Changes in carotenoid, physicochemical and sensory values of deep-fried carrot chips during storage

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Summary Deep-fried carrot chips were packaged in layered film (metallized polyester and linear low-density polyethylene) pouches under a partial vacuum of <1% O_2 concentration. Packages containing chips were stored in dark chambers at three conditions: 0–1 °C, 94–98% relative humidity (r.h.) (A); 22–23 °C, 31–45% r.h. (B); and 29–31 °C, 89–93% r.h. (C) for 0–5 months. Retention of α- and β-carotene content and vitamin A activity were >82% over 5 months for all conditions. Colour values (*L, a, b*) were unchanged over 5 months for A and B, but decreased gradually ($P < 0.05$) for C. No changes in moisture content, fat content, water activity, texture values and sensory values were observed over time for A and B, but changed ($P < 0.05$) for C. No sensory differences were observed by condition or time in colour. Carrot chips, packaged in partially vacuumed opaque pouches, can be stored for at least 5 months at 0–1 °C, 94–98% r.h. or 22–23 °C, 31–45% r.h.

Keywords Colour, shelf-life, storage conditions, texture, vitamin A activity, water.

Introduction

Carotenoids are the primary source of vitamin A for most people living in developing countries (Boileau *et al.*, 1999), where vitamin A deficiencies are still highly prevalent (Chakravarty, 2000). Carotenoids also are thought to have a variety of different actions that are related to the decreased risk of some degenerative diseases (Institute of Medicine, National Academy of Sciences, 2000).

Deep-fried carrot (*Daucus carota*) chips have high carotenoid concentrations, mainly in the forms of α-carotene, β-carotene and *cis*-9-β-carotene (Skrede *et al.*, 1997; Sulaeman *et al.*, 2001a), thus having high vitamin A potency. Deep-fried carrot chips may potentially be used in intervention programmes to combat vitamin A deficiency. As carotenoids are very susceptible to environmental conditions such as oxygen, light and heat (Ramakrishnan & Francis, 1979; Rodriguez-Amaya, 1993), proper packaging and storage is important to maximize the provitamin A benefits of carrot chips. Moreover, the fat content in this product may increase the carotenoid bioavailability (Jalal *et al.*, 1998), but may also reduce the shelf-life of this product because of lipid oxidation (Min & Schweizer, 1983).

Gee (1979) reported that β-carotene could be protected from light by opaque packaging material and protected from O_2 in vacuum, nitrogen or CO_2 atmospheres. Baloch *et al.* (1977) reported that increasing nitrogen levels in the atmosphere improved the β-carotene stability in model systems containing sulphite. Emenheiser *et al.* (1999) reported that β-carotene retention was enhanced incrementally as the apparent availability of O_2 was reduced. The purposes of this study were to evaluate the changes in carotenoid concentrations, physicochemical properties and sensory

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values of packaged deep-fried carrot chips during 0–5 months storage, and to estimate their shelf-lives under different storage conditions: 0–1 °C, 94–98% relative humidity (r.h.) (A); 22–23 °C, 31–45% r.h. (B); and 29–31 °C, 89–93% r.h. (C). These conditions were chosen to simulate the weather conditions in both developing and developed countries.

Materials and methods

Deep-fried carrot chip preparation and packaging

Deep-fried carrot chips were prepared according to the procedures of Sulaeman *et al.* (2001a,b) from fresh jumbo carrots (*D. carota* cv. Navajo; Grimmway Farms, Bakersfield, CA, USA), using partially hydrogenated soybean oil (PHSO, melting point 41.7 °C, 13.5% trans fatty acids; Bunge Food, Bradley, IL, USA) as frying oil. These carrot roots had been stored in the dark at 0–1 °C and 98% r.h. for about 8 months. Briefly, carrots were trimmed and cut into 55 mm lengths and mechanically peeled using a Hobart Peeler Machine (Hobart Manufacturing Co., Troy, OH, USA) at the lowest speed for 1 min (only to remove the outer layer of the carrots) and sliced into 1.5 mm thickness using a Dito Dean Slicer (Model TR-22; Dean Food Preparation, Los Angeles, CA, USA). The carrot slices were steam-blanched in a blancher (made and designed in our pilot plant) for 4 min, cooled under running tap water for 4 min, soaked in 0.2% sodium metabisulphite (w/v) solution for 15 min, drained and deep-fried (500 g drained carrot slices per batch) in PHSO using a Toastmaster Fryer (Model 1427; Elgin, IL, USA) at 165 °C for 5 min or until there were no visible bubbles because of residual water. The fried carrot chips were drained on paper towels, and shaken with 1.0% (w/w) salt.

The carrot chip products were then packaged (30 g per bag) in layered film (2.50 mil or 0.063 mm thick, metallized polyester and linear low-density polyethylene) pouches (16.5 cm × 20.3 cm o.d.; Kapak Co., Minneapolis, MN, USA) using a Multivac AG500/AG900 (Multivac Inc., Kansas City, MO, USA). The moisture and oxygen permeabilities of this pouch were 0.837 g m^{-2} 24 h^{-1} (at 37.8 °C, 100% r.h.) and 1.2 cm^3 m^{-2} 24 h^{-1} (at 22.8 °C, 0% r.h. and 100% O_2), respectively, according to the manufacturer. A partial vacuum was drawn on the pouches, and they were flushed with nitrogen gas until the O_2 concentration in the pouches was <1% (Emenheiser *et al.*, 1999). The packages were then stored in dark chambers at three storage conditions: 0–1 °C, 94–98% r.h. (A); 22–23 °C, 31–45% r.h. (B); and 29–31 °C, 89–93% r.h. (C) for 0–5 months. The chambers were equipped with temperature and humidity controllers and both were monitored twice daily, morning and afternoon. At the end of each monthly storage period, the pouches were removed from the chambers and stored at −50 °C until ready for carotenoid, physicochemical and sensory analyses. At this temperature, we assumed no chemical, physicochemical and sensory changes would happen (Lee, 1986). The carrot chips were removed from the freezer18 h prior to sensory and physicochemical analysis and the analyses were done at room temperature (Melton *et al.*, 1993).

HPLC analyses of carotenoids

Carotenoid analyses were performed using high-performance liquid chromatography as previously described (Sulaeman *et al.*, 2001a). The system consisted of the following Waters Associates, Inc. (Milford, MA, USA) equipment: a 600E solvent delivery system, a U6K injector, a 484 UV detector, and a 5200 printer-plotter. The carotenoids were separated by using a reversed-phase Microsorb-MV (5 μm 250 × 4.6 mm i.d.) C_{18} column (Rainin, Woburn, MA, USA), which was protected with a guard column of C_{18} material (30 mm length × 4.6 mm i.d.) packed with spheri-5-C_{18} (5 μm particle size). The methods used for extracting and measuring the carotenoids have been described previously (Sulaeman *et al.*, 2001a).

Vitamin A activity was calculated as retinol activity equivalents (RAE) using 12 μg per RAE for all-*trans* β-carotene and 24 μg per RAE for all-*trans* α-carotene (Institute of Medicine, National Academy of Sciences, 2001). The retention values (%) of carotenoids in the carrot chips, as affected by storage, were calculated by comparing the carotenoid contents at certain storage times with those at the 0 storage time as control.

Physicochemical analyses

Physicochemical parameters of the carrot chips including colour, texture, water activity, moisture and fat content were measured using instruments and methods as previously described (Sulaeman *et al.*, 2001a). Peroxide values were measured using the method of Asakawa & Matsushita (1980). Headspace O_2 and CO_2 concentrations of the pouches were measured using a Pac Check® 650 Dual Headspace Analyser (Mocon, Minneapolis, MN, USA).

Sensory analyses

Twelve trained panellists evaluated the sensory values of carrot chips using the modified method of Reilly & Man (1994). Prior to the testing, the panellists were trained (Carpenter *et al.*, 2000) to evaluate the attributes of the chips measured in this study. Several training sessions were included so that the panellists became proficient. The panellists were asked to score chips for colour, crispness, odour, sweetness, flavour and overall acceptability directly against the control (no storage) on a 1–7 scale, where 7 = equal or better than the control, 6 = slightly different from the control, 5 = more distinct difference but still acceptable, 4 = beginning to lose acceptability, 3 = more distinct loss of acceptability, 2 = very distinct loss of acceptability and 1 = unacceptable. The chips used as control had been placed into a freezer at −50 °C immediately following processing and packaging. In this evaluation, the control was assumed as representing the best and most acceptable for each parameter (score 7), based on our previous study in which this carrot chip product was judged as acceptable (Sulaeman *et al.*, 2001b). Carrot chips were removed from the freezer 18 h before testing (Melton *et al.*, 1993), and the chips were kept at room temperature when tested. Testing was conducted in individual booths equipped with white fluorescent lights.

Shelf-life determinations

Shelf-life determinations of the stored carrot chips were determined based on the degradation of total carotenes (Arya *et al.*, 1979) and the degree of loss of sensory attributes. It was assumed that each parameter followed first order kinetics (Haralampu & Karel, 1983), which is given by the following equation (Singh, 1994):

$$\ln \frac{Q}{Q_0} = -kt \tag{1}$$

where Q_0 is the initial value of the quality attribute, Q is the value of the quality attribute left at time t, and k is the rate constant. At the end of shelf-life, t_s, for a certain final level of quality attribute Q_e, the equation can be written as

$$\ln \frac{Q_e}{Q_0} = -kt_s \tag{2}$$

If we define shelf-life as the time required to elicit a 50% decrease in the quality attributes, $Q_e = 0.50Q_0$, then:

$$t_s = 0.693/k \tag{3}$$

Statistical analyses

Statistical analyses of data were performed using the General Linear Model (GLM) procedure in SAS version 6 (SAS Institute Inc., Cary, NC, USA) to determine the effects of storage conditions and storage times. Significant differences among means for the storage condition–storage time interaction were determined by the PDIFF option of GLM. A two-way analysis of variance (ANOVA) with treatments and judges as sources of variation was used on sensory data to determine differences among the treatments (Shamaila *et al.*, 1996). Correlations between observed parameters were also determined (Steel *et al.*, 1997). For all analyses, differences were considered significant at $P < 0.05$.

Results and discussion

Carotenoid content and vitamin A activity

Carotenes are very unstable compounds, being highly oxidizable, and their preservation in foods is necessary to ensure a stable amount of vitamin A during storage (Desobry *et al.*, 1998). Our results for packaged deep-fried carrot chips (Table 1) indicate that storage condition and storage time significantly affect ($P < 0.05$) α-carotene, β-carotene, *cis*-9-β-carotene, and total carotene, as well as vitamin A activity. Carotenoid contents of the

Table 1 Carotene concentration (μg per 100 g chips) and vitamin A activity (μg RAE per 100 g chips) of deep-fried carrot chips stored at different storage conditions and times

Storage condition*	Storage time (month)	α-Carotene	β-Carotene	*cis*-9-β-Carotene	Total carotenes†	Vitamin A activity‡
A	0	15 844^{a}	30 420^{a}	9624^{b}	55 887^{a}	3195^{a}
	1	15 200^{ab}	29 275^{bc}	9682^{b}	54 157^{bc}	3073^{bc}
	2	15 178^{ab}	28 743^{bcd}	9746^{b}	53 666^{bcd}	3028^{cd}
	3	14 894^{ab}	28 717^{bcd}	10 124^{a}	53 735^{bcd}	3014^{cd}
	4	14 877^{ab}	28 621^{bcd}	10 081^{a}	53 578^{bcd}	3005^{cd}
	5	14 723^{abc}	27 980^{d}	10 117^{a}	52 820^{cde}	2945^{d}
B	0	15 844^{a}	30 420^{a}	9624^{b}	55 887^{a}	3195^{a}
	1	15 625^{ab}	30 555^{a}	8393^{c}	54 573^{ab}	3198^{a}
	2	15 528^{ab}	30 867^{a}	7302^{d}	53 697^{bcd}	3220^{a}
	3	15 627^{ab}	30 627^{a}	6417^{e}	52 571^{cde}	3204^{a}
	4	15 636^{ab}	30 561^{a}	6026^{f}	52 223de	3199^{a}
	5	15 658^{ab}	30 844^{a}	5777^{f}	52 279de	3223^{a}
C	0	15 844^{a}	30 420^{a}	9624^{b}	55 887^{a}	3195^{a}
	1	15 214^{ab}	30 708^{a}	6008^{f}	51 592^{ef}	3193^{a}
	2	15 116^{ab}	30 390^{a}	4582^{g}	50 087^{f}	3163^{a}
	3	14 959^{ab}	30 309^{a}	3898^{h}	49 165^{f}	3149^{ab}
	4	14 558^{bc}	29 348^{b}	3634^{h}	47 539^{g}	3053^{c}
	5	13 745^{c}	28 511^{cd}	3821^{h}	46 077^{g}	2949^{d}
Significance		***P*-values**				
Storage condition (SC)		0.0075	0.0001	0.0001	0.0001	0.0001
Storage time (ST)		0.0337	0.0001	0.0001	0.0001	0.0001
Interaction (SC × ST)		0.5634	0.0009	0.0001	0.0002	0.0018

Values within a column with the same letters are not significantly different ($P \geq 0.05$).
*A = 0–1 °C, 94–98% r.h.; B = 22–23 °C, 31–45% r.h.; C = 29–31 °C, 89–93% r.h.
†Total carotenes = α-carotene + β-carotene + *cis*-9-β-carotene.
‡μg retinol activity equivalent (RAE) = (μg α-carotene/24) + (μg β-carotene/12).

carrot chips, especially those stored at condition C, were significantly decreased during 5 months storage. Nevertheless, the changes in concentrations of α-carotene, β-carotene, total carotenes and vitamin A activity were minimal (Table 1). The retention of β-carotene was >90%; α-carotene, >87%; total carotenes, >82%; and vitamin A activity, >92%, over 5 months for all the conditions.

The high retention of carotenoids in the current study may be attributed to beneficial factors in the carrot chip processing (Sulaeman *et al.*, 2001b). Blanching of carrot slices provided positive effects on the preservation of carotenoids because of the inactivation of peroxidase and lipoxygenase, which catalyse the destruction of carotenoids and lipids during storage (Rodriguez-Amaya, 1993). Baloch *et al.* (1987) found that sulphiting had a marked effect on the stability of carotenoids in both unblanched and blanched carrots during dehydration and storage at 37 °C.

The packaging and storage systems applied in the present study probably contributed to the high retention of carotenoids in the carrot chips. As mentioned earlier, the deep-fried carrot chips were packaged in pouches that have very low moisture and oxygen permeability. In addition, a partial vacuum was drawn on the pouches, and they were flushed with nitrogen until the O_2 concentration in the pouch headspace was <1%. The pouches were then stored in the dark. Gee (1979) found that dried carrots packaged in foil–polyester–polyolefin ink laminated pouches and flushed with nitrogen lost only 8% β-carotene after 5 months storage. The findings indicated that the packaging system and the dark storage applied in the present study protected the carotenoid content of the carrot chips.

Carotenoid *cis*-isomers may play a role in radical chain-reaction termination (Boileau *et al.*, 1999). *cis*-9-β -carotene has been shown *in vivo* and *in vitro* to be a better free radical scavenger than

the all-*trans* form (Levin *et al.*, 1997). The current data indicated that *cis*-9-β-carotene was significantly increased in condition A, indicating the high degradation of *trans* β-carotene, but significantly decreased in B and C storage conditions. As in B and C conditions the temperatures were higher and the r.h. lower than A, the degradation of *cis*-9-β-carotene perhaps took place first, before the *trans*-isomer, and this protected the other carotenes.

More α-carotene, β-carotene and vitamin A activity were retained under storage condition B than A and C. It was expected that in C the destruction of carotenoids would be higher than in B as the storage temperature was increased (Rodriguez-Amaya, 1993; Wagner & Warthesen, 1995). However, we expected the destruction in A to be lower than B as A had a lower temperature. The high r.h. in A perhaps promoted lipid hydrolysis, which then induced the oxidation of carotenoids. Negi & Roy (2000) found that dehydrated carrots packed in double layers of high-density polyethylene film and stored at 7.5–8.5 °C and 70–75% r.h. retained higher β-carotene content after 3 and 9 months storage, but at the end of 6 months of storage, the β-carotene content was similar to samples stored at higher ambient temperatures (15.0–37.5 °C, 40–85% r.h.).

Colour

The orange colour of carrot chips was described by the lightness (L), redness (a), yellowness (b) and hue angle (Hue °) parameters. The L, a and b values of stored carrot chips were statistically unchanged over 5 months for conditions A and B, but decreased gradually for C, whereas the Hue° values were unchanged for all storage conditions (Table 2). This implies that only the intensity of the colour (a, b), and not the relation between red and yellow, is changed during storage. There were positive correlations between the decreased redness value and the decreased concentrations of α-carotene ($r = 0.65$, $P < 0.05$), β-carotene ($r = 0.34$, $P < 0.05$), *cis*-9-β-carotene ($r = 0.49$,

Table 2 Colour values (Hunter L, a, b and Hue °) of deep-fried carrot chips stored at different storage conditions and times

Storage condition*	Storage time (months)	*L*	*a*	*b*	Hue°
A	0	39.65^{a}	22.77^{abc}	19.90^{a}	41.16^{ab}
	1	39.51^{ab}	22.51^{abc}	19.31^{ab}	41.13^{ab}
	2	39.23^{abc}	22.74^{abc}	19.35^{ab}	40.40^{abcde}
	3	39.46^{ab}	22.47^{abc}	19.63^{ab}	41.14^{ab}
	4	39.00^{abc}	22.17^{bcd}	19.42^{ab}	41.22^{a}
	5	39.18^{abc}	23.01^{ab}	19.55^{ab}	40.36^{bcde}
B	0	39.65^{a}	22.77^{abc}	19.90^{a}	41.16^{ab}
	1	39.01^{abc}	22.70^{abc}	19.57^{ab}	40.77^{abc}
	2	39.00^{abc}	22.42^{abc}	19.28^{ab}	40.70^{abcd}
	3	39.04^{abc}	22.30^{abcd}	19.17^{ab}	40.61^{abcd}
	4	38.40^{cd}	22.83^{abc}	19.22^{ab}	39.97^{cdef}
	5	39.13^{abc}	23.30^{a}	19.48^{ab}	39.88^{defg}
C	0	39.65^{a}	22.77^{abc}	19.90^{a}	41.16^{ab}
	1	38.53^{bcd}	22.72^{abc}	18.88^{bc}	39.74^{efgh}
	2	37.76^{dc}	22.59^{ebc}	18.30^{cd}	39.01^{h}
	3	37.29^{ef}	21.84^{cd}	17.97^{de}	39.44^{fgh}
	4	36.57^{f}	21.34^{d}	17.34^{ef}	39.10^{gh}
	5	35.15^{g}	19.76^{e}	16.84^{f}	40.48^{abcd}
Significance		***P*-values**			
Storage condition (SC)		0.0001	0.0005	0.0001	0.0001
Storage time (ST)		0.0001	0.0661	0.0001	0.0009
Interaction (SC × ST)		0.0006	0.0010	0.0024	0.0042

Values within a column with the same letters are not significantly different ($P \geqslant 0.05$).
*A = 0–1 °C, 94–98% r.h.; B = 22–23 °C, 31–45% r.h.; C = 29–31 °C, 89–93% r.h.

$P < 0.05$), total carotenes ($r = 0.70$, $P < 0.05$) and vitamin A activity ($r = 0.45$, $P < 0.05$) in the current study. The decreased colour values in C seemed to be reflecting the degradation in carotenoid content of the carrot chips. As the carotenoid content in the chips decreased, the colour values, mainly the redness (a) and yellowness (b), also decreased. Wagner & Warthesen (1995) reported that the yellow and red colour reflected the carotenoid content of carrot slices. Lin *et al.* (1998) found that a decrease in redness values in air-dried and vacuum microwave-dried carrot slices compared to freeze-dried slices correlated with the loss of α- and β-carotenes. As in our previous study (Sulaeman *et al.*, 2001a), the Hue° values did not reflect the decrease of carotenoid content in the carrot chips during storage.

Increasing the storage temperature increased the colour degradation, perhaps because of the increased carotenoid oxidation. Wagner & Warthesen (1995) reported that an increase in storage temperature led to an increase in the rate constant (k) for both α- and β-carotene degradation in all hydrolysed starch-encapsulated carrot products. Lee *et al.* (1992) also found that colour deterioration increased with the storage temperature in ground red peppers at temperatures varying from 5 to 40 °C.

Headspace gas and peroxide values

No significant changes in the headspace O_2 content were observed during storage (Table 3). There were significant changes in headspace CO_2; however, the magnitude of the changes was relatively low (Table 3). These facts indicated that no major chemical changes related to O_2 or CO_2 occurred in the packaged carrot chips. This also indicated that the packaging materials used in the current experiment were able to maintain the headspace O_2 at $<1\%$. Goldman *et al.* (1983) found the presence of O_2 in the headspace to be a crucial

Table 3 Moisture content, water activity, fat content, peroxide value, headspace O_2 and headspace CO_2 of deep-fried carrot chips stored at different storage conditions and times

Storage condition*	Storage time (months)	Headspace O_2 (%)	Headspace CO_2 (%)	Peroxide value (meq g^{-1})	Moisture content (% w/w)	Water activity	Fat content (% w/w)
A	0	0.467^{a}	0.41^{ef}	1.158^{defg}	3.30^{fg}	0.44^{de}	57.25^{b}
	1	0.715^{a}	0.50^{d}	1.256^{abcde}	3.23^{fgh}	0.41^{e}	57.71^{ab}
	2	0.400^{a}	0.46^{e}	1.293^{abcd}	3.28^{fg}	0.43^{cde}	57.34^{b}
	3	0.709^{a}	0.54^{d}	1.305^{abcd}	3.28^{fg}	0.43^{de}	57.50^{ab}
	4	0.721^{a}	0.56^{d}	1.457^{abc}	3.24^{fgh}	0.41^{e}	58.53^{a}
	5	0.637^{a}	0.48^{e}	1.516^{a}	3.31^{f}	0.41^{e}	57.25^{b}
B	0	0.467^{a}	0.41^{f}	1.158^{defg}	3.30^{fg}	0.44^{cde}	57.25^{b}
	1	0.669^{a}	0.58^{d}	1.012^{efg}	3.14^{ghij}	0.42^{e}	57.69^{ab}
	2	0.560^{a}	0.56^{d}	0.975^{fg}	3.06^{ij}	0.42^{e}	57.23^{b}
	3	0.497^{a}	0.56^{d}	0.915^{g}	3.11^{hij}	0.42^{e}	57.17^{b}
	4	0.434^{a}	0.58^{d}	1.002^{efg}	2.98^{j}	0.42^{e}	57.29^{b}
	5	0.560^{a}	0.50^{d}	0.970^{fg}	3.16^{fghi}	0.43^{e}	57.48^{ab}
C	0	0.467^{a}	0.41^{ef}	1.158^{defg}	3.30^{fg}	0.44^{cde}	57.25^{b}
	1	0.589^{a}	0.76^{c}	1.244^{bcdef}	4.22^{e}	0.46^{cd}	57.43^{b}
	2	0.899^{a}	0.76^{c}	1.163^{defg}	4.61^{d}	0.47^{c}	56.84^{bc}
	3	0.397^{a}	0.92^{b}	1.142^{defg}	5.10^{c}	0.51^{b}	56.01^{cd}
	4	0.287^{a}	1.02^{b}	1.203^{cdef}	5.44^{b}	0.53^{b}	55.90^{cd}
	5	0.663^{a}	1.30^{a}	1.478^{ab}	5.67^{a}	0.58^{a}	55.74^{d}
Significance		***P*-values**					
Storage condition (SC)		0.0809	0.0001	0.0001	0.0001	0.0001	0.0001
Storage time (ST)		0.7448	0.0001	0.1327	0.0001	0.0036	0.1324
Interaction (SC × ST)		0.6460	0.0001	0.2151	0.0001	0.0001	0.0540

Values within a column with the same letters are not significantly different ($P \geq 0.05$).
*A = 0–1 °C, 94–98% r.h.; B = 22–23 °C, 31–45% r.h.; C = 29–31 °C, 89–93% r.h.

factor in β-carotene degradation. Even low concentration (1–2%) led to significant losses of pigments. The shelf-life, defined by degradation time at 50% retention of β-carotene, was 37, 25, 10, 7 and 5 days at 1, 2, 10, 15 and 20.9% oxygen, respectively. When O_2 was excluded from the headspace, β-carotene deterioration was only 12% after 60 days of storage.

Peroxides are primary intermediates of lipid autoxidation (King *et al.*, 1993; Nawar, 1998). Factors influencing lipid oxidation include free fatty acids, O_2 concentration, temperature and water content. The availability of O_2 clearly plays a critical role in determining competitive oxidative pathways. Rates of reaction increase with increased temperature (Nawar, 1998). The peroxide values (meq kg^{-1}) of stored carrot chips in the current study were 1.16 initially, and after 5 months were 1.52 for A and 1.48 for C, but were unchanged for B (Table 3). Min & Schweizer (1983) reported a negative correlation between peroxide values and headspace O_2 content of stored potato chips. Peroxide values increased as the O_2 content in the headspace decreased, which suggested that peroxides were formed by the reaction of O_2 and potato chips. In the current study, where the headspace O_2 was little changed, no such relationships were found. The very low O_2 concentration in the headspace presumably prevented lipid oxidation in the packaged carrot chips. In addition, the carotenoids contained in the carrot chips as well as the antioxidants contained in the frying oil may also prevent lipid oxidation. Carotenoids have been shown to be an excellent antioxidant in singlet O_2 oxidation (King *et al.*, 1993).

Moisture content, water activity and fat content

The initial moisture content (% w/w) and water activity (a_w) of stored carrot chips were 3.30 and 0.44, respectively (Table 3). This lower moisture content and water activity may help the carrot chips maintain carotenoid content during storage. Arya *et al.* (1979) reported that carotenoids are relatively more stable in the range of 0.32–0.57a_w, the maximum stability being near 0.43a_w. Below and above this level the rates of carotenoid destruction were observed to increase significantly. After 5 months of storage in the present study, no significant changes in moisture content and water activity were observed for A and B, but both were significantly increased for C (Table 3). The high temperature and high r.h. in C may have caused migration of water into the pouch, increasing the moisture content and water activity of the carrot chips. The fact that the water permeability of this pouch was quite high made this migration possible during 5 months storage.

The moisture content of carrot chips after storage was inversely correlated ($P < 0.05$) with α-carotene($r = -0.59$), *cis*-9-β-carotene($r = -0.75$) and total carotene ($r = -0.86$) content. Increased moisture content during storage decreased the carotenoid content of the chips, probably because of less concentration or accelerated degradation. As the colour was influenced by the carotenoid content, the increased moisture content and water activity also significantly decreased the colour values (L, a, b and Hue °) of the stored carrot chips. The moisture content and water activity inversely correlated ($P < 0.05$) with the L ($r = -0.91$ and $r = -0.92$, respectively), a ($r = -0.68$ and $r = -0.77$, respectively), b ($r = -0.94$ and $r = -0.91$, respectively) and Hue° ($r = -0.63$ and -0.50, respectively) values.

The initial mean fat concentration of stored carrot chips was 57.3% (w/w) and remained unchanged over time for A and B, but significantly decreased for C after 2 months (Table 3). This may be related to the increased moisture content of the chips stored in C that changed the proportion of fat in the chips (Table 3).

Texture values

The textural values, as measured by fracturability, peak force or maximum force (F) and work (W) from deformation curves required to break the chips on a TAXT2 Texture Analyser (Texture Technologies Corp., Scarsdale, NY, USA), may reflect the crispness of the chips (Sulaeman *et al.*, 2001b). A crisp food should be firm and snap easily when deformed, emitting a crunching sound (Moreira *et al.*, 1995). No differences were observed over time in crispness values (force and work) for conditions A and B, but the F and W values for condition C immediately increased significantly, indicating that the chips became less crispy (Table 4). Katz & Labuza (1981) reported

Table 4 Texture values of deep-fried carrot chips stored at different storage conditions and times

Storage condition*	Storage time (months)	F_{max} (g)	W (g mm)
A	0	502.55^{c}	370.30^{c}
	1	553.60^{bc}	330.65^{c}
	2	560.70^{bc}	400.95^{c}
	3	572.50^{bc}	448.35^{c}
	4	575.85^{bc}	414.45^{c}
	5	549.90^{bc}	447.95^{c}
B	0	502.55^{c}	370.30^{c}
	1	506.20^{c}	346.00^{c}
	2	517.05^{bc}	400.95^{c}
	3	499.30^{c}	448.35^{c}
	4	505.50^{c}	414.45^{c}
	5	549.90^{bc}	447.95^{c}
C	0	502.55^{c}	370.30^{c}
	1	597.00^{b}	624.05^{b}
	2	685.85^{a}	776.90^{a}
Significance		***P*-values**	
Storage condition (SC)		0.0019	0.0001
Storage time (ST)		0.0563	0.0026
Interaction (SC × ST)		0.2252	0.0062

Values within a column with the same letters are not significantly different ($P \geq 0.05$).
*A = 0–1 °C, 94–98% r.h.; B = 22–23 °C, 31–45% r.h.; C = 29–31 °C, 89–93% r.h.

that the peak force (F), work (W) or cohesiveness were indicators of crispness for puffed corn curls. In the current study, the increased F and W values were significantly correlated with the increased moisture content ($r_F = 0.85$; $r_W = 0.93$) and water activity ($r_F = 0.51$; $r_W = 0.73$).

Sensory values

The sensory quality of a packaged food is the result of complex interactions between the food, the packaging and the environment (Stöllman *et al.*, 1994). Trained panellists indicated that there were no changes over time in crispness, odour, sweetness, flavour and overall acceptability in conditions A and B, but significant changes in these variables were noted over time for C (Table 5). No differences were observed by condition or time in colour (Table 5). At 5 months of storage, chips stored in conditions A and B were still acceptable for all sensory attributes. However, C chips became less acceptable after 2 months of storage especially for crispness, sweetness, flavour and overall acceptability.

Significant negative correlations were observed between the crispness score from sensory evaluation and maximum force ($r = -0.94$) and work ($r = -0.93$) values from texture analyses. This is in agreement with the findings of Seymour & Hamann (1988) that the maximum force and work necessary to break the food correlated inversely with crispness and crunchiness for low-moisture foods. Park *et al.* (1996) reported that storage temperature and time had negative effects on the crispness of potato chips. Crispness decreased sharply as storage temperature and time increased. In the current study, similar effects were observed in carrot chips stored at 29–31 °C and 89–93% r.h. (C).

Fried-food flavour intensity was the best indicator of overall flavour quality in fresh potato chips (Warner *et al.*, 1997). This seemed also to be true for carrot chips in the current study. For the three storage conditions, significant positive correlations were observed between overall acceptability and the scores for crispness ($r = 0.98$), odour ($r = 0.94$), sweetness ($r = 0.98$) and flavour ($r = 0.99$), which meant that chips that were more acceptable in crispness, odour, sweetness and flavour also had higher overall acceptability. However, the acceptability of colour did not reflect the overall acceptability of the carrot chips. As shown in Table 5, until 5 months of storage, the colour acceptability for C was still high, but the overall acceptability was very low.

Estimated shelf-life of deep-fried carrot chips

The shelf-life of a packaged product will depend upon a series of variables associated with the product's composition and processing, its packaging material and storage conditions (Hernandez & Giacin, 1998). The package is a functional barrier, regulating the transfer of gases, vapours, water vapour and other low-molecular-weight compounds, as well as the transfer of heat and penetration of electromagnetic radiation of varying wavelengths. As the pouches were stored in the dark, any effects of light on the packaging material were not tested in the present study.

Table 5 Sensory values* of deep-fried carrot chips stored at different conditions and times

Storage condition†	Storage time (months)	Colour	Crispness	Odour	Sweetness	Flavour	Overall acceptability
A	0	7.00^{a}	7.00^{a}	7.00^{a}	7.00^{a}	7.00^{a}	7.00^{a}
	1	6.75^{a}	6.38^{abc}	6.75^{ab}	6.06^{b}	6.00^{bc}	6.00^{b}
	2	6.63^{a}	6.25^{bc}	6.69^{abc}	6.06^{b}	6.19^{b}	6.00^{b}
	3	6.75^{a}	6.25^{bc}	6.19^{bcd}	5.31^{cd}	5.25^{cd}	5.56^{b}
	4	6.88^{a}	6.00^{c}	6.69^{abc}	6.06^{b}	5.94^{bcd}	5.94^{b}
	5	6.75^{a}	6.25^{bc}	6.63^{abc}	5.69^{bc}	5.63^{bcd}	5.88^{b}
B	0	7.00^{a}	7.00^{a}	7.00^{a}	7.00^{a}	7.00^{a}	7.00^{a}
	1	6.81^{a}	6.38^{abc}	6.44^{abcd}	6.06^{b}	5.94^{bcd}	6.19^{b}
	2	6.75^{a}	6.50^{abc}	6.50^{abcd}	5.75^{bc}	5.69^{bc}	5.56^{b}
	3	6.88^{a}	6.63^{abc}	6.44^{abcd}	6.00^{bc}	5.75^{bcd}	5.75^{b}
	4	6.56^{a}	6.69^{ab}	6.19^{bcd}	5.81^{bc}	6.06^{b}	5.94^{b}
	5	6.75^{a}	6.38^{abc}	6.13^{cde}	6.13^{b}	6.13^{b}	6.06^{b}
C	0	7.00^{a}	7.00^{a}	7.00^{ab}	7.00^{a}	7.00^{a}	7.00^{a}
	1	6.81^{a}	5.19^{d}	5.94^{de}	5.69^{bc}	5.19^{d}	4.81^{c}
	2	6.94^{a}	3.75^{e}	5.94^{de}	4.63^{d}	4.38^{e}	3.69^{d}
	3	6.56^{a}	2.44^{f}	5.31^{f}	3.63^{e}	3.13^{f}	2.81^{e}
	4	6.81^{a}	2.25^{fg}	4.25^{g}	3.19^{ef}	2.75^{fg}	2.44^{e}
	5	6.63^{a}	1.75^{g}	4.25^{g}	2.63^{f}	2.31^{g}	2.19^{e}
Significance		***P*-values**					
Storage condition (SC)		1.0000	0.0001	0.0001	0.0001	0.0001	0.0001
Storage time (ST)		0.0994	0.0001	0.0001	0.0001	0.0001	0.0001
Interaction (SC × ST)		0.5136	0.0001	0.0001	0.0001	0.0001	0.0001

Values within a column with the same letters are not significantly different ($P \geq 0.05$).
*7 = equal or better than the control, 6 = slightly different from the control, 5 = more distinct difference but still acceptable, 4 = beginning to lose acceptability, 3 = more distinct loss of acceptability, 2 = very distinct loss of acceptability and 1 = unacceptable.
†A = 0–1 °C, 94–98% r.h.; B = 22–23 °C, 31–45% r.h.; C = 29–31 °C, 89–93% r.h.

Degradation of carotenoids has been reported to play an important role in determining the overall storage-life of dehydrated carrots (Arya *et al.*, 1979). Reportedly, off-flavours became noticeable when about 20–45% of total carotenoids had been destroyed (Arya *et al.*, 1979). Figure 1 shows that the degradation of total carotenes in stored carrot chips follows a first order reaction. Increasing storage temperature significantly increased ($P < 0.05$) the rate constant (k) of the reaction. The rate constants (k) for A, B and C were 0.0089, 0.0140 and 0.0360 month^{-1}, respectively. From these k values, the estimated shelf-lives of carrot chips, defined by degradation time at 50% retention of total carotenes, for A, B and C storage conditions were 52.5, 44.4 and 17.3 months, respectively, from eqn 3. However, if we consider the acceptability of the stored carrot chips (Reilly & Man, 1994), the shelf-life, defined by degradation time

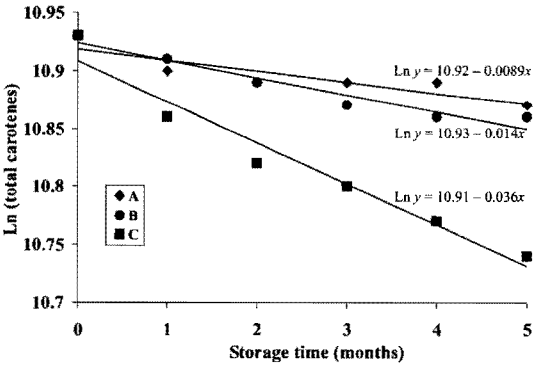

Figure 1 Apparent first order degradation of total carotene of deep-fried carrot chips at different storage conditions: ◆ A = 0–1 °C, 94–98% r.h.; ● B = 22–23 °C, 31–45% r.h.; ■ C = 29–31 °C, 89–93% r.h. Each point is the mean of duplicate samples.

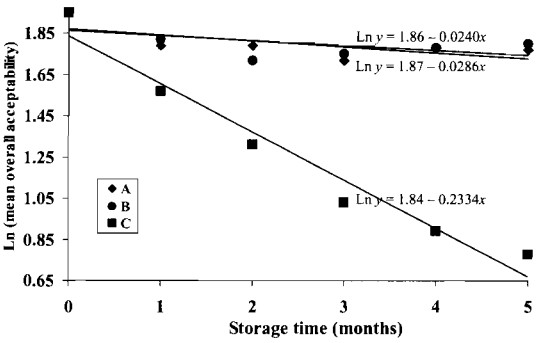

Figure 2 Apparent first order loss of overall sensory acceptability of deep-fried carrot chips stored at different storage conditions: ◆ A = 0–1 °C, 94–98% r.h.; ● B = 22–23 °C, 31–45% r.h.; ■ C = 29–31 °C, 89–93% r.h. Each point is the mean scores from 12 panellists.

at 50% loss of overall acceptability, for A, B and C were 15.8, 16.8 and 2.7 months, respectively (Fig. 2). As the sensory qualities were more likely to determine whether a product will be acceptable than nutritive values, shelf-life should be based on the loss of sensory acceptability. These findings indicate that for extended shelf-life, deep-fried carrot chips should be stored refrigerated or at ambient temperature with low humidity.

Conclusions

Deep-fried carrot chips, packaged in opaque pouches under partial vacuum, can be stored for at least 5 months at 0–1 °C, 94–98% r.h. or 22–23 °C, 31–45% r.h., with only small losses of carotenoid, physicochemical and sensory properties. The degradation of carotenoids and acceptability during storage followed first order kinetics. Storing at higher temperature and relative humidity reduced the shelf-life. To maximize provitamin A activity, the deep-fried carrot chips should be packaged properly and stored at temperatures and relative humidities that optimize retention of provitamin A carotenoids as well as the sensory qualities. The optimal long-term storage condition for the carrot chips was, therefore, 22–23 °C and 31–45% r.h.

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References

Arya, S.S., Natesan, V., Parihar, D.B. & Vijayaraghavan P.K. (1979). Stability of carotenoids in dehydrated carrots. *Journal of Food Technology*, **14**, 579–586.

Asakawa, T. & Matsushita, S. (1980). A colorimetric micro-determination of peroxide values utilizing aluminium as the catalyst. *Lipids*, **15**, 965–967.

Baloch, A.K., Buckle, K.A. & Edwards, R.A. (1977). Stability of β-carotene in model systems containing sulphite. *Journal of Food Technology*, **12**, 309–316.

Baloch, A.K., Buckle, K.A. & Edwards, R.A. (1987). Effect of sulphur dioxide and blanching on stability of carotenoids of dehydrated carrot. *Journal of the Science of Food and Agriculture*, **40**, 179–187.

Boileau, T.W.M., Moore, A.C. & Erdman, J.W. Jr. (1999). Carotenoids and vitamin A. In: *Antioxidant Status, Diet, Nutrition, and Health* (edited by A.M. Papas). Pp. 133–158. Boca Raton, FL: CRC Press.

Carpenter, R.P., Lyon, D.H. & Hasdell, T.A. (2000). *Guidelines for Sensory Analysis in Food Product Development and Quality Control*. Pp. 71–91. Gaithersburg, MD: Aspen Publishers, Inc.

Chakravarty, I. (2000). Food-based strategies to control vitamin A deficiency. *Food and Nutrition Bulletin*, **21**, 135–143.

Desobry, S.A., Netto, F.M. & Labuza, T.P. (1998). Preservation of beta-carotene from carrots. *Critical Reviews in Food Science and Nutrition*, **38**, 381–396.

Emenheiser, C., Watkins, R.H., Simunovic, N. *et al.* (1999). Packaging preservation of β-carotene in sweet potato flakes using flexible film and an oxygen absorber. *Journal of Food Quality*, **22**, 63–73.

Gee, M. (1979). Stability of ascorbic acid, thiamin and β-carotene in some low temperature dried vegetables. *Lebensmittel Wissenschaft-Technolologie*, **12**, 147–149.

Goldman, M., Horev, B. & Saguy, I. (1983). Decolorization of β-carotene in model systems simulating dehydrated foods, mechanism and kinetic principles. *Journal of Food Science*, **48**, 751–754.

Haralampu, S.G. & Karel, M. (1983). Kinetic models for moisture dependence of ascorbic acid and β-carotene degradation in dehydrated sweet potato. *Journal of Food Science*, **48**, 1872–1873.

Hernandez, R.J. & Giacin, J.R. (1998). Factors affecting permeation, sorption, and migration processes in package-product systems. In: *Food Storage Stability* (edited by I.A. Taub & R.P. Singh). Pp. 269–330. Boca Raton, FL: CRC Press.

Institute of Medicine, National Academy of Sciences (2000). *Dietary Reference Intakes for Vitamin C, Vitamin E, Selenium, and Carotenoids*. Pp. 325–382. Washington, DC: National Academy Press.

Institute of Medicine, National Academy of Sciences (2001). *Dietary Reference Intakes for Vitamin A, Vitamin K, Arsenic, Boron, Chromium, Copper, Iodine, Iron, Manganese, Molybdenum, Nickel, Silicon, Vanadium, and Zinc*. Pp. 82–161. Washington, DC: National Academy Press.

Jalal, F., Nesheim, M.C., Agus, Z., Sanjur, D. & Habicht, J.P. (1998). Serum retinol concentrations in children are

affected by food sources of β-carotene, fat intake, and antihelmintic drug treatment. *American Journal of Clinical Nutrition*, **68**, 623–629.

Katz, E.E. & Labuza, T.P. (1981). Effect of water activity on the sensory crispness and mechanical deformation of snack food products. *Journal of Food Science*, **46**, 403–409.

King, D.L., Hahm, T.S. & Min, D.B. (1993). Chemistry of antioxidant in relation to shelf life of foods. In: *Shelf Life Studies of Foods and Beverages* (edited by G. Charalambous). Pp. 629–705. New York: Elsevier Science.

Lee, C.Y. (1986). Changes in carotenoid content of carrots during growth and post-harvest storage. *Food Chemistry*, **20**, 285–293.

Lee, D.S., Chung, S.K. & Yam, K.L. (1992). Carotenoid loss in dried red pepper products. *International Journal of Food Science and Technology*, **27**, 179–185.

Levin, G., Yeshurun, M. & Mokady, S. (1997). In vivo antiperoxidative effect of 9-*cis*-β-carotene compared with that of the all-*trans* isomer. *Nutrition and Cancer*, **27**, 293–297.

Lin, T.M., Durance, T.D. & Scaman, C.H. (1998). Characterization of vacuum microwave, air and freeze dried carrot slices. *Food Research International*, **31**, 111–117.

Melton, S.L., Trigiano, M.K., Penfield, M.P. & Yang, R. (1993). Potato chips fried in canola and/or cottonseed oil maintain high quality. *Journal of Food Science*, **58**, 1079–1083.

Min, D.B. & Schweizer, D.Q. (1983). Lipid oxidation in potato chips. *Journal of American Oil and Chemical Society*, **60**, 1662–1665.

Moreira, R.G., Palau, J.E. & Sun, X. (1995). Deep-fat frying of tortilla chips: an engineering approach. *Food Technology*, **49**, 146–150.

Nawar, W.W. (1998). Biochemical processes: lipid instability. In: *Food Storage Stability* (edited by I.A. Taub & R.P. Singh). Pp. 89–104. Boca Raton, FL: CRC Press.

Negi, P.S. & Roy, S.K. (2000). Effect of low-cost storage and packaging on quality and nutritive value of fresh and dehydrated carrots. *Journal of the Science of Food and Agriculture*, **80**, 2169–2175.

Park, J.W., Testin, R.F., Vergano, P.J., Park, H.J. & Weller, C.L. (1996). Application of laminated edible films to potato chips packaging. *Journal of Food Science*, **61**, 766–768, 777.

Ramakrishnan, T.V. & Francis, F.J. (1979). Stability of carotenoids in model aqueous systems. *Journal of Food Quality*, **2**, 177–189.

Reilly, A. & Man, C.M.D. (1994). Potato crisps and savoury snacks. In: *Shelf Life Evaluation of Foods* (edited by C.M.D. Man & A.A. Jones). Pp. 202–215. New York: Blackie Academic & Professional.

Rodriguez-Amaya, D.B. (1993). Stability of carotenoids during the storage of foods. In: *Shelf Life Studies of Foods and Beverages* (edited by G. Charalambous). Pp. 591–628. New York: Elsevier Science.

Seymour, S.K. & Hamann, D.D. (1988). Crispness and crunchiness of selected low moisture foods. *Journal of Texture Studies*, **19**, 79–95.

Shamaila, M., Durance, T. & Girard, B. (1996). Water blanching effects on headspace volatiles and sensory attributes of carrots. *Journal of Food Science*, **61**, 1191–1195.

Singh, R.P. (1994). Scientific principles of shelf life evaluation. In: *Shelf Life Evaluation of Foods* (edited by C.M.D. Man & A.A. Jones). Pp. 3–25. New York: Blackie Academic & Professional.

Skrede, G., Nilson, A., Baardseth, P., Rosenfeld, H.J., Enersen, G. & Slinde, E. (1997). Evaluation of carrot varieties for production of deep fried carrot chips: III. Carotenoids. *Food Research International*, **30**, 73–81.

Steel, R.G.D., Torrie, J.H. & Dickey, D.A. (1997). *Principles and Procedures of Statistics: a Biometrical Approach*. Pp. 253–351. New York: McGraw-Hill.

Stöllman, U., Johansson, F. & Leufven, A. (1994). Packaging and food quality. In: *Shelf Life Evaluation of Foods* (edited by C.M.D. Man and A.A. Jones). Pp. 52–71. New York: Blackie Academic & Professional.

Sulaeman, A., Keeler, L., Giraud, D.W., Taylor, S.L., Wehling, R.L. & Driskell, J.A. (2001a). Carotenoid content and physicochemical and sensory characteristics of carrot chips deep-fried in different oils at several temperatures. *Journal of Food Science*, **9**, 1257–1264.

Sulaeman, A., Keeler, L., Taylor, S.L., Giraud, D.W. & Driskell, J.A. (2001b). Carotenoid content, physicochemical, and sensory quality of deep-fried carrot chips as affected by dehydration/rehydration, antioxidant, and fermentation. *Journal of Agricultural and Food Chemistry*, **49**, 3253–3261.

Wagner, L.A. & Warthesen, J.J. (1995). Stability of spray-dried encapsulated carrot carotenes. *Journal of Food Science*, **60**, 1048–1053.

Warner, K., Orr, P. & Glynn, M. (1997). Effect of fatty acid composition of oils on flavour and stability of fried foods. *Journal of American Oil and Chemical Society*, **74**, 347–356.