THE EFFECTS OF PACKAGING FILM AND STORAGE TEMPERATURE ON THE INTERNAL PACKAGE ATMOSPHERE AND FERMENTATION ENZYME ACTIVITY OF SWEET POTATO SLICES

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ABSTRACT

Fresh-cut sweet potato slices were packaged in low- (PD900), medium- (PD961) and high-permeability (PD941) film bags, and were stored at 2 or 8C for 14 days. Changes in O_2, CO_2, ethanol and acetaldehyde concentrations in the headspace were monitored over 14 days. The activities of fermentation enzymes and the concentration of fermentation volatiles were measured from tissue extracts on days 0, 7 and 14. Storage at 8C was an excessively high temperature for fresh-cut sweet potatoes to maintain aerobic respiration for 14 days. Low-permeability film bags resulted in anaerobiosis at 2 and 8C. Medium-permeability film bags were able to maintain a higher O_2 and a lower CO_2 level than PD900 film bags at 2C. However, they behaved similarly at 8C. High-permeability film bags maintained an aerobic atmosphere during the 14 days of storage at both temperatures.

PRACTICAL APPLICATIONS

Consumer demand for convenience, ease of preparation and ready-to-eat forms of fresh fruit and vegetables have contributed to the significant market growth in the fresh-cut produce sector during the last several decades. However, minimally processed forms of sweet potatoes have only recently

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become available in the U.S. commercial produce trade. Many consumers perceive these value-added forms of sweet potatoes to be healthy food items, high in nutritional value.

Utilization of selectively permeable modified atmosphere packaging (MAP) is standard in the distribution of fresh-cut produce. The success of MAP depends on the proper selection of the appropriate semipermeable polymeric film to match the product respiration rate and holding temperature. Polymeric films, which allow for the establishment of acceptable internal package O_2 and CO_2 atmospheres while maintaining aerobic respiration of the fresh-cut product, are the most desirable. Undesirably low O_2 and/or excessive CO_2 concentrations inside the package may result in anaerobic respiration of the product that is detrimental to edible quality. The results of this study provide useful information to fruit and vegetable processors on the appropriate semipermeable polymeric film package and holding temperature for maintaining fresh-cut sweet potato quality. Commercial foodservice firms targeting fresh-cut sweet potatoes as a convenience food will potentially benefit from the information in this article.

INTRODUCTION

Packaging is mandatory for distribution of fresh-cut products. These items are typically packaged for the consumer in sealed polymeric film bags, rigid plastic trays, sealed across the top with polymeric films on overwrapped trays (Schlimme and Rooney 1994). Polyolefins are the predominant polymeric materials used for packaging of fresh products (Kader *et al.* 1989).

In a sealed permeable film package containing fresh produce inside, a modified atmosphere is created as a result of the balance between the respiration process (O_2 uptake and CO_2 external production) and the exchange of gases through the film. Eventually, steady-state concentrations of O_2 and CO_2 are established at a given temperature when the rates of O_2 consumption and CO_2 production of the produce equal the rates of permeation of these gases through the package (Kader *et al.* 1989).

The success of modified atmosphere packaging (MAP) depends on the selection of polymeric films having proper O_2, CO_2 and water vapor transmission rates for produce. Too low O_2 and too high CO_2 inside the package results in anaerobic respiration of the produce that is detrimental to its edible quality (Carlin *et al.* 1990). Anaerobic conditions can also create a favorable environment for the growth of human pathogens (Hintlian and Hotchkiss 1986). A minimum of 1–3% O_2 is required to avoid a shift from aerobic to anaerobic respiration, depending on the plant species (Kader 1986). The tolerance limit of intact sweet potato to low oxygen was reported to be 1.5% (Kilili 1999).

Anaerobic respiration leads to undesirable metabolic reactions, such as tissue breakdown, and accumulation of acetaldehyde and ethanol in the plant tissue, which results in off-odor and off-flavor (Kader *et al.* 1989). Endogenous production of acetaldehyde and ethanol is regulated by pyruvate decarboxylase (PDC), which catalyzes the decarboxylation of pyruvate to acetaldehyde and by alcohol dehydrogenase (ADH), which converts acetaldehyde to ethanol (Kennedy *et al.* 1992).

Maintenance of a stable, low temperature maximizes the benefits from the MAP of intact or fresh-cut fruits and vegetables. In practice, many fresh-cut products are prepared, shipped and stored at 5C, and sometimes as high as 10C (Watada *et al.* 1996). The possibility of exposure to elevated temperatures during handling and distribution is taken into consideration in modeling MAP for fresh produce (Cameron *et al.* 1993). Any change in temperature will affect the rate of respiration and equilibrium conditions within the package, unless the rate of gas diffusion through the film is changed with temperature by exactly the same extent as respiration (Exama *et al.* 1993).

Fresh-cut fruits and vegetables require 7- to 14-day shelf life for adequate distribution and marketing time (Watada *et al.* 1996). The success of MAP is based on achieving a steady state of O_2 and CO_2 as soon as possible (Talasila *et al.* 1995), and maintaining equilibrium under temperature fluctuation (Stewart *et al.* 1993; Cameron *et al.* 1995).

Vegetable industry data indicate approximately 15% of all vegetables marketed in the U.S.A. are now in more consumer-friendly convenient forms. For this reason, there is interest in transitioning some of the total production into "minimally processed," e.g., peeled and packaged, or peeled, cut and packaged, or "preprocessed," ready-to-eat and ready-to-use products. These include products typified by sliced fresh-frozen "coins" for use in salads or as a "ready-to-use" pre-prepared ingredient for consumers or food services, and strips for French-fry preparation (Burden 2005). Sweet potatoes are currently marketed as a fresh-cut item and have considerable potential in this form to create new value-added market opportunities.

The objective of this study was to determine the effects of low-, medium- and high-permeability packaging films at different storage temperatures on the internal package atmosphere of fresh-cut sweet potatoes.

MATERIALS AND METHODS

Cured "Beauregard" sweet potatoes stored at 14C for 3–4 months were obtained from the Louisiana State University Agricultural Center Sweetpotato Research Station, Chase, LA. Prewashed roots were peeled using a Hobart

TABLE 1.
CHARACTERISTICS OF THREE MULTILAYERED CROSS-LINKED POLYOLEFIN MAP FILM BAGS (CRYOVAC SEALED AIR CO., DUNCAN, SC)

Film	Gauge (mm)	OTR*	CTR*
PD900	0.061	3,000	9,800
PD961	0.032	7,000	21,000
PD941	0.019	16,500	36,000

* OTR and CTR are O_2 and CO_2 transmission rates, respectively, and are expressed in terms of $cm^3/m^2/day^1$ at 1 atm pressure differential for a film 1 mil (0.0254 mm) thick at 23C.

abrasive peeler (Hobart Co., Troy, OH). U.S. No. 1 grade roots were cut into 3.2-mm-thick slices using a Hobart Model 410 slicer. Slices were separated into 500-g portions and were placed in 16-cm wide × 30.5-cm long, multilayered polyolefin low-permeability (PD900), medium-permeability (PD961) and high-permeability (PD941) film bags (Cryovac Sealed Air Co., Duncan, SC) The thickness and gas exchange characteristics of these film bags are shown in Table 1.

The film bags were vacuum-evacuated with a Westglen vacuum packager, Model VM20011 (Westglen Co., Los Angeles, CA), using a setting of 50, and were heat-sealed at a setting of 2.5. Four sealed film bag replications per treatment were kept at either 2 or 8C and 88 ± 3% relative humidity (RH) for 14 days.

The recommended storage temperature for fresh-cut vegetables is 2–6C (Barry-Ryan and O'Beirne 1998). However, these products are often held at higher temperatures in normal retail distribution (Carlin *et al.* 1990). Temperatures in retail display areas of major grocery stores in Baton Rouge for fresh-cut products range from 2 to 8C. Therefore, 2 and 8C were chosen as the test storage temperatures. Temperature and RH were monitored with a hygrothermograph during storage.

Percent O_2 and CO_2 in the headspace of the film bags were monitored daily during the first 3 days and after 7 and 14 days using a Model 3600 O_2/CO_2 analyzer (Illinois Instrument Inc., Ingleside, IL). The O_2/CO_2 analyzer was calibrated daily with ambient air and a calibration gas of 4% CO_2. Ten milliliters of gas volume was taken from inside the packages by inserting a needle through a Teflon septum applied to the outside of the package. The needle was attached to the sample port of the analyzer with a syringe and sampling wand.

Internal headspace inside the film bags was also analyzed for fermentation volatiles (acetaldehyde and ethanol) 6 h after sealing and on days 1–7 and

14 at 2 and 8C. Fifty microliters of headspace gas was taken by inserting the needle into the package through the Teflon septum applied to the outside of the package. The sample was injected into a Varian 3700 gas chromatograph (Varian, Inc., Palo Alto, CA) equipped with a flame ionization detector (140C) and a column containing 5% Carbowax 20 M on 80/120 Graphpak support (Alltech Associates, Deerfield, IL) at 90C. Helium was used as the carrier gas at a flow rate of 23 mL/min. The concentrations of acetaldehyde and ethanol in the headspace of the film bags were compared to external standards and were expressed in parts per million (ppm).

Fermentation enzymes (PDC and ADH) and fermentation volatiles (acetaldehyde and ethanol) were extracted from the tissues of fresh-cut sweet potato slices before placing into film bags and after storing in the film bags for 7 and 14 days at 2 and 8C. A composite sample of tissue was taken from each of the four replications of film bags of sweet potato slices and was ground into fine powder in liquid nitrogen using a prechilled mortar and pestle. Fifteen milliliters of extraction buffer for each enzyme and 32.5 mL of HCl (100 mmol/L) solution was added separately to 6 g of finely pulverized powder in a 50-mL centrifuge tube, and were mixed for 2 min with an Adams Cyclo-Mixer (Clay-Adams Inc., New York, NY) at full speed. The homogenates were centrifuged for 35 min in a DuPont Instruments Sorvall RC-5B Refrigerated Super Speed Centrifuge (Sorvall, Newtown, CT) at $23{,}200 \times g_n$. The supernatants in the enzyme buffer solutions were retained for measuring PDC and ADH activities. The supernatant in the HCl solution was used for measuring concentrations of acetaldehyde and ethanol. Extraction and assay of PDC and ADH followed the procedure described by Huang *et al.* (2002). The activities of PDC and ADH were expressed as nmol/g fresh weight and μmol/g fresh weight, respectively. The concentration of acetaldehyde and ethanol was determined by a modification of the procedure described by Huang *et al.* (2002). Five milliliters of volatile extract was transferred to a 10-mL screw cap test tube sealed with a Teflon septum, and was kept at −20C until analysis. Analysis of the fermentation volatiles was performed after 24 h. The extracts were incubated for 90 min at 80 ± 1C. Then, 50 μL of headspace gas was analyzed for acetaldehyde and ethanol by a Varian 3700 gas chromatograph as previously described. Volatile concentrations were converted from ppm to nanomole for acetaldehyde, and micromole for ethanol, and were expressed on a gram fresh weight basis.

Data were subjected to analysis of variance using Proc GLM of SAS software (SAS 1998) as a 3×2 factorial experiment with four replicates in a randomized complete block design. The Proc Means of SAS software was used to calculate the mean and its respective standard error for each treatment.

RESULTS

Changes in O_2 and CO_2 Concentrations in the Film Bags

Changes in O_2 and CO_2 concentrations inside the low-permeability (PD900) film bags are shown in Fig. 1. O_2 was depleted rapidly below 1% during the first 2–3 days. O_2 depletion at 8C was more than at 2C. An O_2 concentration below 1% was reached at 8C one day earlier than 2C. The CO_2 concentration increased throughout the storage, and reached about 9 and 20% after 14 days at 2 and 8C, respectively.

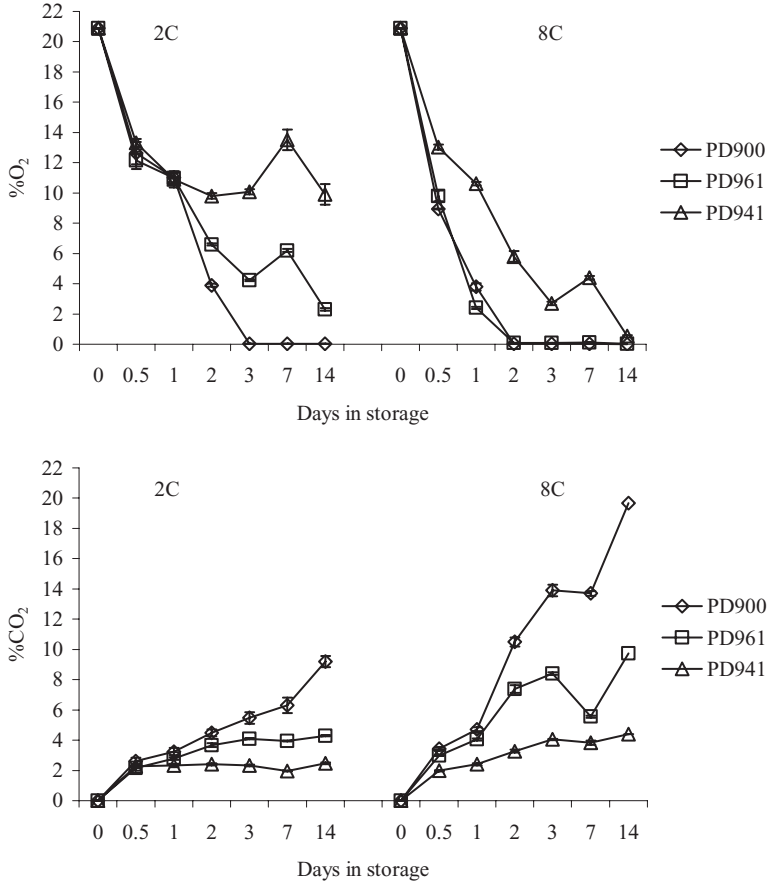

FIG. 1. O_2 AND CO_2 CONCENTRATIONS INSIDE PD900, PD961 AND PD941 FILM BAGS OF FRESH-CUT SWEET POTATOES STORED AT 2 AND 8C FOR 14 DAYS
Vertical bars represent the standard error and when absent falls within the area of the symbol. Each point represents the mean of four replicates.

The decrease in oxygen and increase in carbon dioxide inside the medium-permeability (PD961) film bags occurred at a lower rate compared to the PD900 film bags at 2C storage (Fig. 1). After reaching 4% at day 3, the O_2 concentration in PD961 film bags rose to 6% at day 7 and then decreased to 2%. The carbon dioxide concentration inside the PD961 film bags reached about 4% at day 2 and remained at that level throughout the 2C storage. At 8C, the trend of O_2 concentration was similar to that observed for PD900 film bags. Two days after bag sealing, the O_2 concentration in the PD961 film bags fell below 1% and remained constant thereafter. The CO_2 concentration increased gradually (except for a fluctuation at day 7). The highest CO_2 level reached was about 10%.

The oxygen concentration inside the high-permeability (PD941) film bags was significantly higher than in the PD900 and PD961 film bags at 2C (Fig. 1). A steady O_2 level of 10% was achieved 24 h after sealing (with a fluctuation at day 7). The carbon dioxide concentration in the PD941 film bags reached 2% at 12 h after sealing and remained constant thereafter. At 8C, O_2 levels inside the PD941 film bags decreased significantly, except for an increase at day 7. The final O_2 concentration after 14 days was 0.5%. A 3–4% steady-state CO_2 level was achieved at day 3 of the 8C storage, with a slight decrease at day 7.

Changes in Acetaldehyde and Ethanol Vapor in the Headspace of the Film Bags

Acetaldehyde accumulation was lower than ethanol accumulation in the fresh-cut sweet potatoes, regardless of the type of film bags and the storage temperature. The 2C storage temperature resulted in lower acetaldehyde and ethanol accumulation than the 8C storage (Table 2). The low-permeability film bags resulted in significantly higher volatile accumulation in the headspace than the medium-permeability film bags at both storage temperatures (Table 2). Neither acetaldehyde or ethanol vapor was detectable in the headspace of the high-permeability (PD941) film bags at 2 or 8C storage for 14 days (Figs. 2 and 3). Acetaldehyde and ethanol vapor started to accumulate in the headspace of the low-permeability (PD900) and medium-permeability (PD961) film bags at day 14 during 2C storage and at day 7 during 8C storage (Figs. 2 and 3).

Changes in Acetaldehyde and Ethanol Concentrations in the Tissue Extracts

Figures 4 and 5 show the changes in acetaldehyde and ethanol concentrations in the tissue extracts of fresh-cut sweet potato slices. Acetaldehyde concentration (34–850 nmol/g) was lower than ethanol concentration (0.24–

TABLE 2.
THE EFFECTS OF PACKAGING FILM AND STORAGE TEMPERATURE AND DURATION ON THE FERMENTATION VOLATILES AND FERMENTATION ENZYMES OF FRESH-CUT SWEET POTATOES

Factors		Headspace acetaldehyde content (ppm)	Headspace ethanol content (ppm)	Acetaldehyde concentration (nmol/g)	Ethanol concentration (µmol/g)	PDC activity (nmol/g)	ADH activity (µmol/g)
Film							
PD900		0.63	92.71	271.53	13.69	83.94	1.99
PD961		0.37	28.00	203.97	7.81	75.81	1.81
PD941		0.00	0.00	37.95	0.60	61.74	1.61
Storage temperature (C)							
2		0.04	27.93	72.58	1.93	33.49	1.23
8		0.64	52.01	269.72	12.80	114.17	2.38
Days in storage							
0		0.00	0.00	34.14	0.24	23.41	1.17
7		0.22	14.16	131.23	2.98	54.97	1.85
14		0.78	105.75	348.07	18.88	143.10	2.39
$LSD^{\dagger}_{(0.05)}$ (film)		0.04	2.26	4.79	0.57	3.80	0.03
$LSD_{(0.05)}$ (temperature)		0.04	1.84	3.91	0.47	3.10	0.02
$LSD_{(0.05)}$ (day)		0.04	2.26	4.79	0.57	3.80	0.03
Source	df	MS	MS	MS	MS	MS	MS
Film (F)	2	2.38*	54,508.00*	346,730.13*	1,030.28*	3,025.55*	0.865*
Temperature (T)	1	5.97*	10,442.53*	699,507.92*	2,126.72*	117,161.08*	23.851*
Day (D)	2	3.85*	79,083.81*	620,008.49*	2,433.20*	92,353.81*	9.003*
F × T	2	1.61*	9,218.43*	172,703.41*	478.87*	1,606.99*	0.652*
F × D	4	1.07*	38,643.99*	154,319.38*	618.90*	950.87*	0.498*
T × D	2	2.56*	2,976.30*	289,638.32*	1,431.26*	55,491.98*	7.187*
F × T × D	4	0.70*	4,239.48*	93,688.34*	326.31*	945.61*	0.423*
Error	54	0.01	15.22	68.52	0.98	43.15	0.002

* Significant at $P < 0.01$.

† Least significant difference (LSD). Mean separation ($n = 4$) was performed by Fisher's LSD test.

PDC, pyruvate decarboxylase; ADH, alcohol dehydrogenase; df, degrees of freedom; MS, mean square.

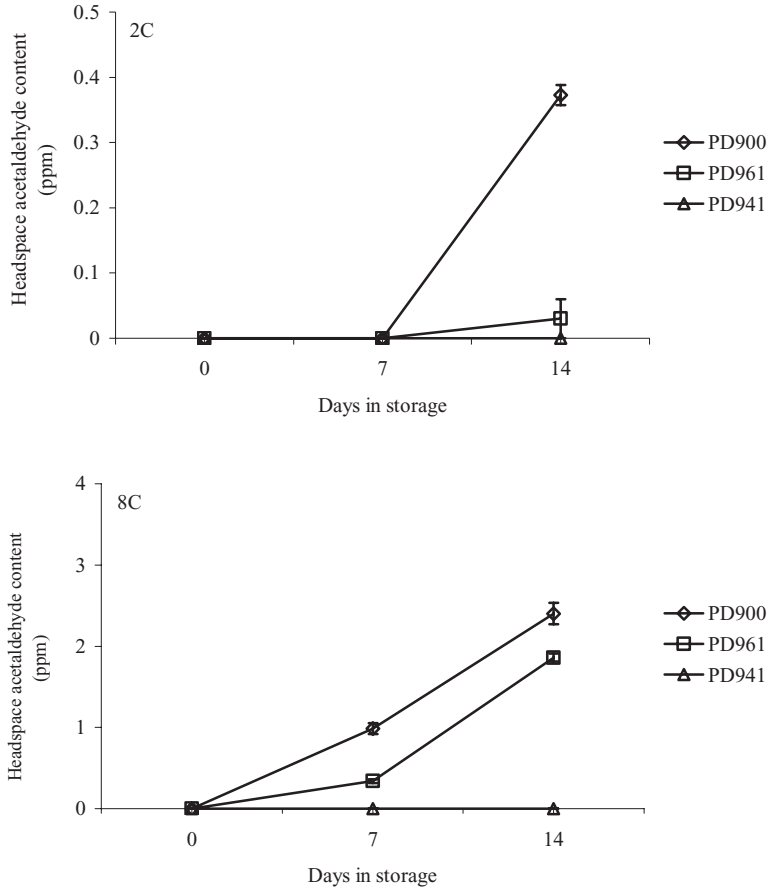

FIG. 2. HEADSPACE ACETALDEHYDE CONTENT OF PD900 AND PD961 FILM BAGS OF FRESH-CUT SWEET POTATOES STORED AT 2 AND 8C FOR 14 DAYS
Vertical bars represent the standard error and when absent falls within the area of the symbol. Each point represents the mean of four replicates.

19 μmol/g) in fresh-cut sweet potatoes during storage (Table 2). Fresh-cut sweet potatoes packaged in PD900 film bags showed a two- to fourfold weekly increase in acetaldehyde concentration (Fig. 4), and a six- to 10-fold weekly increase in ethanol concentration during 2C storage (Fig. 5). Slices from PD961 and PD941 film bags maintained the initial acetaldehyde and ethanol concentration for 14 days at 2C (Figs. 4 and 5). Fresh-cut sweet potatoes stored at 2C had a lower acetaldehyde and ethanol concentration than at 8C (Table 2). At the end of 7 days, fresh-cut sweet potatoes from PD900 film bags

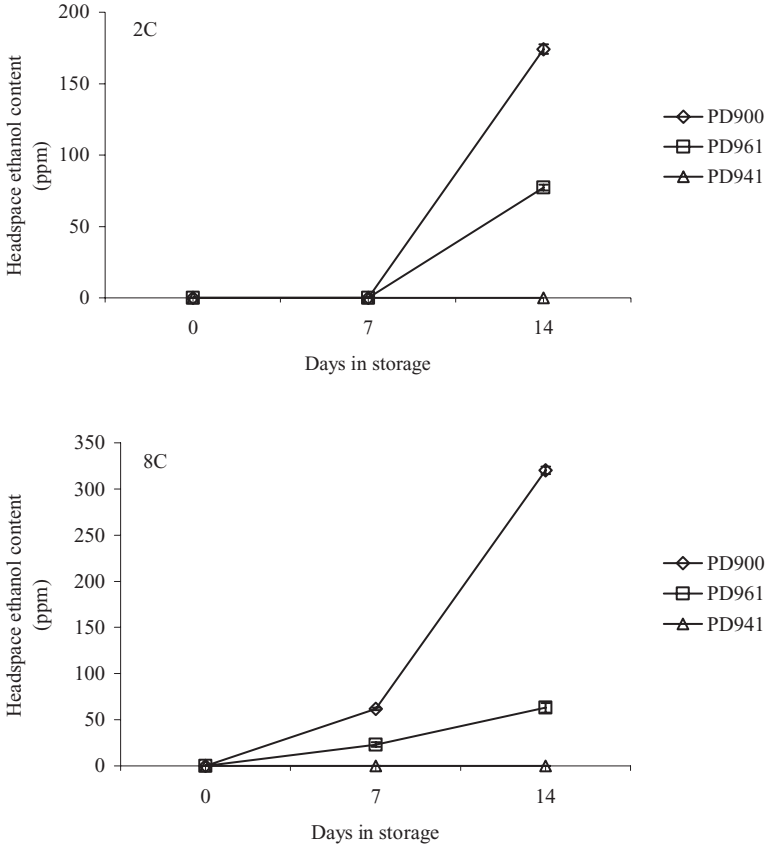

FIG. 3. HEADSPACE ETHANOL CONTENT OF PD900 AND PD961 FILM BAGS OF FRESH-CUT SWEET POTATOES STORED AT 2 AND 8C FOR 14 DAYS
Vertical bars represent the standard error and when absent falls within the area of the symbol. Each point represents the mean of four replicates.

had a significantly higher acetaldehyde concentration than PD961 film bags, but both were similar after 14 days at 8C (Fig. 4). The ethanol level was significantly higher in the slices from PD900 film bags than from PD961 film bags during 14 days at 8C (Fig. 5). Packaging with PD941 film bags did not lead to significant acetaldehyde or ethanol production in fresh-cut sweet potatoes during 8C storage (Figs. 4 and 5).

Changes in PDC and ADH Activities in the Tissue Extracts

PDC activity was lower than ADH activity in fresh-cut sweet potatoes. Changes in enzyme activities followed a similar trend among the bag types

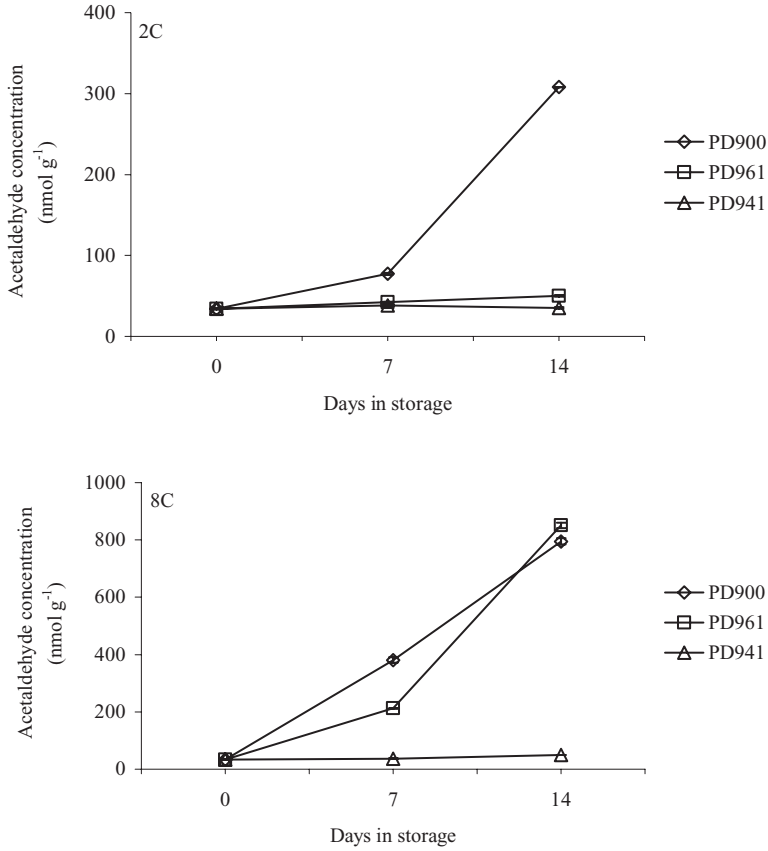

FIG. 4. CHANGES IN ACETALDEHYDE CONCENTRATIONS OF FRESH-CUT SWEET POTATO SLICES PACKAGED IN PD900, PD961 AND PD941 FILM BAGS STORED AT 2 AND 8C FOR 14 DAYS
Vertical bars represent the standard error and when absent falls within the area of the symbol. Each point represents the mean of four replicates.

and storage temperatures (Figs. 6 and 7). Storage at 8C resulted in significantly higher PDC and ADH activities in the slices than at 2C storage (Table 2). The PDC and ADH activities of fresh-cut sweet potato slices from the low-permeability (PD900) film bags increased significantly during 14 days of storage at 2C (Figs. 6 and 7). With the medium-permeability (PD961) and high-permeability (PD941) film bags, PDC activity of the slices remained near their initial levels up to day 7, and then increased

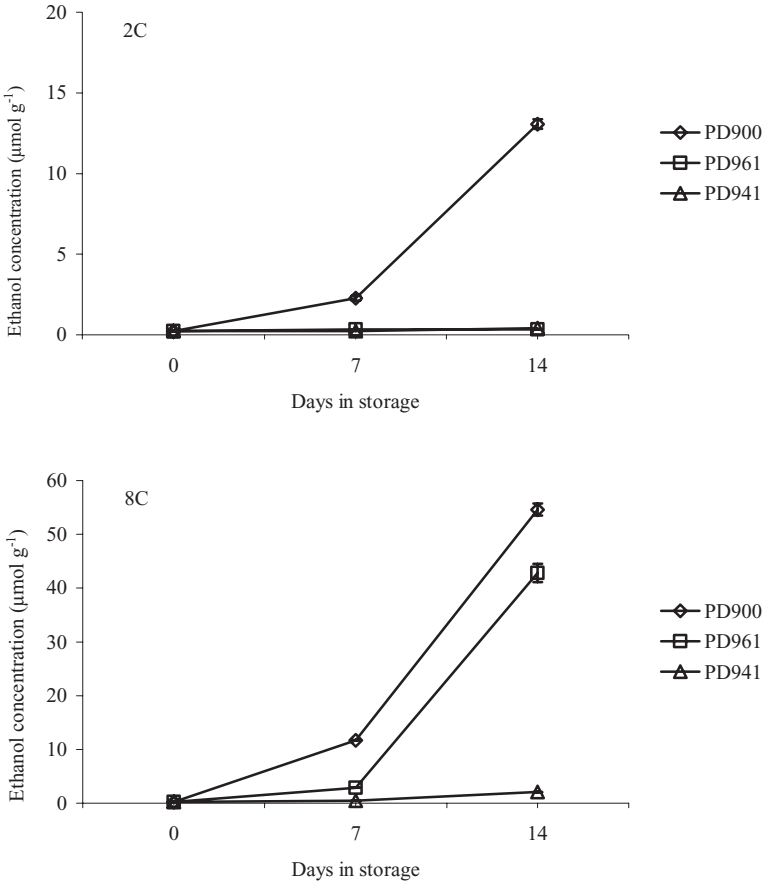

FIG. 5. CHANGES IN ETHANOL CONCENTRATIONS OF FRESH-CUT SWEET POTATO SLICES PACKAGED IN PD900, PD961 AND PD941 FILM BAGS STORED AT 2 AND 8C FOR 14 DAYS
Vertical bars represent the standard error and when absent falls within the area of the symbol. Each point represents the mean of four replicates.

significantly at day 14 during 2C storage. A 10-fold increase in PDC and a threefold increase in ADH activities were observed in the slices from PD900 and PD961 film bags at day 14 compared to the beginning of storage at 8C. Although PDC and ADH activity of the slices from PD941 film bags was significantly lower (almost at the initial level) than from PD900 and PD961 film bags at day 7, it reached a level similar to the other film types by day 14.

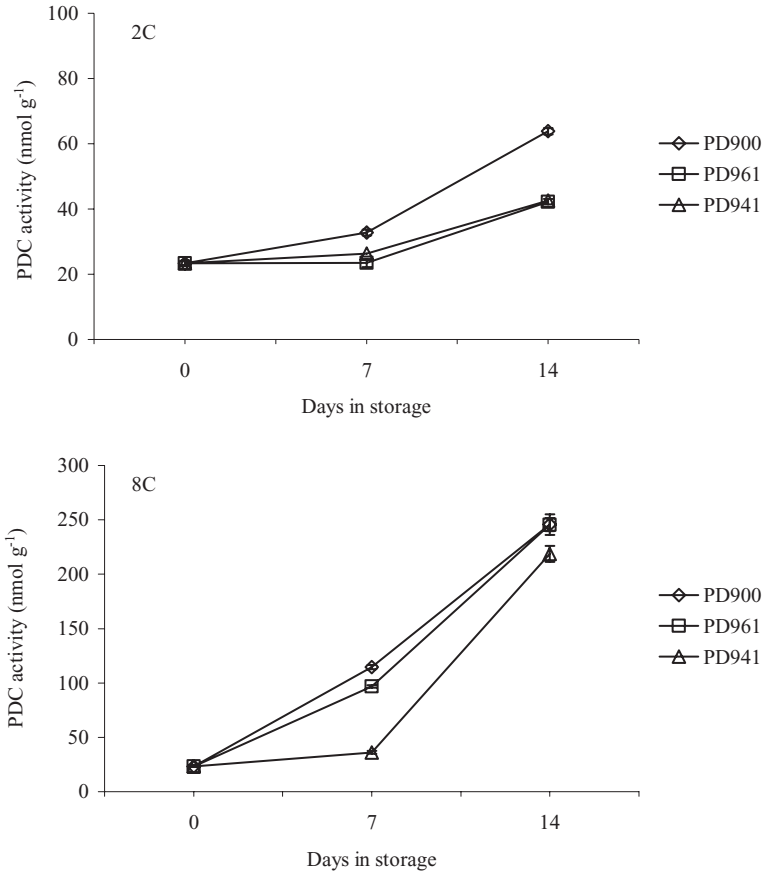

FIG. 6. PYRUVATE DECARBOXYLASE (PDC) ACTIVITY OF FRESH-CUT SWEET POTATO SLICES PACKAGED IN PD900, PD961 AND PD941 FILM BAGS STORED AT 2 AND 8C FOR 14 DAYS
Vertical bars represent the standard error and when absent falls within the area of the symbol. Each point represents the mean of four replicates.

DISCUSSION

PD900 film bags were the least permeable to O_2 and CO_2 exchange, followed by PD961 and PD941 film bags (Table 1). The difference in permeability characteristics of the film bags correlated with the changes in internal O_2 and CO_2 concentrations. The rate of decrease in O_2 concentration and increase in CO_2 concentration was significantly higher at 8C than at 2C. Acetaldehyde and ethanol concentrations from the tissue extracts were con-

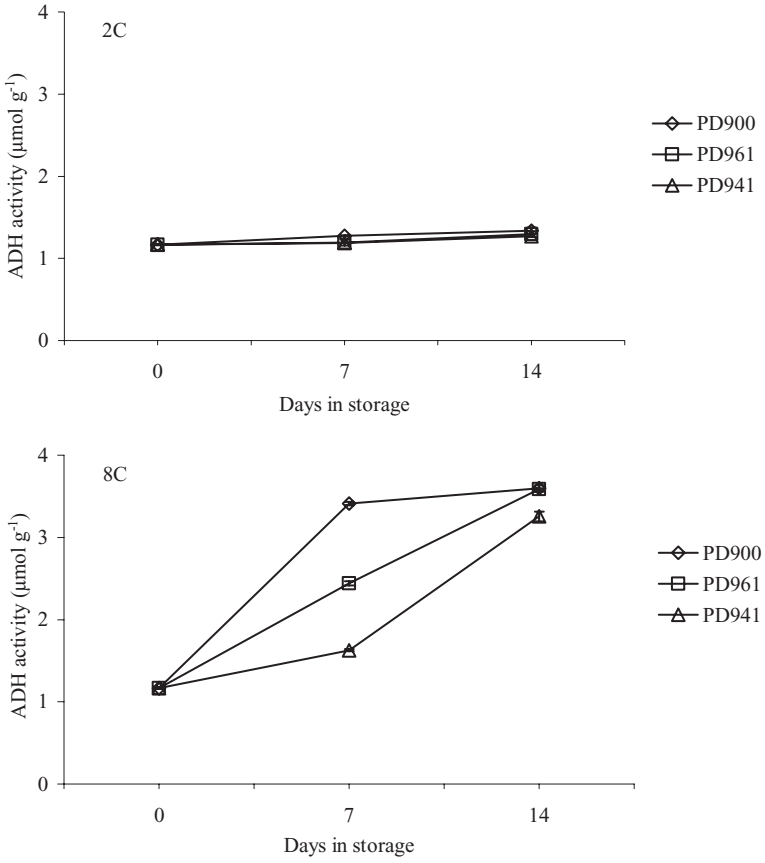

FIG. 7. ALCOHOL DEHYDROGENASE (ADH) ACTIVITY OF FRESH-CUT SWEET POTATO SLICES PACKAGED IN PD900, PD961 AND PD941 FILM BAGS STORED AT 2 AND 8C FOR 14 DAYS
Vertical bars represent the standard error and when absent falls within the area of the symbol. Each point represents the mean of four replicates.

sistent with headspace acetaldehyde and ethanol content of the film bags, and reflected the effects of O_2 depletion and CO_2 elevation of the fresh-cut sweet potatoes. Changes in PDC and ADH activity were correlated with acetaldehyde and ethanol production by fresh-cut sweet potato slices.

O_2 concentration in PD900 film bags remained constant at about 1% O_2 or below after 2–3 days of storage while CO_2 concentration increased throughout the 14-day period, regardless of storage temperature (Fig. 1). This indicated that the fresh-cut sweet potatoes in PD900 film bags shifted from aerobic to anaerobic respiration at 2 and 8C. Under anaerobic conditions, glycolysis

keeps functioning to provide some energy because it does not require oxygen. Pyruvate is no longer oxidized but is decarboxylated by PDC to form CO_2 and acetaldehyde. Acetaldehyde is then converted to ethanol by ADH (i.e., Pasteur effect) (Kennedy *et al.* 1992). Because there was no demand for O_2 by the anaerobically respiring sweet potato slices, O_2 level remained constant. Meanwhile, the level of CO_2 produced by anaerobic respiration continuously increased. At 2C, PDC (Fig. 6) and ADH activity (Fig. 7), and acetaldehyde (Fig. 4) and ethanol concentration (Fig. 5) of fresh-cut sweet potato slices in the PD900 film bags were significantly higher at day 7 compared to initial levels. This was associated with <1% O_2 and 6.3% CO_2 levels (Fig. 1), but the accumulation of ethanol and acetaldehyde in the headspace (Figs. 2 and 3) of these film bags did not start until day 14 at 2C. At 8C, the increase in PDC (Fig. 6) and ADH activity (Fig. 7), and acetaldehyde (Fig. 4) and ethanol concentration (Fig. 5) of fresh-cut sweet potato slices packaged with the PD900 film bags were at higher rates than at 2C after 7 days of storage, and were accompanied by the accumulation of ethanol and acetaldehyde in the headspace (Figs. 2 and 3) of these film bags. Generally, increasing concentrations of the fermentation volatiles (acetaldehyde and ethanol) in the headspace gas samples (Figs. 2 and 3) and tissue extracts (Figs. 4 and 5), and activities of the fermentation enzymes (PDC and ADH) in the tissue extracts (Figs. 6 and 7) during 2 and 8C storage confirmed the anaerobic respiration of fresh-cut sweet potatoes in PD900 film bags. Low-permeability film bags were not suitable for fresh-cut sweet potato packaging because PD900 film bags resulted in anaerobic respiration at both storage temperatures. Gunes and Lee (1997) reported similar results from French fry-type cut potatoes packaged with PD900 film bags at 2C storage. PD900 film bags contained about 0.3% O_2 and 9.3% CO_2, which resulted in anaerobic respiration in potato strips.

O_2 concentration in the PD961 film bags fluctuated during storage at 2C. After reaching 4% at day 3, the O_2 concentration rose to 6% at day 7 and then decreased to 2.5% (Fig. 1). The fluctuation in the O_2 levels between day 3 and day 7 was probably due to an adjustment to O_2 demands of the enclosed slices. The CO_2 levels increased until day 3 and attained a steady state thereafter with a slight decrease at day 7 during 2C storage. The pattern of internal O_2 and CO_2 changes inside the PD961 film bags at 2C showed a typical equilibration pattern of internal and external gases, involving a rapid decline in O_2 and increase in CO_2 (Smith *et al.* 1987). Jeon and Lee (1999) observed similar O_2 and CO_2 changes inside the PD961 film bags of American ginseng roots. There was no indication of anaerobic respiration of slices in the PD961 bags at 2C because neither acetaldehyde (Fig. 2) nor ethanol (Fig. 3) vapor was detectable in the headspace over 14 days. The concentration of these volatiles in the sliced tissue extracts remained at the initial level during 14 days (Figs. 4 and 5). PDC and ADH activity of the sliced tissue extracts was not significantly

different from the initial levels until day 14 at 2C (Figs. 6 and 7). At 8C, a high respiratory activity of sweet potato slices led to depletion of O_2 and elevation of CO_2 in PD961 bags. Two days after bag sealing, O_2 concentration fell below 1% while CO_2 concentration increased gradually, except for a fluctuation at day 7 (Fig. 1). At day 7, the fresh-cut sweet potato slices inside PD961 film bags at 8C started to produce significant amounts of acetaldehyde and ethanol, accompanied with significant increases in PDC and ADH activity (Figs. 6 and 7). Packaging sweet potato slices in PD961 film bags could be problematic at 8C because of anaerobic respiration, as indexed by accumulation of ethanol after 7 days. Creation and maintenance of an optimum atmosphere inside MAP depends on the respiration rate of the produce and the permeability of the film to O_2 and CO_2, both of which are affected by temperature. The increase in respiration rate as a function of temperature is substantially greater than the increase in permeability of film (Tano *et al.* 1999). Using PD961 for fresh-cut sweet potato packaging is not recommended because modified atmosphere packages may be exposed to a wide range of external temperatures during handling, transport and subsequent retailing (Cameron *et al.* 1993; Schlimme 1995). The medium-permeability PD961 film bags maintained an aerobic atmosphere at 2C, but an anaerobic atmosphere occurred at 8C for fresh-cut sweet potato slices. Medium-permeability film bags might be acceptable for packaging of fresh-cut sweet potatoes if they are kept at 2C. Gunes and Lee (1997) reported similar results with fresh-cut potatoes. Potato strips inside PD961 film bags had 1.4% O_2 at 2C. They suggested this O_2 level might cause an anaerobic respiration in the absence of temperature control. McConnell *et al.* (2005) suggested the use of the medium-permeability film bags for shredded sweet potatoes, which had a 5% O_2 and 4% CO_2 concentration at 4C. DeEll and Toivonen (2000) reported that broccoli heads held in PD961 film bags developed slight to moderate alcoholic off-odors, and high acetaldehyde, ethanol and ethyl acetate content after 28 days at 1C.

O_2 (10%) and CO_2 (2%) levels in PD941 film bags reached an equilibrium within 24 h after sealing, and remained near these levels for 14 days at 2C (Fig. 1). Fresh-cut sweet potatoes in PD941 film bags maintained the initial levels of acetaldehyde (Fig. 4) and ethanol content (Fig. 5), and acetaldehyde (Fig. 2) and ethanol (Fig. 3) vapor was not detectable in the headspace at 2C. ADH (Fig. 6) and PDC (Fig. 7) activity also remained constant at the initial level. These data indicated that aerobic respiration of fresh-cut sweet potatoes continued in these film bags during the 14-day storage at 2C. At 8C, O_2 level inside PD941 film bags decreased, except for an increase at day 7. The CO_2 remained mostly steady during 14 days with a slight decrease at day 7. At the end of 14 days at 8C, the PD941 package atmosphere contained 0.5% O_2 and 4% CO_2. Compared to other film bags at 8C, PD941 film bags contained relatively high O_2 and low CO_2 levels (Fig. 1), which sustained the aerobic

respiration of fresh-cut sweet potato slices. This was consistent with tissue acetaldehyde (Fig. 4) and ethanol (Fig. 5) concentrations that remained unchanged from the initial levels, and the lack of acetaldehyde (Fig. 2) and ethanol (Fig. 3) vapor in the headspace during 14 days of storage. In contrast, the PDC activity of sweet potato slices in PD941 film bags was very low at day 7, but it reached a similar level with the other film bags by day 14 (Fig. 6). The final O_2 concentration in PD941 film bags at 8C was 0.5%. This O_2 level might start a shift from aerobic to anaerobic respiration just before or at day 14. Our data indicated the anaerobic shift activates PDC, but it takes time to build up the anaerobic end product. High-permeability PD941 film bags provided a 14-day shelf life because there was no indication of anaerobic respiration at 2 and 8C until 14 days. PD941 film bags were also tested as film packages for carrot sticks. O_2 and CO_2 equilibrated at 11–14 and 1%, respectively, three days after sealing (Howard and Griffin 1993). Our results with PD941 film bags for sweet potatoes were similar with Howard and Griffin's findings. Gunes and Lee (1997) found significantly lower O_2 and higher CO_2 levels in PD941 film bags for fresh-cut potatoes (2% O_2 and 6% CO_2 at 2C). This atmosphere combination was considered sufficient to prevent anaerobic respiration in fresh-cut potatoes. PD941 film bags were recommended for broccoli packaging versus PD961 film bags at 1C. The atmosphere of 3% O_2 and 5% CO_2 inside PD941 film bags provided optimum MAP conditions for broccoli (DeEll and Toivonen 2000). Carlin *et al.* (1990) reported packaging of fresh, ready-to-use grated carrots with high-permeable films (22,000 cc/m^2/day, 1 atm at 25C) allowed for better shelf life preservation, with considerable reduction in electrolyte leakage, ethanol production, lactic acid bacteria and improved quality retention. Similarly, Varoquaux and Wiley (1994) reported that using a high-permeable film (20,000 cc/m^2/day, 1 atm) resulted in a better physiological condition of fresh-cut fruits and vegetables. Polyvinylchloride (PVC) film, having permeability to O_2 and CO_2 of 11,232 and 48, 552 cc/m^2/day at 1 atm, respectively, preserved the quality of raw grated beetroots for seven days at 0C (Lopez Osornio and Chaves 1997).

Initial ethanol concentration of intact sweet potato roots was reported to be 1.5 µmol/g fresh weight (Huang *et al.* 2002). The initial ethanol concentration of fresh-cut sweet potatoes was 0.24 µmol/g fresh weight. The lower initial ethanol content in fresh-cut slices might be due to a lower PDC activity initially. Acetaldehyde concentration was much lower than ethanol. A similar trend was reported for intact sweet potato roots (Kilili 1999) and fresh-cut carrots (Kato-Noguchi and Watada 1997) under a low oxygen atmosphere. Acetaldehyde is a product of anaerobic respiration, but it may be reduced to ethanol and may react further to form ethyl acetate (Larsen and Watkins 1995). Kato-Noguchi and Watada (1997) reported that acetaldehyde concentration was 1.2% of ethanol concentration in fresh-cut carrots under a 0.5% O_2

regime. When O_2 levels fall below the level at which respiration shifts from aerobic to anaerobic, high ethanol concentrations without acetaldehyde formation, or low ethanol and acetaldehyde concentrations, might not cause injury, depending on the species. Under 0.5% O_2 and 10% CO_2 at 5C, shredded carrots were acceptable at 17 µmol/g ethanol and 0.15 µmol/g acetaldehyde levels for three weeks (Kato-Noguchi *et al.* 1998). Carrot cells were reported to withstand a 40–80 µmol/g ethanol level if acetaldehyde was not formed (Perata and Alpi 1991). With fresh-cut sweet potatoes, the highest ethanol and acetaldehyde concentrations were 54 µmol/g and 850 nmol/g, respectively (Figs. 4 and 5). Because there was no obvious injury during 14 days at 8C, our results indicated that fresh-cut sweet potatoes could tolerate these levels.

Plant responses to very low O_2 and/or very high CO_2 concentrations include induction of fermentation pathways, accumulation of succinate and/or alanine, and a decrease in internal pH and ATP levels. One pathway of fermentative metabolism results in the accumulation of acetaldehyde and ethanol catalyzed by the enzymes PDC and ADH, respectively. The major function of fermentative metabolism is to utilize NADH and pyruvate when electron transport and oxidative phosphorylation are inhibited, so that glycolysis can continue. This will allow for the production of some ATP through substrate phosphorylation, which permits the plant tissues to temporarily survive (Kader 1995). Increased activities of PDC and ADH were observed when intact sweet potato (Chang *et al.* 1983; Kilili 1999), fresh-cut carrot (Kato-Noguchi and Watada 1997), pear (Ke *et al.* 1994) and avocado (Ke *et al.* 1995) were kept in low O_2 and/or high CO_2 concentrations. PDC activity was lower than ADH activity in fresh-cut sweet potatoes regardless of storage temperature and duration and film type (Table 2). These results are consistent with the results from intact sweet potato roots (Chang *et al.* 1983; Huang *et al.* 2002). By day 14, PDC activity increased sixfold depending on storage temperature and film bag type, while ADH increased only twofold. Similar results were reported from intact sweet potato roots (Huang *et al.* 2002) and beetroots (Zang and Greenway 1994) under low oxygen treatments. "Beauregard" sweet potatoes had 21- to 28-fold less PDC activity than ADH activity under 21% O_2, but a low O_2 atmosphere resulted in a greater increase in PDC activity (Huang *et al.* 2002). Low oxygen in the film bags was accompanied by an elevation of CO_2 because of anaerobic respiration of fresh-cut sweet potatoes. This coincided with the activation of PDC and ADH activity. Along with low O_2, high CO_2 levels contributed to fermentation. Lowering cytoplasmic pH had a strong affect on PDC activation (Chang *et al.* 1983; Ke *et al.* 1994). A decrease in pH slightly inhibited the high ADH activity (Ke *et al.* 1995). This may explain the lower increase in ADH activity of anaerobically respiring fresh-cut sweet potato tissues over time compared to PDC activity.

Storage at 8C resulted in a higher rate of O_2 depletion and CO_2 elevation, accompanied by higher rates of PDC and ADH activities, and acetaldehyde and ethanol production compared to 2C. Fresh-cut sweet potatoes store better at 2C than at 8C, which appeared to be an excessively high temperature. Chilling injury occurs when intact sweet potatoes are stored at temperatures less than 12C, depending on the length of exposure (Kays *et al.* 1992). Internal chilling injury symptoms, primarily darkening of the cambium and vascular bundles (Picha 1987), are often unnoticed until a return to higher temperatures. It is not surprising that 2C stored fresh-cut slices did not show any chilling injury symptoms after 14 days. Storage of chilling-sensitive fresh-cut produce at nonchilling temperatures would likely result in more deterioration from microbial and metabolic activity compared to chilling injury damage when the same produce is stored at low temperatures. Therefore, fresh-cut sweet potatoes should be held at a chilling temperature (i.e., 2C) for the relatively short time period required to market the product.

CONCLUSION

Between the two storage temperatures, 2C was superior for fresh-cut sweet potatoes. High-permeability PD941 film bags appeared to be a good candidate for MAP material because fresh-cut sweet potatoes in these film bags maintained aerobic respiration for 14 days at both 2 and 8C. Although ethanol was undetectable in the high-permeability film bags at day 14, increased PDC activity indicated anaerobic respiration had begun. This suggests a shelf life limit of 14 days at 8C in case of using high-permeability PD941 film bags. Medium-permeability film bags might be acceptable for packaging of fresh-cut sweet potatoes if they are kept at 2C, because the permeability characteristics allowed the slices to maintain aerobic respiration only at 2C. The possibility of exposure to elevated temperatures during handling and distribution should be taken into consideration in the selection of MAP for fresh-cut sweet potatoes. Medium-permeability PD961 film bags could be problematic for fresh-cut sweet potatoes at 8C because of anaerobic metabolism. However, anaerobic respiration, which occurred in the sweet potato slices inside the low- and medium-permeability film bags, did not result in deleterious external symptoms, although an off-odor was detected. Therefore, low-permeability film bags cannot be recommended as a packaging material for fresh-cut sweet potatoes.

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