103.8	104.2	107.2	109.9	105.4	106.1	106.7	109.6
10	104.2	104.8	104.8	107.4	107.4	102.5	105.2	106.4	108.8	104.2	106.5	109.0	112.3

[a] S.E. = 0.87, LSD ($P \leq 0.05$) = 2.42.
[b] S.E. = 0.45, LSD ($P \leq 0.05$) = 1.26.
[c] S.E. = 0.62, LSD ($P \leq 0.05$) = 1.73.

Table 3
Analysis of variance of the main quality attributes of fresh-cut 'Lisbon' lemon products stored at 0, 2, 5, and 10 °C for up to 10 days

	d.f.	SSC	pH	TA	Ascorbic acid	Dehydro-ascorbic acid	Total vitamin C	Ethanol	Acetaldehyde
Main effects									
A: temperature	3	1.6[a] NS	1.2***	1.3***	1.3 NS	0.4 NS	1.3 NS	12.1***	18.0***
B: time	3	21.1***	80.6***	63.1***	43.5***	36.9***	27.7***	25.4***	14.6***
C: cut	3	17.3***	6.7***	15.7***	5.9***	19.0***	13.0***	5.9***	0.2 NS
Interactions									
A × B	9	7.8***	2.5***	2.5***	5.3**	13.0***	8.9***	25.1***	26.6***
A × C	9	3.8 NS	0.3 NS	0.6 NS	0.8 NS	1.4 NS	1.2 NS	5.1***	6.0***
B × C	9	12.9***	2.5***	5.8***	7.5***	9.9***	9.6***	5.9***	3.8**
A × B × C	27	6.0 NS	1.0 NS	1.4 NS	11.0**	7.7***	12.9***	10.2***	10.3***
Residual	128	29.5	5.2	9.6	24.7	11.7	25.4	10.3	20.5
SCT (sum total squares)	191	12.9	1.4	79.5	7848.2	1598.6	11152.5	130234.0	1725.2

NS: not significant. *,**,***Significant to $P \leq 0.05$, 0.01, and 0.001, respectively.
[a] Percentage sum of total squares.

3.3. Sensory evaluation

Slight dehydration was observed after 4 days in most cut types at all temperatures while after 7 days of storage the severity of dehydration symptoms reached the limit of usability for all cut types stored at all temperatures. After 10 days, the 1/4 slices stored at all temperatures and the slices and 1/2 slices stored at 10 °C exhibited severe dehydration, while the dehydration of the wedges was still within the range of acceptability. This fact can be related to the lightness increase reported above.

No chilling injury symptoms were detected at any time in any treatment while very slight albedo and membrane browning occurred in a few treatments. Moderate and severe off-odors were detected after 7 and 10 days, respectively, in all cut types stored at 10 °C. A severe to extreme segment separation was observed after 10 days at 10 °C in all cut types except the wedges at 10 °C where this disorder was moderate. No leakage was found at any time except in most 1/4 slice treatments after 7 and 10 days where this disorder was rated from slight to moderate.

According to all these sensory quality attributes, the four cut types can be stored up to 7 days at 0–10 °C, but visual appearance was maintained better at 5 °C or lower temperatures. Lemon wedges, slices, and half slices were still acceptable after 10 days at 0, 2 and 5 °C. The shelf-life of lemon wedges kept in air at 5 °C is in the same range as the 7 days reported by Pretel et al. (1998) as shelf-life at 4 °C of wedges of 'Salustiana' oranges that were peeled enzymatically or manually and stored under MAP conditions. Rocha et al. (1996) obtained a 5 day shelf-life (based on sensory quality) of orange sections stored at 4 °C.

Table 4
Interaction (temperature × time) in SSC pH and TA of fresh-cut 'Lisbon' lemon products stored at 0, 2, 5, and 10 °C for up to 10 days

Temperature (°C)	Time (days)			
	Initial	4	7	10
SSC (%)[a]				
0	7.3	7.2	7.6	7.3
2	7.3	7.1	7.6	7.3
5	7.3	7.3	7.4	7.2
10	7.3	7.4	7.4	7.3
pH[b]				
0	2.64	2.79	2.81	2.71
2	2.64	2.82	2.82	2.69
5	2.64	2.80	2.82	2.70
10	2.64	2.87	2.82	2.72
TA as citric acid (mg L^{-1})[c]				
0	57.6	49.3	44.7	44.8
2	57.6	51.7	46.5	46.3
5	57.6	52.0	46.1	46.0
10	57.6	50.9	46.4	40.9

[a] S.E. = 0.05, LSD ($P \leq 0.05$) = 0.4.
[b] S.E. = 0.01, LSD ($P \leq 0.05$) = 0.06.
[c] S.E. = 0.7, LSD ($P \leq 0.05$) = 6.2.

Table 5
Interaction (cut type × time) in SSC, pH and TA of fresh-cut 'Lisbon' lemon products stored at 0, 2, 5, and 10 °C for up to 10 days

Cut	Time (days)			
	Initial	4	7	10
SSC (%)[a]				
Wedges	7.3	7.4	7.7	7.2
Slices	7.3	7.3	7.6	7.4
1/2 slices	7.3	7.2	7.6	7.4
1/4 slices	7.3	7.0	7.2	7.1
pH[b]				
Wedges	2.64	2.77	2.78	2.67
Slices	2.64	2.80	2.81	2.69
1/2 slices	2.64	2.83	2.83	2.71
1/4 slices	2.64	2.87	2.85	2.75
TA as citric acid (mg L^{-1})[c]				
Wedges	57.6	56.5	49.8	48.2
Slices	57.6	51.8	47.2	46.7
1/2 slices	57.6	49.6	45.3	44.1
1/4 slices	57.6	46.0	41.4	39.2

[a] S.E. = 0.05, LSD ($P \leq 0.05$) = 0.3.
[b] S.E. = 0.01, LSD ($P \leq 0.05$) = 0.05.
[c] S.E. = 0.7, LSD ($P \leq 0.05$) = 4.3.

Table 6
Interaction (temperature × time × cut type) in ascorbic acid, dehydroascorbic acid and total content in vitamin C of fresh-cut 'Lisbon' lemon products stored at 0, 2, 5, and 10 °C for up to 10 days

Temperature (°C)	Time												
	Initial	Day 4				Day 7				Day 10			
		Wedges	Slices	1/2 slices	1/4 slices	Wedges	Slices	1/2 slices	1/4 slices	Wedges	Slices	1/2 slices	1/4 slices
Ascorbic acid[a]													
0	384	345	390	405	408	254	289	288	303	341	339	367	379
2	384	376	344	471	360	270	256	209	370	326	352	338	331
5	384	312	410	435	413	261	230	298	293	307	307	345	354
10	384	315	382	412	357	291	306	270	307	362	321	354	385
Dehydroascorbic acid[b]													
0	72	66	76	90	93	65	119	119	133	89	130	111	130
2	72	84	100	137	96	56	100	64	119	85	116	122	122
5	72	44	83	91	96	65	89	133	126	84	101	127	123
10	72	73	61	90	90	55	108	75	104	109	140	159	172
Total vitamin C[c]													
0	456	411	466	495	501	319	409	407	436	430	469	478	509
2	456	460	444	608	456	326	355	273	489	411	468	460	454
5	456	356	494	526	508	326	318	431	419	392	408	473	477
10	456	388	443	502	447	346	413	345	411	471	461	513	557

Values are expressed in mg L^{-1} of juice.
[a] S.E. = 22, LSD ($P \leq 0.05$) = 63.
[b] S.E. = 7, LSD ($P \leq 0.05$) = 20.
[c] S.E. = 27, LSD ($P \leq 0.05$) = 76.

3.4. Vitamin C content

The analysis of variance in ascorbic acid, dehydroascorbic acid and total vitamin C contents (Table 3) shows how the three factors, and their interactions, are the most relevant due to the low residual values obtained. It also indicates that the storage time factor is the most significant factor since it had the highest percentage of variance explanation.

The initial ascorbic acid content (384 ± 3 mg L^{-1} juice) was generally preserved in all cut types after shelf-life at the four storage temperatures tested. However slight increases were found in the dehydroascorbic acid initial content (72 ± 6 mg L^{-1} juice). The greater increases (up to two-fold) were observed after 10 days in slices, 1/2 and 1/4 slices (Table 6).

The total vitamin C content measured on the processing day was 456 ± 9 mg L^{-1} juice with ascorbic acid contributing more than 84% of the total ascorbic acid content (Table 6). Our data recorded on the processing day are similar to values obtained for California 'Eureka' lemons grown on six different rootstocks with a range of 450–510 mg L^{-1} juice (Bitters, 1951 cited by Sinclair, 1984).

In contrast to our finding of good retention of total vitamin C in fresh-cut lemon products, minimal processing resulted in a 13% loss in ascorbic acid concentration in segments of 'Avana' mandarins and 'Okitsu' satsuma fruit after 12 days of storage at 4 °C under MAP conditions (Piga et al., 2002). Del Caro et al. (2004) also found an ascorbic acid decrease ranging from 1.63 to 5.10 mg g^{-1} dry matter in 'Minneola' tangelo and 'Salustiana' orange segments stored 12 days at 4 °C, while no differences were observed in 'Shamouti' orange segments.

3.5. Fermentative metabolites

The main fermentative metabolites found were ethanol and acetaldehyde for which analyses of variance are presented in Table 3. Traces of ethyl acetate were also detected but not quantified. The three-way interaction between factors is significant for both metabolites and changes occurred in all conditions tested are shown in Table 7.

Ethanol and acetaldehyde at low concentrations enhance flavor of fresh fruit, but high concentrations can induce off-flavors. Ke and Kader (1990) estimated that 20 and 1000 μL L^{-1} of acetaldehyde and ethanol, respectively, are the concentrations above which off-flavors can be induced in 'Valencia' oranges; the threshold levels for lemons may be lower because of the lower sugar content, which influences perception of off-flavors, and this should be further studied.

Among the total fermentative metabolites quantified on processing day (74.3 ± 4.6 μL L^{-1}) ethanol contributed more than 88% (65.8 ± 4.5 μL L^{-1}). Slight increases were found after 4 and 7 days of shelf-life but the greatest increases occurred after 10 days, when more than a three-fold increase was measured. Ethanol content increased for 1/4 slices after 10 days at all temperatures tested, and also increases were found at 10 °C for all the tested cut types. The maximum ethanol amount (215.2 ± 25.2 μL L^{-1}) was reached after 10 days at 10 °C by 1/4 slices (Table 7) and may have contributed to some of the off-odors detected. The ethanol content found

Table 7
Interaction (temperature × time × cut) in ethanol and acetaldehyde of fresh-cut 'Lisbon' lemon products stored at 0, 2, 5, and 10 °C for up to 10 days

Temperature (°C)	Time												
	Initial	Day 4				Day 7				Day 10			
		Wedges	Slices	1/2 slices	1/4 slices	Wedges	Slices	1/2 slices	1/4 slices	Wedges	Slices	1/2 slices	1/4 slices
Ethanol[a]													
0	65.8	67.6	90.5	86.3	110.4	66.5	64.1	63.0	74.6	78.4	75.9	89.4	90.9
2	65.8	87.6	79.4	79.2	83.4	60.6	72.8	80.2	75.1	76.6	75.5	84.0	89.3
5	65.8	76.7	76.5	73.0	75.4	81.0	79.5	74.6	82.3	81.4	79.4	81.3	99.8
10	65.8	70.6	84.5	96.0	100.5	80.1	73.2	71.6	93.9	99.1	125.1	185.9	215.2
Acetaldehyde[b]													
0	8.5	8.2	14.1	11.6	12.8	7.3	7.3	8.5	4.8	5.8	7.7	10.1	9.3
2	8.5	9.7	3.2	4.0	5.9	12.6	13.5	10.1	8.2	7.3	4.9	7.5	5.9
5	8.5	8.1	7.7	4.3	7.1	7.5	3.4	3.4	4.2	4.2	3.6	4.2	4.4
10	8.5	5.9	7.6	8.1	5.0	5.0	5.7	5.2	6.1	2.1	1.7	2.9	4.2

Values are expressed in $\mu L\,L^{-1}$.
[a] S.E. = 5.92, LSD ($P \leq 0.05$) = 16.6.
[b] S.E. = 0.96, LSD ($P \leq 0.05$) = 2.7.

on processing day was similar to that determined at harvest in 'Eureka' lemons treated for commercial storage (Cohen et al., 1990). Pretel et al. (1998) found a significant increase in ethanol content, after 7 days at 4 °C in wedges of peeled 'Salustiana' oranges stored under MAP conditions. This can be due to anaerobic respiration because of the low O_2 reached within the packages since the increase was more pronounced in the orange wedges packed in high barrier film.

The initial acetaldehyde amount found was $8.5 \pm 1.0\,\mu L\,L^{-1}$ and slight decreases were generally detected with time at 5 and 10 °C. The initial acetaldehyde content is in the same range as the $5\,\mu L\,L^{-1}$ found at harvest in 'Eureka' lemons (Cohen et al., 1990).

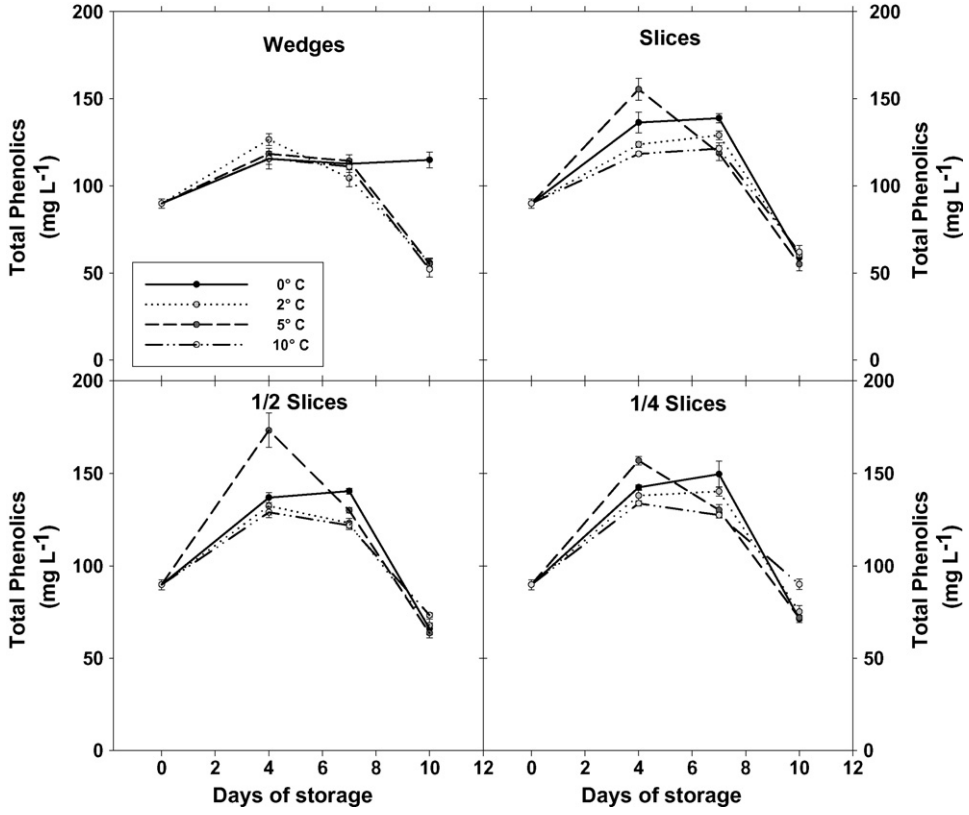

Fig. 1. Total phenolic compounds changes in fresh-cut 'Lisbon' lemon products stored at 0, 2, 5 and 10 °C. The results are expressed as gallic acid equivalents (GAE) in mg L^{-1} of lemon juice. Each value is the mean of three replicates ± S.D.

3.6. Total phenolic compounds content

As a general trend, the total phenolic compounds content (89.8 ± 2.0 mg L^{-1}) decreased gradually throughout the storage period for all cut types and storage temperatures tested except in wedges kept at 0 °C (Fig. 1). A decrease in phenolic compounds with maturation and ripening in other fruit such as banana, guava, and pomegranate fruit has previously been reported (Kulkarni and Aradhya, 2005). However we found a correlation between the cut type and the quantity of phenolic compounds after shelf-life. Wedges lost 39.6% of their phenolic compounds after 10 days, as an average of the four temperatures tested, when compared to the initial values. These values are in the same range as the losses found for slices with 34.4% and lower losses were found for 1/2 slices (24.7%) and 1/4 slices (14.2%) (Table 8). A possible explanation for these differences is the fact that phenolic compounds are involved in many interactions of plants in response to biotic and abiotic stresses. It could be the reason that the highest quantity of phenolic compounds (a lower decrease) was found in 1/4 slices in which the greatest wounding-induced stress occurred.

During the first 4 days of storage, an increase in total phenolic compounds content was noted in all cut types and temperatures tested (Fig. 1). This may be related to the fact that phenolic compounds are involved in the synthesis of lignins and this lignification in fruit can be related to an increase in the phenolic metabolism after wounding (Macheix et al., 1990).

3.7. Total antioxidant activity

Antioxidant activity remained constant or slightly decreased in all cut types and storage temperatures tested (Fig. 2). The most noticeable changes occurred in wedges, slices and 1/2 slices where slight decreases were observed in fruit stored up to 10 days at 0 and 2 °C when compared to initial values (51.0 ± 1.5 mM mL^{-1}). However these decreases are very small and can be due to variability among fruit pieces analyzed.

A high correlation between phenolic compounds and total antioxidant capacity in different fruit and vegetables has widely been reported. In citrus fruit, ascorbic acid contributes from 33% to 100% of the total antioxidant capacity (Gardner et al., 2000; Marín et al., 2002). This contribution may be influenced by species, cultivars, geographic origin, growing seasons, agricultural practices and analytical methods (Chun et al., 2005). As our results also show good vitamin C retention throughout the storage period under all temperatures tested, its important contribution to total antioxidant capacity is corroborated.

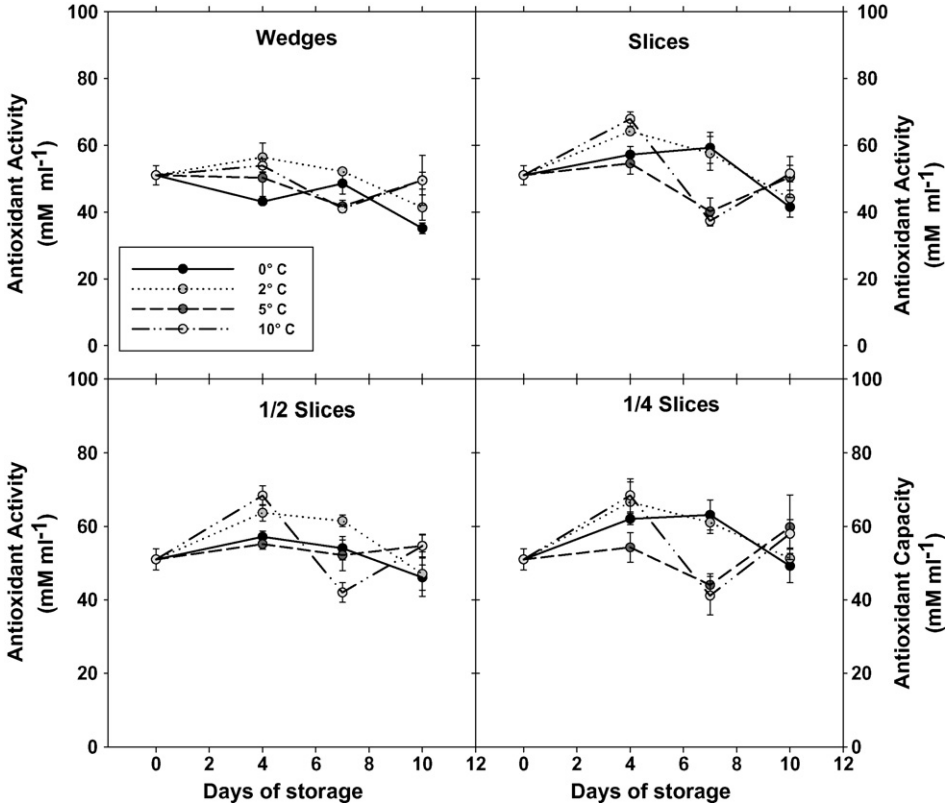

Fig. 2. Antioxidant activity in fresh-cut 'Lisbon' lemon products stored at 0, 2, 5 and 10 °C. The results are expressed as ascorbic acid equivalent antioxidant capacity (AEAC) in mM mL^{-1} of lemon juice. Each value is the mean of three replicates ± S.D.

Table 8
Concentration of phenolic compounds in fresh-cut 'Lisbon' lemon products stored at 0, 2, 5 and 10 °C

Treatment	Total phenolics on processing day (GAE mg L^{-1} juice)	Average of total phenolics after shelf life[a] (GAE mg L^{-1} juice)	% lost in total phenolics after shelf life
Wedges	89.8	54.3[b]	39.6[b]
Slices	89.8	58.9	34.4
1/2 slices	89.8	75.3	27.4
1/4 slices	89.8	77.0	14.2

[a] Average of the all temperatures tested at the end of storage period.
[b] Average of the all temperatures tested at the end of storage period with exception of 0 °C.

4. Conclusions

Fresh-cut lemon products (wedges, slices, 1/2 and 1/4 slices) stored at temperatures up to 10 °C retained marketable quality for up to 7 days. To reach a 10-day shelf-life period, wedges, slices and 1/2 slices of fresh-cut 'Lisbon' lemons should be kept at 0–5 °C and protected from water loss by proper packaging with high relative humidity during distribution. Under these conditions, sensory quality of these fresh-cut lemon products was preserved with good retention of vitamin C and antioxidant capacity. However a decrease of the total phenolics compounds throughout the shelf-life was observed.

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