# QUALITY CHANGES AND RESPIRATION RATES OF FRESH-CUT SUNCHOKE TUBERS (*HELIANTHUS TUBEROSUS* L.)

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## ABSTRACT

Changes in quality attributes (discoloration, surface dehydration, translucency, color values, texture), respiration, phenolics and phenylalanine ammonia lyase (PAL) and polyphenol oxidase activities of sunchoke tuber slices were studied at 0, 5 and 10C. Cleanly cut smooth surfaces had less wound-induced discoloration and surface drying than rougher cut surfaces. The main quality defect was red discoloration, and $a^*$ and hue color values were highly correlated to this defect. The time course of discoloration was related to wound-induced respiration and PAL activity but not polyphenol oxidase activity or concentrations of soluble phenolics. Respiration rates of slices at 0, 5 and 10C averaged 5, 14 and 26 μL $CO_2$/g-h, respectively, during 7 days. No decay was observed under any condition. Storage at 0 and 5C effectively retarded surface discoloration, but 0C was clearly better. A shelf life of 9–12 and 6–8 days was obtained with sunchoke slices at 0 and 5C, respectively, while shelf life was 3 days at 10C.

## PRACTICAL APPLICATIONS

Sunchoke tubers contain indigestible inulins and have potential as a fresh-cut product or a component in fresh-cut mixtures to be consumed raw or cooked. Sliced tubers retain quality when held at 0–5C, but discoloration, the main defect limiting shelf life, will occur more rapidly at 5C. The rate and severity of discoloration was related to storage temperature and to wound-induced increases in respiration and PAL activity. With this information, strategies to effectively control discoloration can be implemented.

## INTRODUCTION

Sunchoke, also commonly known as topinambour or Jerusalem artichoke (*Helianthus tuberosus* L.), is a member of the sunflower family and an indigenous crop of North America. The tubers produced in California are often referred to as sunchokes, although a hybrid (*H. annuus* × *H. tuberosus*) has also been given this name (Kays and Nottingham 2008). The tubers, which are crisp with a unique sweet nutty flavor, can be eaten raw similar to jicama, or cooked similar to potatoes or water chestnuts (Bach *et al.* 2012). Sunchoke tubers contain inulins, nondigestible oligosaccharides that are reported to have numerous health benefits (Niness 1999). Considerable research was conducted on this crop in the past for its biofuel potential, but the tubers are currently recognized as a health food (Niness 1999; Kays and Nottingham 2008). Depending on cultivar and maturity, tubers can be stored at 0 to 5C for 6 months or longer (Modler *et al.* 1993; Kays and Nottingham 2008). Dehydration, decay and sprouting occur with increased storage time as well as changes in the composition of the inulins and sugars (Saengthongpinit and Sajjaanantakul 2005).

It is desirable to develop new fresh-cut or minimally processed products that meet consumer expectations for convenience, flavor, nutrition and novelty (Cantwell and Suslow 2002; Barrett *et al.* 2010; Francis *et al.* 2012). Minimizing the wound damage associated with the processing of these fresh-cut products is essential. Cutting destroys the integrity of cells at the cut surface, resulting in increased respiration rates and other metabolic reactions associated with increased rates of deterioration (Saltveit 1997; Cantwell and

Suslow 2002; Toivonen and DeEll 2002; Brecht *et al.* 2004). The degree of damage affects the wound-induced changes in metabolism and corresponding loss of quality (Saltveit 1997; Brecht *et al.* 2004). Wound damage can be minimized by selecting better cutting equipment or preparation methods as shown by Barry-Ryan and O'Beirne (1998) for carrots slices or by Portela and Cantwell (2001) for melon pieces.

Undesirable color changes are common defects of fresh-cut products (Adams and Brown 2007; Toivonen and Brummell 2008; Barrett *et al.* 2010). Biosynthesis, oxidation and polymerization of phenolic compounds are often associated with discoloration and other color changes (Martinez and Whitaker 1995). A high correlation has been demonstrated between the induced activity of phenylalanine ammonia lyase (PAL) and discoloration of intact (Hyodo *et al.* 1978) and cut lettuce leaves (López-Gálvez *et al.* 1996). Discoloration becomes apparent when phenolic compounds are oxidized in reactions catalyzed by polyphenol oxidase (PPO) and other enzymes, with final nonenzymatic polymerization into brown pigments (Martinez and Whitaker 1995). The relationships between PAL, PPO activities, phenolic content and browning have been widely researched but results have been variable depending on the product (López-Gálvez *et al.* 1996; Cantos *et al.* 2002; Adams and Brown 2007; Luna *et al.* 2012; Mishra *et al.* 2013).

Quality changes in fresh-cut vegetables differ depending on the unique composition and physical characteristics of the intact vegetable (Brecht *et al.* 2004; Toivonen and Brummell 2008; Francis *et al.* 2012). To date, there has been no research on sunchoke tubers as a fresh-cut product. The purpose of this study was to investigate aspects of the physiology, quality changes and phenolic metabolism of sunchoke slices principally in relation to storage temperatures.

## MATERIALS AND METHODS

### Raw Material

Common sunchoke tubers (medium size, light-skinned nobby with white flesh, cultivar unknown) grown in California and Washington were purchased on three occasions from a wholesale distributor in Sacramento CA and were stored for 2 to 5 months. Tubers were packaged in bulk in unsealed low density polyethylene (LDPE) bags in fiberboard cartons and stored at 0C until used. Tubers were sorted and small or defective (damage, decay, sprouting) tubers were discarded.

### Preparation of Fresh-Cut Slices

The tubers were scrub-washed with potable water and then rinsed in 200 ppm sodium hypochlorite solution for 5 min, drained and air dried. Cleaned tubers were placed into clean LDPE bags at 5C before they were cut. The terminal ends and protuberances (daughter tubers) were removed, leaving the midsections. Tubers were manually cut into 10 mm thick slices with a sharp stainless steel knife in one experiment and into 5 mm thick slices using a V-Slicer Primamandoline (Borner, Niederkail, Germany) for other experiments. The slices were rinsed with 50 ppm sodium hypochlorite (pH 7.0), drained and blot dried with clean cheesecloth or paper towels to remove excess moisture, and placed into small unsealed LDPE bags (eight to 10 pieces per bag). The ends were folded over and bags were placed on plastic trays inside unsealed large LDPE bags. Slices were typically evaluated after 0, 4, 8 and 12 days with three replicates per evaluation. The quality evaluations and objective color measurements were repeated in two sets of independent experiments at the three storage temperatures (0, 5 and 10C). Respiration rates and phenolic metabolism were studied in one experiment.

### Translucency and Juice Release

The internal appearance of the tubers was variable, with some tubers having a more translucent aspect toward the center of the slices. An experiment was performed to compare known differences in translucency with objective color values. Sunchoke slices were stored at 0, 5 and 10C and evaluated periodically for quality changes and color measurements on both sides of each slice.

Slicing with the mandoline produced slices with a distinct appearance on each side and these differences contributed to data variability. In one experiment, piece orientation was carefully maintained and when the rougher and smoother sides of the slices became distinguishable after a few days at 5 or 10C, they were evaluated for color values and quality parameters to assess the magnitude of this sidedness.

A test was conducted to determine if the greater discoloration on the rougher side was related with more juice release at slicing. Tubers were scrub-washed and dried with a paper towel and then seven tubers were sliced from the distal end to the stem end and other tubers were sliced in the opposite direction. The cutting direction was marked and recorded. After slicing, pieces were immediately placed between two paper towels that had been previously weighed. All slices from one tuber were positioned upward in the same cutting direction. The paper towels were then gently patted against the slices and reweighed to measure the juice absorbed from each side of the slices. The slices were stored at 5C and evaluated after 6 days on each side and compared with slices that had not been blot dried.

## Quality Evaluations

Overall visual quality was evaluated by an experienced operator on a 9-to-1 scale, where 9 = excellent, fresh cut, no defects, 7 = good, minor defects, 5 = fair, moderate defects, 3 = poor, major defects, 1 = unusable. A score of 6 was considered the limit of salability and shelf life was defined at the days required to reach a score of 6. Red discoloration was evaluated on a scale of 1 to 5, where 1 = none, 2 = slight, 3 = moderate, 4 = severe and 5 = extreme browning. Surface dehydration, translucency and macroscopic decay were evaluated on scales of 1 to 5, where 1 = none, 2 = slight (up to 5% surface affected), 3 = moderate (5–20% surface affected), 4 = moderately severe (20–50%) and 5 = extreme (>50% surface affected).

## Color

CIE $L^*a^*b^*$ values were determined on the slice surface midpoint from peel to the center with a Minolta Chroma Meter (Model CR-200/300, Minolta, Ramsey, NJ) with illuminant A and a 10° viewing angle and calibrated on a white reference tile ($L^* = 97.95$, $a^* = -0.39$, $b^* = 2.00$). Chroma ($C^* = [a^{*2} + b^{*2}]^{1/2}$) and hue ($h° = \tan^{-1}[b^*/a^*]$) were calculated.

## Texture

Texture was measured as the maximum force (N) to rupture the tissue. Texture was determined on 10 mm thick slices using a TA-HD texture analyzer (Texture Technologies Corporation, Scarsdale, NY) with a flat, cylindrical 5-mm probe at a penetration rate of 1 mm/s to a depth of 5 mm.

## Respiration

Respiration rates of intact and sliced tubers were measured at 0, 5 and 10C. Three tubers or about 100 g of slices were placed in chambers through which humidified air (~90–95%) flowed at rates to obtain $CO_2$ concentrations between 0.25 and 0.5%. One milliliter samples were taken from the outlet streams of the containers, and $CO_2$ was determined by infrared analysis (model PIR-2000, Horiba, Kyoto, Japan). Calculations were based on difference between inlet and outlet concentrations and respiration rates were expressed as μL $CO_2$ produced per gram fresh tissue per hour.

## Phenolics and Enzymes

Total phenolics were determined by a Folin–Ciocalteu method described by Singleton and Rossi (1965). Four grams of finely chopped tissue was frozen at –80C until homogenizing (Ultra-Turrax T25, Janke & Kunkel, Staufen, Germany) for 1 min at 13,500 rpm with 15 mL 80% ethanol and vacuum filtering through Whatman #1 paper. Reagent A was 2.7% sodium potassium tetrahydrated tartrate, Reagent B was 2.0% sodium carbonate (w/v) in 0.1 N sodium hydroxide, Reagent C was one part of Reagent A plus 98 parts of Reagent B (prepared at time of analysis), and Reagent D was one part of commercial Folin–Ciocalteu reagent and one part water (prepared at time of analysis). For analysis, 0.25 mL of filtered phenolic extract plus 2.5 mL Reagent C was mixed and let stand 10 min at ambient temperature, 0.25 mL Reagent D was added and agitated and absorbance was measured at 660 nm after 40 min. Calculations were based on a standard curve of *p*-coumaric acid.

PAL activity was determined from 4 g finely chopped sample (without peel) placed into a plastic test tube on ice containing 0.4 g soluble polyvinylpolypyrrolidone and frozen at –80C until analyzed. For analysis (Ke and Saltveit 1986), 16 mL of 50 mM borate buffer (pH 8.5) v/v 400 μL/1000 mL 2-mercaptoethanol was added, homogenized (Ultra-Turrax for 1 min at 13,500 rpm, filtered through four layers of cheesecloth on ice, and centrifuged at 15,000 × g for 20 min. Two tubes of 5 mL of supernatant were heated at 40C for 5 min, 0.55 mL of 100 mM L-phenylalanine was added to one tube and 0.55 mL water (blank) was added to the other tube. After mixing, absorbance was measured at 290 nm and tubes were incubated at 40C for 1 h and the absorbance was measured again. One unit of PAL activity corresponded to the formation of 1 μmol cinnamic acid in 1 h.

PPO activity was measured from 4 g finely chopped sample (without peel) weighed into a plastic test tube on ice containing 0.4 g insoluble polyvinylpolypyrrolidone and frozen at –80C until analyzed. For analysis (Siriphanich and Kader 1985), 16 mL phosphate buffer (50 mM pH 6.2) was added and the sample was homogenized (Ultra-Turrax) for 1 min at 13,500 rpm. The homogenate was filtered through four layers of cheesecloth on ice. The filtrate was centrifuged at 12,000 × g for 20 min at 4C and the supernatant was used for determination of PPO. An aliquot of 67 μL caffeic acid was added to 933 μL of enzyme extract. One unit of PPO activity was defined as the amount of the enzyme that produced an increase of 0.1 absorbance units in 1 min.

## Statistics

Experiments were conducted in a completely randomized design with a minimum of three replicates per treatment (one replicate = eight or 10 pieces). Data were calculated as averages ± standard deviations or analyzed by analysis of

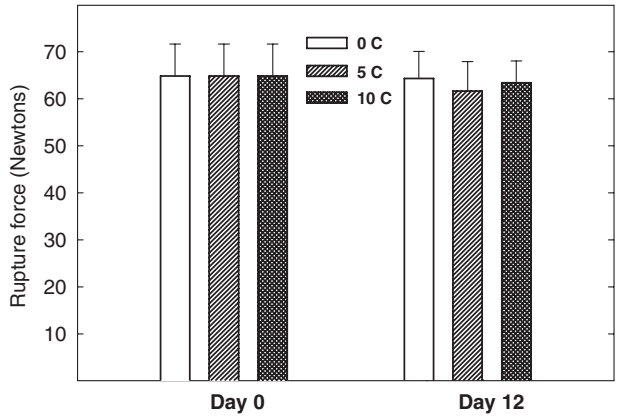



**FIG. 1.** TEXTURE OF FRESH-CUT SUNCHOKE TUBERS STORED AT 0, 5 OR 10C FOR 0 OR 12 DAYS. DATA ARE MEANS OF THREE REPLICATES OF 10 SLICES + STANDARD DEVIATION

variance (Sigmaplot 11.0, Systat Software, Inc., Redmond, WA) with mean separation by LSD 0.05 or Tukey's test.

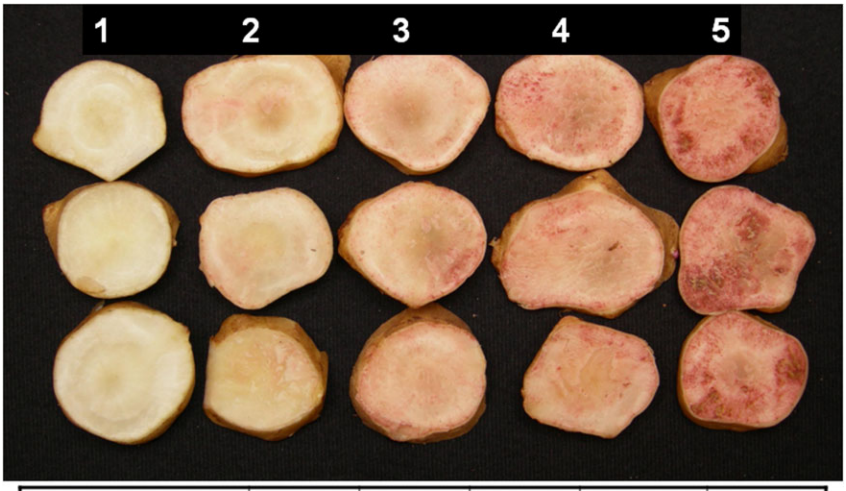
## RESULTS

### Quality Changes at Different Temperatures

The main visual quality changes in fresh-cut sunchoke tubers were discoloration and surface dehydration. No macroscopic decay was observed during any of the storage conditions (data not shown). There were no differences in the texture of slices measured every 4 days for 12 days at 0, 5 or 10C (Fig. 1). Maximum rupture forces averaged 64.9 ± 6.8 to 61.7 ± 6.3 N from day 0 to day 12. No further texture measurements were made.

Discoloration was the most important factor affecting the quality of fresh-cut sunchoke (Fig. 2). Slice surfaces had a red discoloration by 3 days at 10C after cutting. From data at 0, 5 or 10C, the correlation equations and coefficients between the $L$, $a^*$, $b^*$, chroma and hue values and the discoloration scores (D) were: $L^* = -1.099D + 70.584$, $R^2 = 0.423$; $a^* = 3.340D - 5.322$, $R^2 = 0.988$; $b^* = 1.914D + 7.402$, $R^2 = 0.801$; chroma = 2.411D + 7.036, $R^2 = 0.832$ and hue = $-14.993D + 116.98$, $R^2 = 0.98$. The color values $a^*$ and hue were the best indicators of discoloration in fresh-cut sunchoke slices. As the surface of the slice turned red or brown, $a^*$ values increased from negative to positive values (Figs. 2 and 3). In contrast, the hue values decreased and were inversely correlated with discoloration. The color values $a^*$ and hue were used throughout the remainder of the study to objectively measure tissue discoloration.

Discoloration was retarded by low temperature storage (Figs. 3 and 4). Three days after cutting, average $a^*$ value was below 0. The discoloration score of sunchoke slices was 3 (moderate) at 10C, the score was slightly above 1 at 5C, indicating the first sign of visible discoloration, and there was no change in appearance of slices at 0C. By 6 days after




| Score | L* | a* | b* | Chroma | Hue |
|---|---|---|---|---|---|
| 1 = none | 70.4 | -1.8 | 11.8 | 12.0 | 98.6 |
| 2 = slight | 67.7 | 3.0 | 15.5 | 15.8 | 79.0 |
| 3 = moderate | 64.2 | 5.9 | 14.9 | 16.0 | 68.2 |
| 4 = mod.severe | 63.3 | 7.6 | 15.6 | 17.4 | 63.9 |
| 5 = severe | 60.2 | 10.3 | 14.3 | 17.6 | 54.4 |

**FIG. 2.** DISCOLORATION RATING SCALE FOR FRESH-CUT SUNCHOKE TUBERS WITH CORRESPONDING COLOR VALUES

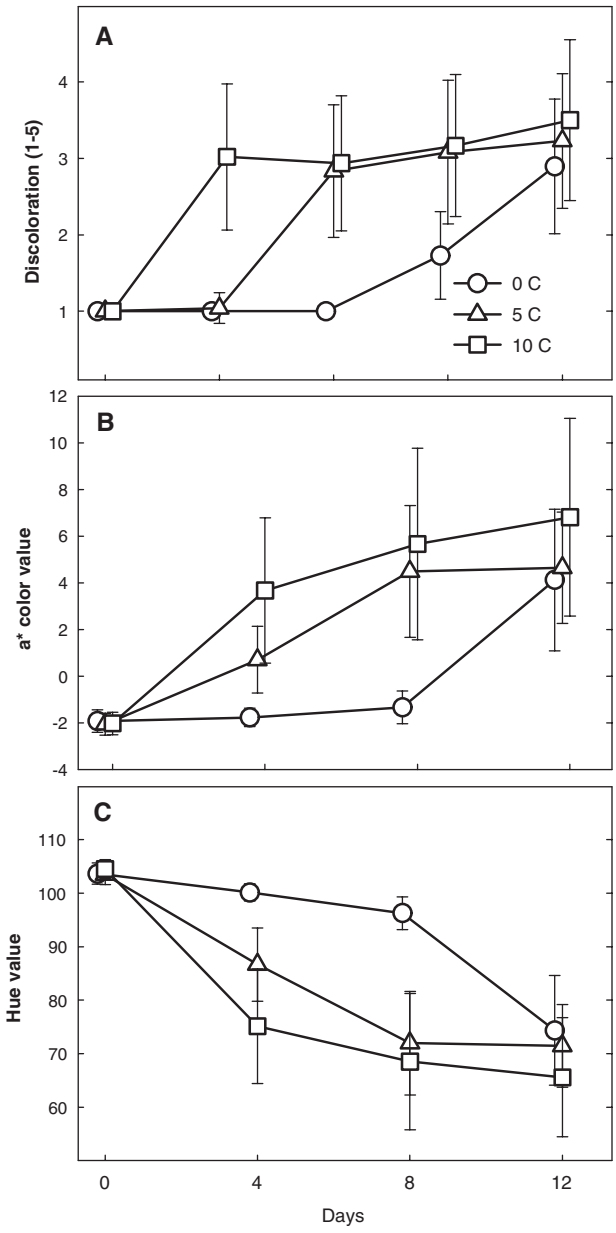



**FIG. 3.** DISCOLORATION (A), *a** (B) AND HUE (C) COLOR VALUES OF FRESH-CUT SUNCHOKE TUBERS STORED IN AIR AT 0, 5 OR 10C. THE 5 MM THICK SLICES WERE CUT ON A MANDOLINE SLICER. DATA ARE MEANS FROM THREE REPLICATES OF EIGHT SLICES ± STANDARD DEVIATION

cutting, the slices stored at 5C had discolored, and by 9 days, the slices stored at 0C had started to discolor. This corresponded to a shelf life (days to reach a visual quality score of 6) of 3, 6 and more than 10 days at 10, 5 and 0C, respectively. During the 12-day storage period, the *a** values at 0C were consistently lower than those of slices at 5 and 10C. The hue values of slices stored at 0C were always higher than those of slices at 5 and 10C.

Storage temperature significantly affected surface dryness of the slices (Fig. 4C). Through the storage period, surface dryness was lower slices at 0C compared with storage at 5 or 10C (Fig. 4C).

There was a translucent aspect to slices prepared from some of the tubers and this might be viewed as a quality defect. Translucency mainly occurred in the medulla tissue and was perhaps partially because of the tissue being squeezed during slicing. The translucency of slices prepared from the ends of the tubers was always less severe than that of slices prepared from the thicker middle part of the tuber. Translucency was variable among tubers and either slightly decreased with storage time (data not shown) or remained constant without being affected by storage temperature (Fig. 4D). When a decrease in translucency was observed, it may have been due to masking by surface drying and discoloration defects. A subjective evaluation score for translucency was not well correlated with any color value; the highest correlation coefficient was obtained between the translucency score and $L^*$ value ($R^2 = 0.493$).

## Cutting Parameters and Slice Quality

Sunchoke tubers have a firm and crisp texture. When the tubers are manually sliced with a sharp knife, both cutting and fracturing occur as the slice is removed from the tuber. The fracturing results in one rougher cut surface and more severe wound-induced damage and discoloration. Although the two sides of the cutting blade were the same, the tissues on the two sides of the blade encountered different forces. The side facing the tuber tended to have a rougher appearance than the other side. The amount of juice released from the rougher side of the slice was significantly higher than that released by the other smoother side (Table 1). There appeared to be no significant differences in juice release or discoloration when tubers were cut from either the stem or distal end (data not shown). A higher amount of juice was clearly associated with more discoloration (Table 1).

Blot drying the slices to remove excess juice resulted in significantly lower discoloration scores and *a** values and higher hue values compared with unblotted slices (Table 2). Removing the juice after cutting effectively reduced the major defect discoloration. In most fresh-cut vegetable processing, pieces exiting the cutting equipment are immediately dropped into a water flume with sanitizer (Cantwell and Suslow 2002). The preparation procedures routinely used in the present study included a rinse with cold water containing 50 ppm sodium hypochlorite, which efficiently removed juice on the cut surfaces.

Usually, slicing resulted in one side having a smoother appearance than the other side. The rougher side corresponded to the side of greater juice release. Differences in

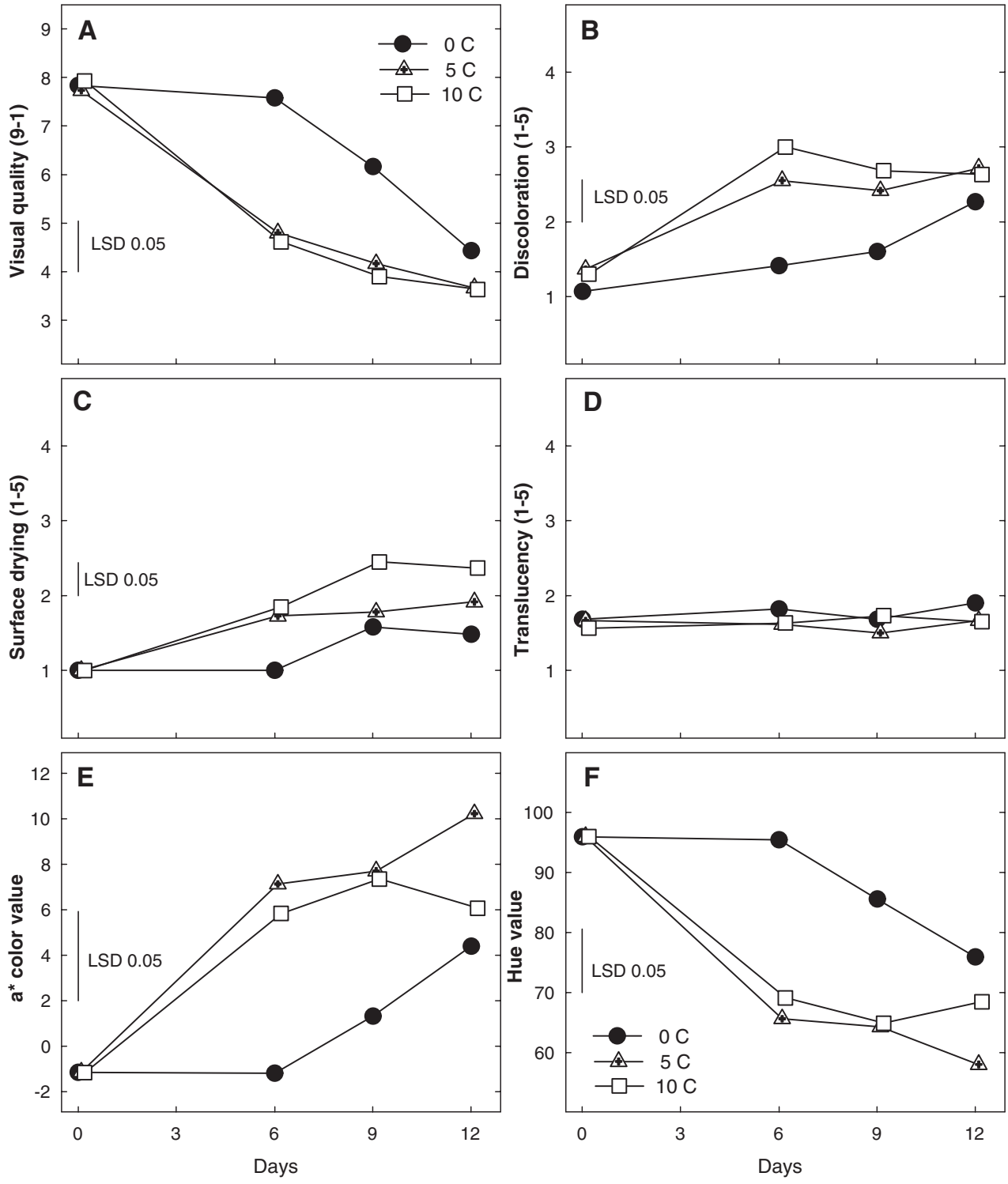



**FIG. 4.** VISUAL QUALITY (A), DISCOLORATION (B), SURFACE DRYING (C), TRANSLUCENCY (D), *a** (E) AND HUE (F) COLOR VALUES OF FRESH-CUT SUNCHOKE TUBERS STORED IN AIR AT 0, 5 OR 10C. THE 8–10 MM THICK SLICES WERE MANUALLY CUT WITH A STAINLESS STEEL KNIFE. DATA ARE MEANS FROM THREE REPLICATES OF EIGHT SLICES EACH WITH MEAN SEPARATION BY LSD 0.05

**TABLE 1.** JUICE RELEASE AT CUTTING AND DISCOLORATION OF SUNCHOKE SLICES AFTER 6 DAYS AT 5C

| Parameter | Rougher surface | Smoother surface |
|---|---|---|
| Juice release (g/tuber) | 0.89 ± 0.30a | 0.28 ± 0.10b |
| Discoloration score | 2.1 ± 0.3a | 1.2 ± 0.2b |

Data are means from eight slices from each of seven tubers ± standard deviation. Different letters for a given parameter indicate significant differences at $P < 0.05$.

**TABLE 2.** DISCOLORATION AND COLOR VALUES OF SUNCHOKE SLICES IN RELATION TO BLOT DRYING AFTER CUTTING

| Parameter | Not dried | Blot dried |
|---|---|---|
| Discoloration score | 3.4 ± 1.1a | 1.7 ± 0.7b |
| *a** color value | 4.32 ± 3.90a | –0.73 ± 1.03b |
| Hue value | 75.80 ± 11.17a | 93.08 ± 3.91b |

Slices were stored for 6 days at 5C. Data are means from three replicates of eight slices ± standard deviation. Different letters for a given parameter indicate significant differences at $P < 0.05$.

discoloration between sides were apparent by day 6 (Fig. 5). In this experiment, there were no differences in discoloration because of storage temperature. From day 6 to day 12, the average discoloration scores of the rough side of the slices varied from 3.4 ± 0.9 to 4.0 ± 0.8), while scores for the smooth side were consistently lower and ranged from 2.4 ± 0.7 to 3.0 ± 0.6. As demonstrated previously, the differences in discoloration scores corresponded to increases in *a** and decreases in hue values.

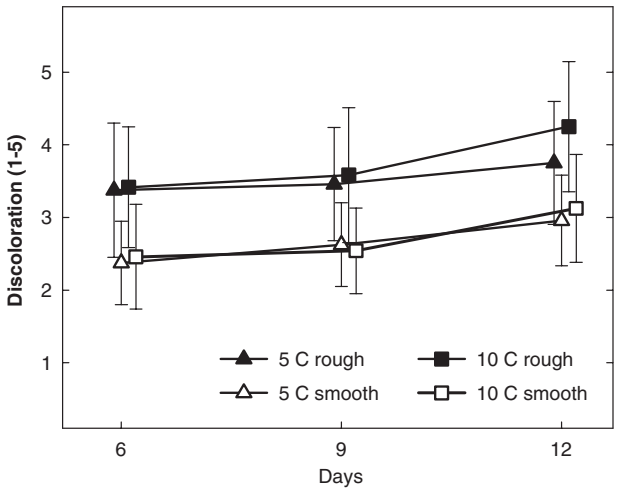



**FIG. 5.** DISCOLORATION SCORES FOR FRESH-CUT SUNCHOKE TUBERS STORED IN AIR AT 5 OR 10C. THE SMOOTHLY CUT AND ROUGHLY CUT SIDES OF THE SLICES WERE EVALUATED SEPARATELY. DATA ARE MEANS FROM THREE REPLICATES OF EIGHT SLICES EACH ± STANDARD DEVIATION

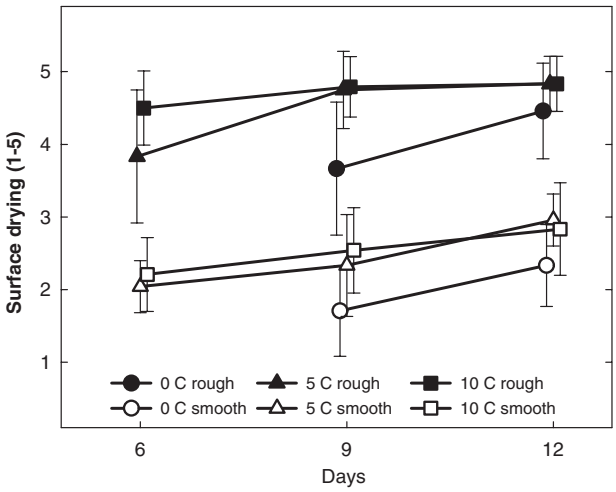



**FIG. 6.** SURFACE DRYING SCORES FOR FRESH-CUT SUNCHOKE TUBERS STORED IN AIR AT 0, 5 OR 10C. THE SMOOTHLY CUT AND ROUGHLY CUT SIDES OF THE SLICES WERE EVALUATED SEPARATELY. DATA ARE MEANS FROM THREE REPLICATES OF EIGHT SLICES EACH ± STANDARD DEVIATION

Differences between the sides in surface dehydration were also apparent by day 6 (Fig. 6). The rougher side had consistently higher scores than the smoother side at any of the storage temperatures. Surface drying was lower at 0C than 5 or 10C until day 12.

## Respiration Rates

Respiration rates of intact sunchoke tubers were low and almost constant over the 14 days of measurement at 0, 5 and 10C (Fig. 7A). Respiration rates at 10C were about 3.4 and 2 times the rates at 0 and 5C, respectively.

Respiration rates of sliced tubers were measured twice with similar results. Temperature greatly affected the respiration rates of fresh-cut sunchoke (Fig. 7B). Rates of slices at 10C increased rapidly to a maximum of 38 μL $CO_2$/g-h after 3 days and then rapidly declined, while maximum rates for slices at 5C were 16 μL $CO_2$/g-h after 5 days followed by a decline. There was no apparent wound-induced increase in respiration rates of the slices at 0C, but the rates gradually increased so that by 10 days, respiration rates of slices at the three temperatures were the same. Average respiration rates during 7 days after slicing were 4.9, 14.4 and 26.1 μL $CO_2$/g-h at 0, 5 and 10C, respectively.

## PAL, PPO, Phenolics and Discoloration

Sunchoke slices stored at 0C retained the best color and visual quality compared with those stored at 5 or 10C. However, storage and handling of fresh-cut products at 5C

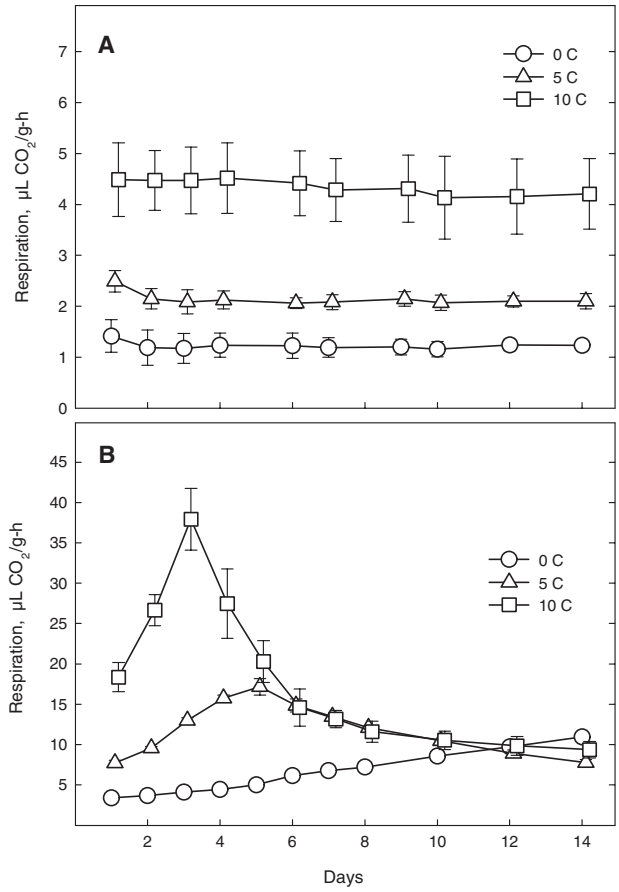



**FIG. 7.** RESPIRATION RATES OF INTACT (A) AND SLICES (B) SUNCHOKE TUBERS STORED AT 0, 5 OR 10C. DATA ARE MEANS FROM THREE REPLICATES ± STANDARD DEVIATION

is a common practice, and at this temperature, undesirable discoloration occurs. To understand the mechanism of discoloration at different storage temperatures, changes in color, respiration, PAL, PPO enzyme activity and total soluble phenolic contents were evaluated in two experiments with similar results. Discoloration changed as previously described (Fig. 8A). In this experiment, the discoloration scores of slices at 10C were very high and there were clear differences in discoloration scores at the three temperatures.

Temperature significantly affected wound-induced changes in PAL activity (Fig. 8B). Storage temperature affected the time course and maximum activities of PAL. The rapid increases in PAL activity in slices at 10C corresponded to more rapid discoloration. At 10C, PAL activity peaked at day 3 and then declined so that by day 6, activity was lower than that at the other temperatures. Maximum rates were similar in slices at 5 and 10C, but at 0C maximum rates were delayed and were higher at a later period of storage.

PPO activities were similar in slices held at the three temperatures and did not appear to change with time (Fig. 8C). The concentrations of total soluble phenolics increased with time (Fig. 8D), but the time course of changes was not related to tissue discoloration. There were essentially no differences in phenolic concentrations of the slices because of temperature.

## DISCUSSION

This is the first study on the physiology and quality of fresh-cut sunchoke tubers, a potentially useful new fresh-cut product that could be consumed raw or cooked. Sunchoke slices had no visible decay under the conditions studied. The main challenges that affected the quality of fresh-cut sunchoke slices were discoloration and surface drying, with the former clearly being the most serious defect.

Temperature is a key factor affecting the shelf life of sunchoke slices as with all fresh-cut products (Cantwell and Suslow 2002; Toivonen and DeEll 2002; Brecht *et al.* 2004; Francis *et al.* 2012). The sunchoke slices at 0C retained excellent quality with no discoloration for 6 to 8 days and were of marketable quality for 9 to 12 days. These estimates are within the 10–14-day range that is expected for many fresh-cut vegetables (Cantwell and Suslow 2002). Because of the high oligosaccharide content of the sunchoke tubers, the fresh-cut product could potentially be stored below 0C, closer to the actual freezing point which is unknown. For many fresh-cut products, additional technologies such as modified atmosphere packaging, or chemical or physical treatments that reduce discoloration are key components of a fresh-cut handling system. High carbon dioxide atmospheres in combination with low oxygen concentrations would be expected to reduce surface browning as found with many other fresh-cut products (Brecht *et al.* 2004; Toivonen and Brummell 2008; Francis *et al.* 2012). For sunchoke tubers, hot water and ethanol treatments applied before and after cutting have been shown to reduce phenolic metabolism and discoloration (Wang *et al.* 2014).

A clean smooth sunchoke slice resulted in less surface drying and less discoloration. Although the amount of water loss from fresh-cut products is relatively small, the effect of water loss from the cut surfaces often impacts quality (Toivonen and DeEll 2002). The "white blush" phenomenon observed on baby peeled carrots is primarily a defect because of surface dehydration of damaged cell wall remnants (Cisneros-Zevallos *et al.* 1995). Low temperature and hygroscopic coatings can reduce surface drying (Toivonen and Brummell 2008; Francis *et al.* 2012). As with other fresh-cut products, using sharp cutting blades is important to achieve the desired quality and shelf life (Barry-Ryan and O'Beirne 1998; Portela and Cantwell 2001). Removal of juice from cut surfaces by blotting or

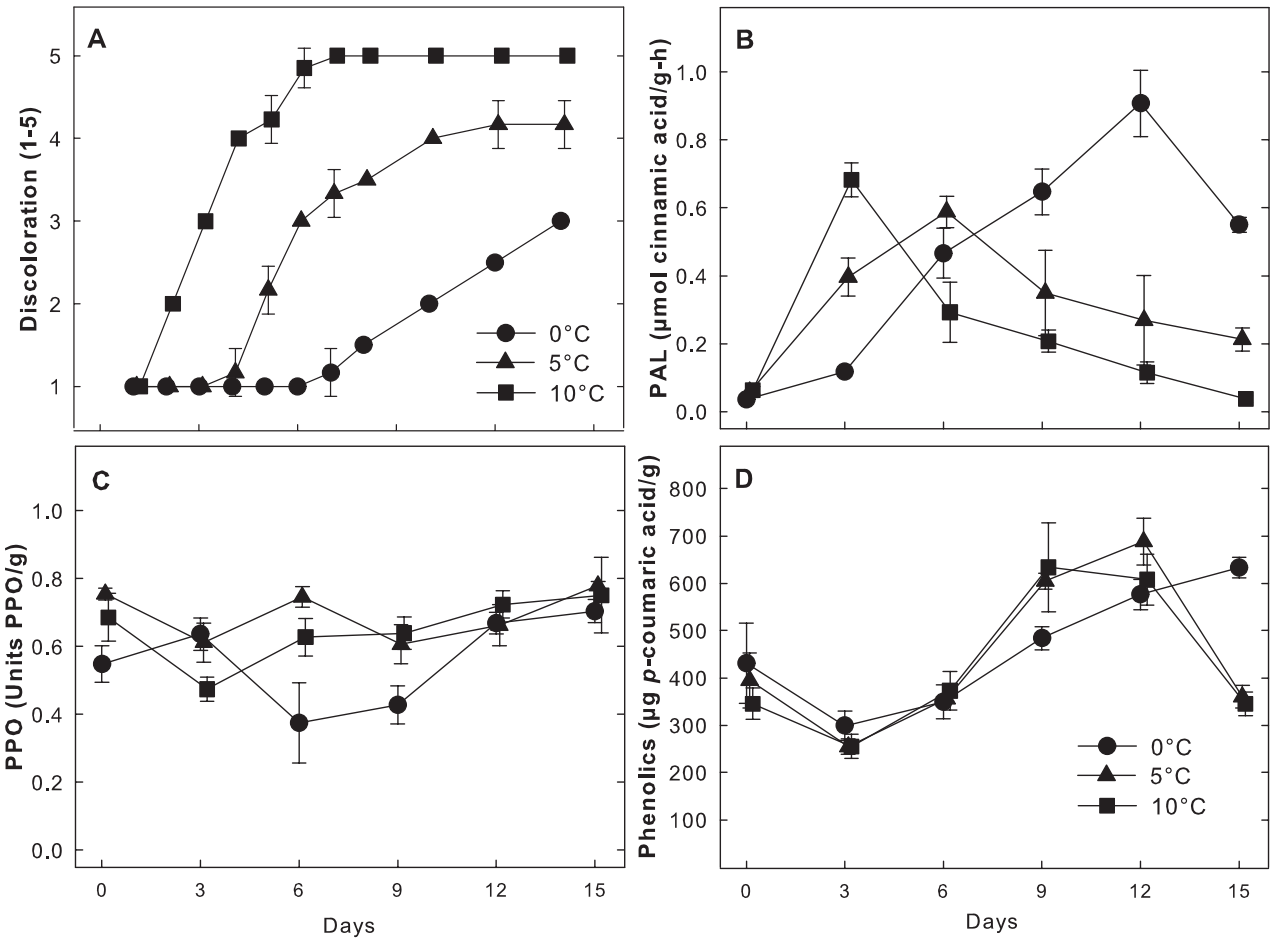



**FIG. 8.** DISCOLORATION (A), PAL (B) AND PPO (C) ACTIVITY AND TOTAL PHENOLICS (D) OF FRESH-CUT SUNCHOKE TUBERS STORED IN AIR AT 0, 5 OR 10C. DATA ARE MEANS FROM THREE REPLICATES ± STANDARD DEVIATION

washing reduced discoloration by minimizing the mixing of enzymes and substrates involved in phenolic metabolism. Fresh-cut processing results in destruction of cellular integrity and the mixing of substrates and enzymes that would otherwise be in separate organelles (Saltveit 1997; Toivonen and Brummell 2008).

Respiration rates of sunchoke tubers at 5 and 10C were similar to those of mature potato tubers measured in our laboratory (Cantwell, 2008), but lower than respiration rates of jicama roots at the same temperatures (Aquino-Bolaños *et al.* 2000). Respiration rates were lower than those previously reported on intact sunchoke tubers by Peiris *et al.* (1997). The tubers in the present study had been stored for 4 to 5 months at 0C and respiration rates would be expected to be low until near the end of storage life when sprouting and compositional changes occur (Modler *et al.* 1993; Kays and Nottingham 2008).

Slicing induced high, but transitory, increases in respiration rates of slices at 10 and 5C. The respiratory patterns of fresh-cut sunchoke are distinct from those reported for other root crops such as jicama (Aquino-Bolaños *et al.* 2000) or potato (Ma *et al.* 2010). In the latter studies, respiration rates increased with time after cutting but did not exhibit the pronounced rapid increase observed with sunchoke slices. The time course of the respiration changes of sunchoke slices coincided with changes in PAL activity and discoloration. After cutting, if respiration rates were high and increased rapidly (10C), the slices would also discolor more rapidly. In contrast, if respiration rates were low and increased very slowly (0C), then the slices would discolor much more slowly. Respiration is a fundamental process needed to provide energy to maintain biological activities. The rapid increases in respiration because of wounding appeared to be closely related to subsequent undesirable phenolic metabolism. The amount of damage caused by cutting was different on each side of the sunchoke slices; it was clear that the side with greater damage had more discoloration.

There was a close temporal relationship between wound-induced PAL activities and increases in discoloration of the tuber slices at the three storage temperatures. The results with sunchoke slices are similar to those reported for cut lettuce (López-Gálvez *et al*. 1996). However, the discoloration observed in sunchoke slices was not directly related to changes in concentrations of phenolics or PPO activity. Mishra *et al*. (2013) reported that phenolics, but not PPO activity, increased with increased browning in fresh-cut eggplant. No relationship between phenolic concentrations and PPO activity was found in potato slices (Cantos *et al*. 2002; Ma *et al*. 2010). Luna *et al*. (2012) found a high phenolic content but less browning in the mid-rid of cut romaine lettuce. Browning is the result of interactions among enzyme activities, substrate availabilities and nonenzymatic polymerization reactions (Martinez and Whitaker 1995). The regulation of phenolic metabolism leading to discoloration may vary considerably among plant species (Adams and Brown 2007; Mattila and Hellström 2007), and comparison of specific sunchoke cultivars would be useful to identify types with low rates of discoloration. Bach *et al*. (2012) observed differences in browning among five cultivars prepared for sensory evaluation.

In conclusion, sunchoke tubers can be prepared as fresh-cut slices which retain good quality, as many other fresh-cut vegetables, at 0 to 5C. However, storage at 0C was clearly superior to storage at 5C in air. Discoloration was the most important defect limiting shelf life and the rate and severity of discoloration was related to storage temperature. Slices with rougher surfaces had more discoloration and juice release than smoother cut surfaces. Sunchoke slices stored at 0C had lower respiration rates and PAL enzyme activity than slices stored at 5 and 10C. Increased respiration rates and wound-induced PAL activity were associated with discoloration. No relationship was found between discoloration and PPO activity and phenolic concentrations.

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## REFERENCES

ADAMS, J.B. and BROWN, H.M. 2007. Discoloration in raw and processed fruits and vegetables. Crit. Rev. Food Sci. Nutr. *47*, 319–333.

AQUINO-BOLAÑOS, E.N., CANTWELLL, M.I., PEISER, G. and MERCADO-SILVA, E. 2000. Changes in the quality of fresh-cut jicama in relation to storage temperatures and controlled atmospheres. J. Food Sci. *65*, 1238–1243.

BACH, V., KIDMOSE, U., THYBO, A.K. and EDELENBOS, M. 2012. Sensory quality and appropriateness of raw and boiled Jerusalem artichoke tubers (*Helianthus tuberosus* L.). J. Sci. Food Agric. *93*, 1211–1218.

BARRETT, D.M., BEAULIEU, J.C. and SHEWFELT, R. 2010. Color, flavor, texture and nutritional quality of fresh-cut fruits and vegetables: Desirable levels, instrumental and sensory measurement, and effects of processing. Crit. Rev. Food Sci. Nutr. *50*, 369–389.

BARRY-RYAN, C. and O'BEIRNE, D. 1998. Quality and shelf-life of fresh cut carrot slices as affected by slicing method. J. Food Sci. *63*, 1–6.

BRECHT, J.K., SALTVEIT, M.E., TALCOTT, S.T., SCHNEIDER, K.R., FELKEY, K. and BARTZ, J.A. 2004. Fresh-cut vegetables and fruits. Hortic. Rev. *30*, 185–251.

CANTOS, E., TUDELA, J.A., GIL, M.I. and ESPIN, J.C. 2002. Phenolic compounds and related enzymes are not rate-limiting in browning development of fresh-cut potatoes. J. Agric. Food Chem. *50*, 3015–3023.

CANTWELL, M. University of California, Davis, CA. Unpublished work, 2008.

CANTWELL, M. and SUSLOW, T.V. 2002. Postharvest handling systems: Fresh-cut fruits and vegetables. In *Postharvest Technology of Horticultural Crops*, 3rd Ed., *Publication 3311* (A.A. Kader, ed.) pp. 445–463, University of California, Oakland, CA.

CISNEROS-ZEVALLOS, L., SALTVEIT, M.E. and KROCHTA, J.M. 1995. Mechanism of surface white discoloration of peeled (minimally processed) carrots during storage. J. Food Sci. *60*, 320–323.

FRANCIS, G.A., GALLONE, A., NYCHAS, G.J., SOFOS, J.N., COLELLI, G., AMODIO, M.L. and SPANO, G. 2012. Factors affecting quality and safety of fresh-cut produce. Crit. Rev. Food Sci. Nutr. *52*, 595–610.

HYODO, H., KURODA, H. and YANG, S.F. 1978. Induction of Phenylalanine-ammonia lyase and increase in phenolics in lettuce leaves in relation to the development of russet spotting caused by ethylene. Plant Physiol. *62*, 31–35.

KAYS, S.J. and NOTTINGHAM, S.F. 2008. *Biology and Chemistry of Jerusalem Artichoke* (*Helianthus tuberosus* L), CRC Press, Taylor & Francis, New York, NY. 459 p.

KE, D. and SALTVEIT, M.E. 1986. Effects of calcium and auxin on russet spotting and phenylalanine ammonia-lyase activity in Iceberg lettuce. HortScience *21*, 1169–1171.

LÓPEZ-GÁLVEZ, G., SALTVEIT, M. and CANTWELL, M. 1996. Wound-induced phenylalanine ammonia lyase activity: Factors affecting its induction and correlation with the quality of minimally processed lettuces. Postharvest Biol Technol. *9*, 223–233.

LUNA, M.C., TUDELA, J.A., MARTÍNEZ-SÁNCHEZ, A., ALLENDE, A., MARÍN, A. and GIL, M.I. 2012. Long-term deficit and excess of irrigation influences quality and browning related enzymes and phenolic metabolism of fresh-cut iceberg lettuce (*Lactuca sativa* L.). Postharvest Biol Technol. *73*, 37–45.

MA, Y., WANG, Q., HONG, G. and CANTWELL, M. 2010. Reassessment of treatments to retard browning of fresh-cut Russet potato with emphasis on controlled atmospheres and low concentrations of bisulphite. Intl. J. Food Sci. Technol. *45*, 1486–1494.

MARTINEZ, M.V. and WHITAKER, J.R. 1995. The biochemistry and control of enzymatic browning. Trends Food Sci. Technol. *6*, 195–200.

MATTILA, P. and HELLSTRÖM, J. 2007. Phenolic acids in potatoes, vegetables, and some of their products. J. Food Compos. Anal. *20*, 152–160.

MISHRA, B.B., GAUTAM, S. and SHARMA, A. 2013. Free phenolics and polyphenol oxidase (PPO): The factors affecting post-cut browning in eggplant (*Solanum melongena*). Food Chem. *139*, 4105–4114.

MODLER, H.W., JONES, J.D. and MAZZA, G. 1993. Observations on long-term storage and processing of Jerusalem artichoke tubers *(Helianthus tuberosus)*. Food Chem. *48*, 279–284.

NINESS, K.R. 1999. Inulin and oligofructose: What are they? J. Nutr. *129*, 1402S–1406S.

PEIRIS, K.J.S., MALLON, J.L. and KAYS, S.J. 1997. Respiratory rate and vital heat of some specialty vegetables at various storage temperatures. HortTechnol. *7*, 46–48.

PORTELA, S.I. and CANTWELL, M.I. 2001. Cutting blade sharpness affects appearance and other quality attributes of fresh-cut cantaloupe melon. J. Food Sci. *66*, 1265–1270.

SAENGTHONGPINIT, W. and SAJJAANANTAKUL, T. 2005. Influence of harvest time and storage temperature on characteristics of inulin from Jerusalem artichoke (Helianthus tuberosus L.) tubers. Postharvest Biol. Technol. *37*, 93–100.

SALTVEIT, M. 1997. Physical and physiological changes in minimally processed fruits and vegetables. In *Phytochemistry of Fruit and Vegetables* (F.A. Tomás-Barberán and R.J. Robins, eds.) pp. 205–220, Clarendon Press, Oxford.

SINGLETON, V.L. and ROSSI, J.A., JR. 1965. Colorimetry of total phenolics with phosphomolybdic-phosphotungstic acid reagents.Amer. J. Enol. Viticult. *16*, 144–158.

SIRIPHANICH, J. and KADER, A. 1985. Effects of CO2 on total phenolics, phenylalanine ammonia lyase, and polyphenol oxidase in lettuce tissue. J. Amer. Soc. Hort. Sci. *110*, 249–253.

TOIVONEN, P.M.A. and BRUMMELL, D.A. 2008. Biochemical bases of appearance and texture changes in fresh-cut fruit and vegetables. Postharvest Biol. Technol. *48*, 1–14.

TOIVONEN, P.M.A. and DEELL, J.R. 2002. Physiology of fresh-cut fruits and vegetables. In *Fresh-cut Fruits and Vegetables. Science, Technology, and Market* (L. Lamikanra, ed.) pp. 91–123, CRC Press, Boca Raton, FL.

WANG, Q., NIE, X. and CANTWELL, M. 2014. Hot water and ethanol treatments can effectively inhibit the discoloration of fresh-cut sunchoke (*Helianthus tuberosus* L.) tubers. Postharvest Biol. Technol. *94*, 49–57.