Mechanism of Surface White Discoloration of Peeled (Minimally Processed) Carrots During Storage

LUIS CISNEROS-ZEVALLOS, MIKAL E. SALTVEIT, and JOHN M. KROCHTA

ABSTRACT

A proposed mechanism of white discoloration development on peeled carrots included both physical and physiological responses to wounding. The physical response is a color change due to reversible surface dehydration. This study was performed at 2.5 and 10°C using a model system controlling relative humidity, at 33, 75 or 98%, and a commercial system with low-density polyethylene (LDPE) plastic film bags. The rate of surface discoloration increased with decreasing RH. When excess surface moisture was left on peeled carrots, rates of white development decreased sharply at all RH compared with a dewetted control. The same effects were observed on peeled carrots stored in LDPE bags. Carrots partially regained their original color when water-dipped, due to reversal of the physical response component.

Key Words: white discoloration, carrots, wounding response, phenolic metabolism

INTRODUCTION

PRECUT FRUIT AND VEGETABLE PRODUCTION is a growing industry. Peeled carrots (*Daucus carota*) represent an important component of the precut vegetable industry. They are produced from whole raw carrots washed, cut into ~5 cm long pieces, peeled, cooled to 1.5° C by hydrocooling with chlorinated water, dewetted (drained) and packaged in low-density polyethylene (LDPE) bags.

Minimal processing of fresh fruits and vegetables, such as trimming, peeling, cutting, slicing and other physical actions, causes injury and damage to tissues, affecting physiological activities and subsequently quality (Watada et al., 1990). Some problems related to cell disruption are leakage of nutrients, enzymatic reactions, mold growth, lactic acid fermentation, loss of texture, development of off-flavors and off-odors, and appearance defects (Carlin et al., 1990). All these factors limit the storage and market life of precut fruits and vegetables.

Surface white discoloration on peeled carrots during storage affects the produce quality and limits storage life. In published studies white appearance is considered a result of either surface dehydration of outer layers (Tatsumi et al., 1991, 1993; Avena et al., 1993a, b) or enzymatic activity and the formation of lignin (Bolin, 1991, 1992; Howard and Griffin, 1993, Howard et al., 1994) as a response to peeling.

When carrots are peeled, the periderm layer is removed, exposing inner tissues. Suberin is a characteristic component of periderm cell walls (O'Rear and Flore, 1983) and is associated with a wax complex (Soliday et al., 1979). Disrupted cell walls exposed to air by cutting or abrasion peeling consist mainly of cellulose, hemicellulose, lignin and other sugar polymers. Cellulose is hydrophilic in native form; lignin is considered hydrophobic, as reported in studies of wetting behavior in vessel walls in the xylem of plants (Laschimke, 1989). Suberized cell walls of the carrot periderm function as a primary barrier to mass transfer, and waxes of the suberin complex appear to cause the greatest impedance to water vapor diffusion (Soliday et al., 1979). Thus, removal of the periderm by peeling increases moisture loss from the carrot. Susceptibility to resulting white blush formation was reported to be influenced by temperature (Buick and Damoglou, 1987), relative humidity (Avena et al., 1993a), degree of peeling (Bolin and Huxsoll, 1991), and type of cutting surface (Tatsumi et al, 1991, 1993; Bolin and Huxsoll, 1991).

Our objective was to elucidate the mechanism by which white formation develops during storage of peeled carrots. Specifically, experiments were designed to determine what portion of peeled carrot white discoloration is attributable to the physical response of surface dehydration. Remaining white discoloration would be presumably due to physiological responses.

MATERIALS & METHODS

Carrot samples

Peeled carrots (unknown cultivar) packaged in low-density polyethylene (LDPE) bags were obtained from a commercial processing plant in Bakersfield, CA., shipped over night under crushed ice to UCD and stored at 2.5°C. The study was performed on different lots from the same processing plant and ~24 hrs after the carrots were processed. Peeled carrots ~5 cm long and 12 to 16 g each were used.

Color evaluation

Color measurements of peeled carrots were made using a Minolta chromameter model CR200 (Minolta Camera Co, Japan), calibrated to a standard orange tile (L = 70.10, +a = 18.23, +b = 32.02). L, a and b values from the CIE (Commission Internationale de l'Eclairage) color scale (Gardner, 1975) were determined. Color measurement on each piece of peeled carrot was the average of 3 readings on different sites of the surface. Each piece of carrot was used as a replicate, using 10–20 replicates/treatment depending on the test. Results were expressed as whiteness index (W.I.), according to Judd (1963), and applied to peeled carrots (Bolin and Huxsoll, 1991).

A visual descriptive scale was used and related to the W.I. scale. The visual scale was defined as five levels of white color: nonwhite (0% white surface), slightly white (25% white surface), moderate white (50% white surface), severe white (75% white surface) and extreme white (100% white surface). To relate it with the W.I. scale, peeled carrots were grouped visually into these different levels of white development and measured with the Chroma-meter. A total of 10 to 20 replicates/group was used.

Wetting, dewetting and rewetting

Peeled carrots are usually dewetted by centrifuging (excess surface moisture removed) in commercial processing. For our study, all peeled carrots were wetted again by dipping in 200 ppm chlorinated distilled water to avoid microbial contamination. To obtain normal surface moisture (dewetted), the peeled carrots were dewetted by centrifuging with a salad spinner. To obtain initial excess surface moisture (wetted), peeled carrots were wetted, but not centrifuged, before storage. After treatment, peeled carrots were stored in controlled RH chambers or LDPE bags. Both dewetted and wetted peeled carrots initially had a moistened appearance. For some experiments, peeled carrots which had been stored were rewet by water-dipping in 200 ppm chlorinated distilled water and then draining.

Controlled RH chambers

Color changes of peeled carrots were studied at different relative humidities. Wetted peeled carrots were held in glass chambers at 10°C and conditioned at 33.5, 75.7 and 98.2% RH, obtained with saturated salt

Authors Cisneros-Zevallos and Krochta are with the Dept. of Food Science & Technology, and Author Saltveit is with the Dept. of Vegetable Crops, Mann Laboratory, Univ. of California, Davis, CA 95616. Address inquiries to Dr. J.M. Krochta.

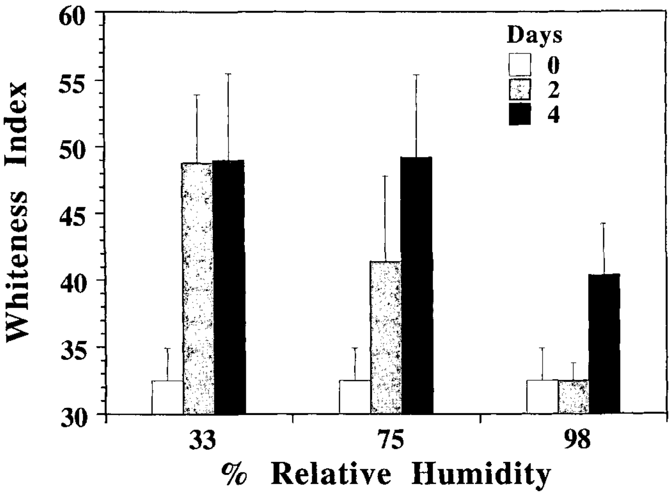

Fig. 1—Effect of relative humidity on Whiteness Index (W.I.) of wetted peeled carrots stored at 10°C. Bars indicate one-sided standard deviations.

Table 1—A visual description of white index values for peeled carrots

Description	White Index (W.I.)[a]
Non-white.	32.6 ± 2.4
Slightly-white.	38.4 ± 1.3
Moderate-white.	43.0 ± 1.8
Severe-white.	47.2 ± 1.7
Extreme-white.	50.9 ± 3.1

[a] Average values with standard deviations.

solutions of $MgCl_2$, NaCl and K_2SO_4 (Fisher Scientific Co., Fair Lawn, NJ), respectively. Preparation was according to ASTM method (1991). The saturated salt solutions were prepared as follows: $MgCl_2$ (500g salt/62.5mL water), NaCl (500g salt/150mL water) and K_2SO_4 (500g salt/273 mL water). A Solomat hygrometer (Solomat Corp., Stamford, CT) was used to measure relative humidity. The experiments were performed mostly without air movement to simulate conditions inside plastic packages. A fan inside each chamber was used only for short periods right after opening and closing the chamber lid to quickly re-equilibrate the RH in the chamber after color measurements had been made. Peeled carrots were placed over a stainless steel metal screen above the saturated salt solution (2.5 cm), avoiding contact between pieces. Ten peeled carrots were used as replicates for each treatment.

Effect of rewetting. Dewetted peeled carrots were stored for 4 or 8 days at relative humidities of 75.7 and 98.2% RH to induce white development. L, a and b values of the peeled carrots were measured and the W.I. values calculated. Carrots were then water-dipped to rewet. The rewetting procedure was performed by dipping 10 peeled carrots (~122 g total) in a glass vessel containing 500 mL of chlorinated distilled water (200 ppm) stirred at room temperature (~23°C). After draining carrots were measured for color. After each measurement, carrots were again dipped in fresh chlorinated distilled water. Results were reported as W.I. related to total dipping time.

Effect of excess surface moisture. Wetted and dewetted peeled carrots were stored at 75.7 and 98.2% RH for a total of 8 days. Color measurements were performed at days 0, 2 and 4. At day 4, ten carrots were rewetted for 10 min and the color measured. The carrots were treated again by wetting or dewetting in a manner identical to day 0. Carrots were then placed back in the chambers and color measurements were performed at days 6 and 8. Finally at day 8, carrots were water dipped for another 10 min and the color measured.

Studies in LDPE bags

White discoloration on peeled carrots was also studied using a commercial packaging system at 2.5 and 10° C, placing 250g of carrots (~20 carrots) in each LDPE plastic bag. Plastic films of 1.5 mil thickness and area of 435 cm^2 (14.5 cm × 15 cm × 2 sides) were used for making the bags. These films had an average water vapor permeability of 9.41 $\times 10^{-6}$g kpa^{-1} hr^{-1} m^{-1} at 20°C, measured with the cup method according to ASTM method (1989). The relative humidity of the storage room was 75 ± 5% with air velocity of 20 m min^{-1}. Plastic bags were sealed using a manual heat sealer (PGC Scientific, Gaithersburg, MD).

Both wetted and dewetted peeled carrots were placed in plastic bags at 10°C. Evaluations were done periodically, monitoring 20 peeled carrots each time/treatment. Two bags/treatment were used. Bags were opened each time color measurements were taken; afterwards, the carrots were placed in new bags and sealed again. Results were reported as W.I. change related to total storage time.

Dewetted peeled carrots were stored at 2.5°C in LDPE bags for 2 and 4 wk. After these periods, 10 peeled carrots were measured for levels of white appearance and then water dipped in chlorinated distilled water (200 ppm) stirred at room temperature. After draining, carrots were measured for color. After each measurement, carrots were again dipped in fresh chlorinated distilled water. Results were reported as W.I. as related to total dipping time.

Statistical analysis

Statview 4.0 was used for statistical analyses (Abacus Concepts, Berkeley, CA). Analysis of variance and Fisher PLSD multiple-comparison tests were performed.

RESULTS & DISCUSSION

White index-sensory scale relationship

The whiteness index scale (W.I.) was related to a visual descriptive scale to achieve a better understanding of W.I. data (Table 1). From this relation, we could define some general limits: a non-visible white as a W.I. of 32.6 ± 2.4, and a moderate white as a value of 43.0 ± 1.8 W.I. Higher values indicated that the peeled carrots had reached their storage life limit. Visual ratings were reported by Bolin and Huxsoll (1991), Bolin (1992) and Avena et al. (1993a, 1993b), but were not directly related to the W.I. scale.

Relative humidity association with color change

Avena et al. (1993a) reported a W.I. development dependence on relative humidity for peeled carrots. We confirmed their results, observing different rates of W.I. appearance on peeled carrots through time at three relative humidities (Fig. 1). These results were related to water loss from the surface, considering the inverse relation with % RH. Rooke and Van den Berg (1985) showed that when whole carrots were exposed to 100% RH, they slowly absorbed some moisture; while at 96–99% RH, whole carrots lost moisture, depending on RH of the air. The equilibrium relative humidity, which is the RH of air in equilibrium with the tissue (no net moisture transfer between tissue and air), is about 99.6–99.8% for whole carrots (Rooke and Van den Berg, 1985). The driving force for moisture loss would be the vapor pressure difference (VPD) between the surrounding air and the peeled carrot surface. The VPD is dependent on temperature and % RH. Buick and Damoglou (1987) observed a temperature effect on color change, which could be related to this dependence of VPD on temperature.

Reversible color change

Dewetted peeled carrots exposed to 75 and 98% RH for 4 days had a W.I. corresponding to a severe white (Fig. 2). When the carrots were dipped into water (rewet), an exponential decay relation between W.I. and water dipping time was observed. After ~4 min of water exposure, a value of W.I. was reached which corresponded to non-visible white color. W.I. continued to decrease with increased dipping time, with no significant ($p < 0.05$) additional reduction after 8 min. Peeled carrots held for 8 days under similar storage conditions also presented lower W.I. value after water dipping, with no ($p < 0.05$) additional reduction after 20 min. The minimum values of W.I. reached in both cases were higher than those corresponding to fresh carrots at day 0. This partial reduction of W.I. values was 75 to 90% of the original color change.

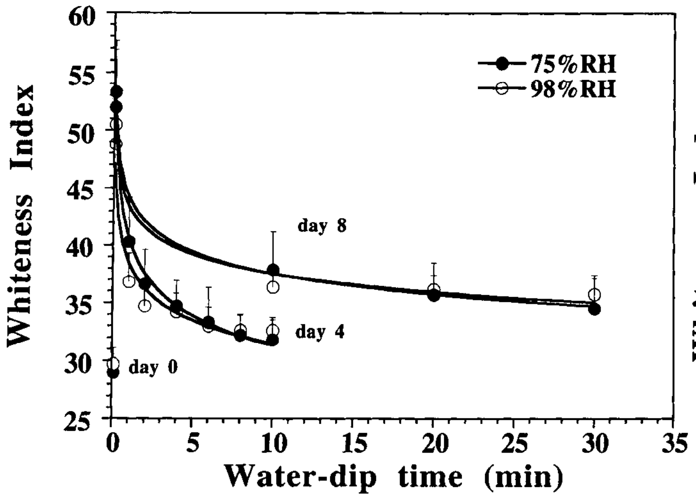

Fig. 2—Effect of water dip time on W.I. of dewetted peeled carrots previously stored for 4 and 8 days at different relative humidities and 10°C. Bars indicate one-sided standard deviations.

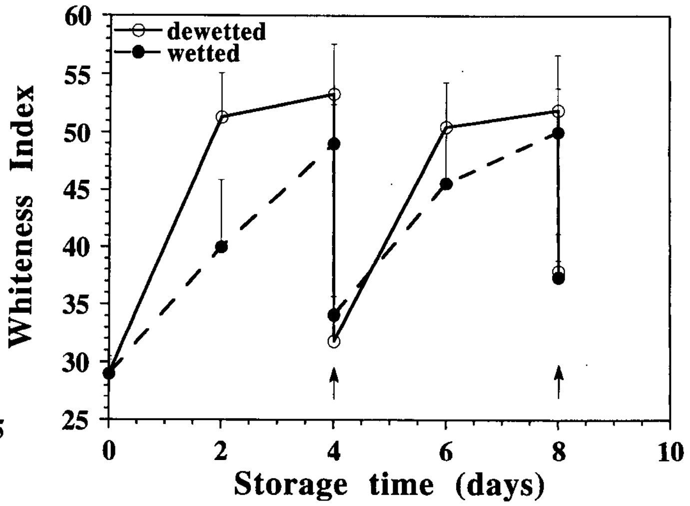

Fig. 4—Effect of initial surface moisture and storage time on W.I. for peeled carrots stored at 75% RH and 10°C. Arrows indicate a ten minute water dip. Bars indicate one-sided standard deviations.

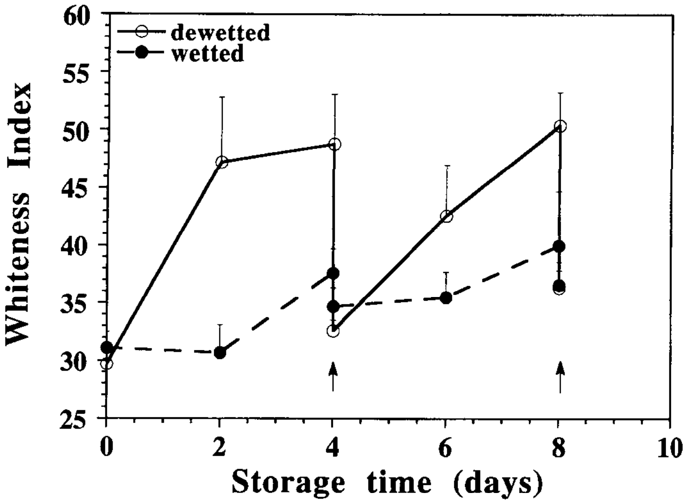

Fig. 3—Effect of initial surface moisture and storage time on W.I. for peeled carrots stored at 98% RH and 10°C. Arrows indicate a ten minute water dip. Bars indicate one-sided standard deviations.

The partial reversibility was likely due to rehydration of the dried surface and the filling with water of spaces between disrupted cell walls or debris. A moistened surface reduces reflectance of light, making more apparent the deep orange color beneath the surface. The cell wall debris of the surface would appear translucent in the presence of water. When the surface of peeled carrots dries, it scatters reflected light, causing the white appearance.

This reversible color change suggests a surface dehydration mechanism and is most likely what Avena et al. (1993a) reported as depending on %RH. The degree of peeling and the type of cutting surface associated with color change (Bolin and Huxsoll, 1991; Tatsumi et al., 1991) could be explained in part by this observation. More disrupted cell walls on a dried surface cause more irregular surface areas. This increased area once dried would increase light scattering and thus white appearance.

Initial surface moisture

Avena et al. (1993a) showed that during surface dehydration, a lag time was observed before W.I. increased. This lag time would depend on the initial amount of water present on the surface of the peeled carrots. After placing wetted and dewetted peeled carrots at 98% RH, different rates of white index development could be observed (Fig. 3). For previously-dewetted peeled carrots, the white development was always higher. After 4 days, the difference in white development was still observed, although in that case initially-wetted peeled carrots had reached a slightly-white stage.

Water dipping (rewetting) caused peeled carrots to regain an orange color, thus a low W.I. value. When placed back in the chambers, the white development was again induced under similar rates, reaching after another 4 days values similar to those reported before. At 75% RH, this effect was observed again (Fig. 4). In that case, the difference between wetted and dewetted peeled carrots was not as notable as at 98% RH. This could be due to the higher driving force or water vapor pressure difference at 75% RH, inducing a higher rate of surface water loss.

The presence of excess surface moisture could help extend the lag time observed before white discoloration appears. Treatments claiming to control enzymatic activity, such as aqueous acid or basic dip treatments (Bolin and Huxsoll, 1991; Bolin, 1992) or steam treatments (Howard et al., 1994) were most likely maintaining a moisture layer over disrupted cell walls. This would delay observed white development, but basically due to an increase of lag time as reported by Avena et al. (1993).

Irreversible color change

Dewetted peeled carrots exposed to 75 and 98% RH and then water dipped did not regain totally their original color (Fig. 2). The same was observed for wetted carrots (Fig. 3, 4). These increased W.I. values were due to an irreversible color change, and according to our observations these values increase with time. It has been reported that when wounding occurs, phenolic metabolism was activated in carrots, inducing lignification of outer cells (Bolin and Huxsoll, 1991; Howard and Griffin, 1993). This physiological response has been proposed as the cause of white discoloration. We propose that the irreversible color change we observed could be related to the irreversible physiological response to wounding reported in other studies. The mechanism that could explain the irreversible color change may be related to the wetting characteristics of lignin, the light reflectance of lignin, or both. Considering that lignin is hydrophobic (Laschimke, 1989), the irreversible W.I. component possibly shows a non-complete rehydration of the outer layers (initially more hydrophilic) during water dipping. Also the lignification process may increase light reflectance and thus white development. From our observations, the irreversible color

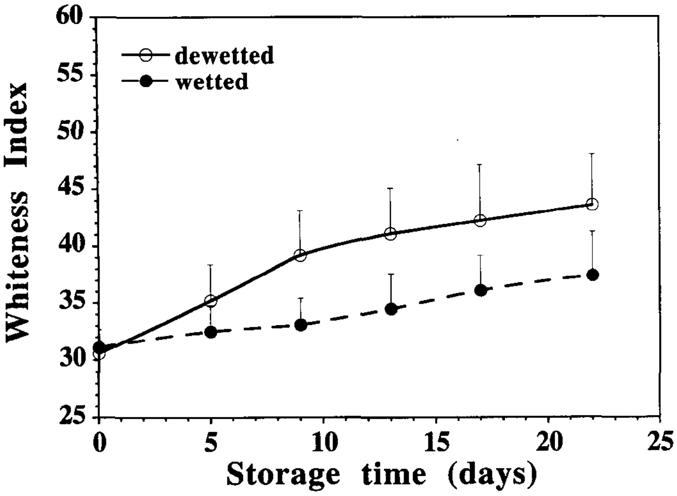

Fig. 5—Effect of storage time on W.I. of wetted and dewetted peeled carrots stored in LDPE bags at 10°C. Bars indicate one-sided standard deviations.

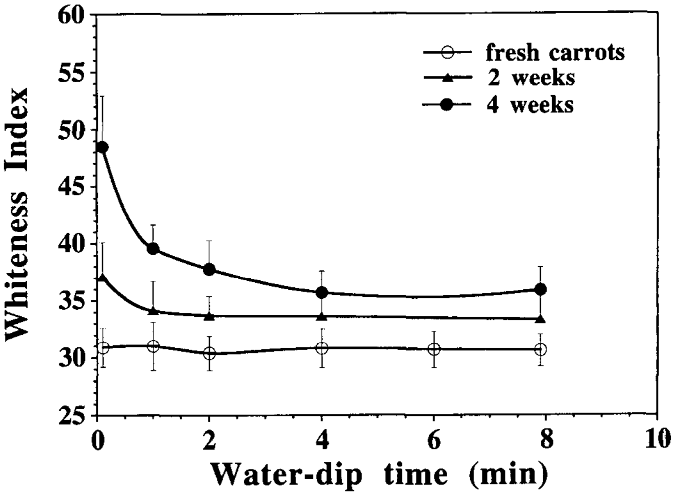

Fig. 6—Reversible and irreversible color change of dewetted peeled carrots previously stored for 2 and 4 wk at 2.5°C in LDPE bags compared to fresh carrots. Bars indicate one-sided standard deviations.

change appears to be independent of storage RH or initial amount of moisture on the peeled carrots surface (Fig. 3, 4). Howard and Griffin (1993) quantified the increase of lignin and phenolic compounds and the increase in phenylalanine ammonia-lyase (PAL) activity on carrot sticks, and correlated it with an increase in total W.I. They observed that upon reducing ethylene, the whiteness index did not decrease. The irreversible color change may be associated with factors related to the phenolic metabolism pathway. Oxygen, ethylene, carbon dioxide, wounding severity (Bolin and Huxsoll, 1991; Tatsumi et al., 1991), cultivar, temperature (Buick and Damagon, 1987), and other factors that could affect gene reading or enzyme activity might influence this response.

Thus, our results suggest that the W.I. development on peeled carrots has two components. First, a physical response component due to surface moisture loss, manifested by the partial reversibility of W.I. once water-dipped. Second, a possible physiological response component due to lignification (Bolin and Huxsoll, 1991; Howard and Griffin, 1993) and appearing as an irreversible increase of W.I. after water dipping. In commercial packaging systems, where fluctuations in storage temperature may occur and water condensation inside bags takes place, localized surface rehydration can occur. The result would be variations in white development among carrots packaged in a bag and between bags in the same storage facility. Considering that potentially the reversible white color change has more effect than the irreversible component, the physiological response may be masked. Studies on enzymatic effects on color change (Bolin and Huxsoll, 1991; Bolin, 1992; Howard and Griffin, 1993; Howard et al., 1994) most likely also have been observing dehydration effects on color.

Carrots stored in LDPE bags

The RH in packaged vegetables and fruits can reach high values. Shirazi and Cameron (1992) reported a relative humidity of 98% in LDPE plastic-film-packaged tomatoes (2 mil thickness at 20°C). The RH inside the plastic bags would also be dependent on the storage room RH and the plastic film permeance (Saguy and Mannheim, 1975). Any other factor, such as cultivar or growing conditions, that affects fruit skin resistance to water loss, may contribute to variations in % RH (Shirazi and Cameron, 1992).

Peeled carrots have very low water vapor resistance (Avena et al., 1993b), indicating high moisture loss. Considering that there is a high relative humidity inside the bags, a small vapor pressure difference between the inside package air (that surrounds the carrots) and the carrot surface would be enough to cause loss of surface water. Using a packaged system where the plastic film defines the rate of water loss from the peeled carrots, similar behavior to that observed in chambers controlled at 98% RH was obtained (Fig. 5). Wetted peeled carrots had a lower rate of W.I. development compared to a control that had been dewetted before packaging. This was evident after 14 days, and the difference was maintained as time increased; but ultimately the W.I. reached similar values (data not shown). In that case, the lag time was extended and the white appearance delayed.

Dewetted peeled carrots stored in LDPE bags at 2.5°C showed reversible and irreversible W.I. change components once water dipped (Fig. 6). In the 2 week storage period, the reversible color change represented 50% of the total change in color; while for the 4 wk storage the reversible color change was ~72% of the total. In both cases, white discoloration was observed due to the physical response.

CONCLUSIONS

A PROPOSED MECHANISM of white discoloration development on peeled carrots includes both physical and physiological responses to wounding. The physical response is reflected in a color change due to surface dehydration which is reversible. As time passes, a possible physiological response occurs involving activation of phenolic metabolism and production of lignin reflected by an irreversible color change. In general, white development due to the physical response increases with lower RH and with time. Initial treatments using excess surface moisture would reduce the rate of white development. In commercial systems, different factors affecting mass transfer should be considered and evaluated. These include relative humidity and air velocity in storage rooms, temperature fluctuations, ratio of weight of produce to film area, thickness and permeability.

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