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Color, vitamin C, β-carotene and sensory quality retention in microwave-assisted thermally sterilized sweet potato puree: Effects of polymeric package gas barrier during storage

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ABSTRACT

In this study, we investigated the effects of package barrier properties on shelf-life of vitamin C-fortified sweet potato puree (SPP) processed with microwave-assisted thermal sterilization (MATS). Results show a change in SPP color during both processing and storage. The vitamin C in SPP decreased from 201.7 ± 4.7 to 185.8 ± 15.6 mg/100g during MATS and further decreased to as low as 13.6 ± 4.1 and 10.0 ± 0.3 mg/100g the end of 9 or 18 month, depending on the oxygen barrier and temperature. The total β-carotene content after processing and storage was slightly higher than before processing. Pouches with oxygen transmission rates (OTRs) of less than 0.3 cc/m^2·day showed higher retention of color, vitamin C, and predicted shelf life than other pouches. However, this did not affect the consumer acceptance. Most panelists considered MATS processed SPP as a desirable baby food throughout the 18 months. Efforts are still needed to stabilize vitamin C content for over 3 years for military and NASA missions.

1. Introduction

Although fresh vegetables are rich in nutrients, they are perishable and have a short shelf life (Rickman, Barrett, & Bruhn, 2007). Thermal processes can ensure the safety of foods and greatly extend their shelf life. However, studies show that nearly all important vitamins in vegetables decrease during thermal processing (Chen, Peng, & Chen, 1995; Howard, Wong, Perry, & Klein, 1999; Peng et al., 2017; Rickman et al., 2007). For example, loss of heat-sensitive vitamins such as vitamin C (*L*-ascorbic acid), can be as high as 90% during conventional thermal processes. However, during the storage retention of vitamins may be better in thermally processed vegetables than in either fresh or frozen products (Howard et al., 1999; Rickman et al., 2007). Development of highly nutritious, thermal-stabilized vegetable products is one of the most effective ways of addressing food security issues. Thermal stabilization also supports military and NASA missions that require ready-to-eat foods with a shelf life of 3–5 years. Food engineers aim to retain both the sensory acceptability and nutritional efficacy of foods throughout long-term storage (Cooper, Douglas, & Perchonok, 2011).

Microwave-assisted thermal sterilization (MATS) has been accepted by both the FDA and the USDA-FSIS as a validated processing method to produce low-acid, shelf-stable packaged foods (Tang, 2015). Fast volumetric heating has been found to retain the color, texture and sensory attributes better than retort processing at the same lethality (Tang et al., 2008; Zhang, Tang, Rasco, Tang, & Sablani, 2016). However, more research is needed on the systematic shelf life of MATS foods. For example, research may help determine whether MATS processing retains major nutrients and sensory attributes in vegetable-based products during long-term storage.

One key factor regarding shelf life for MATS-processed foods is the adaption of polymer-based packaging that is transparent to microwaves during in-package processes. Polymeric materials are lightweight and very flexible, but they provide less barrier protection than metal cans or aluminum foil laminated films (Zhang, Tang et al., 2016). However, MATS processing causes less thermal degradation of the gas barrier properties of polymeric trays or pouch films than retort processing (Dhawan et al., 2014). In our prior work, we found that oxygen transmission rates (OTRs) and water vapor transmission rates (WVTRs)

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had a significant impact on color changes and water loss in a mashed potato model food during storage (Zhang, Tang et al., 2016).

High barrier polymer pouches prevent the oxidation, Millard browning, and other quality degradation reactions that could occurred in foods after thermally processing (Zhang, Bhunia et al., 2016). For thermally processed salmon and pasteurized ready-to-eat mussels, both products favored packaging films with smaller OTR to minimize lipid oxidation (Bhunia, Ovissipour, Rasco, Tang, & Sablani, 2017; Byun, Bae, Cooksey, & Whiteside, 2010). In addition, β-carotene content is retained better in pressure-assisted thermally processed carrots when they are packaged in Nylon/EVOH/EVA film (OTR = 0.91 cc/m^2·day) rather than Nylon/EVA (OTR = 48 cc/m^2·day) and MetPET/PE (OTR = 1.33 cc/m^2·day). The change in the β-carotene content of carrots is also correlated with color change (Ayvaz et al., 2012). NASA investigated the nutrient degradation in International Space Station (ISS) food systems, which are composed of thermally processed foods packed in aluminum foil films. From these studies, they determined that vitamin B_1 and C declined much faster than other vitamins. Vitamin C degraded from 32% to 83% after 3 years of room temperature storage (Cooper, Perchonok, & Douglas, 2017). However, that study did not compare polymer packaging. Packaging can also alter the flavor of packaged foods. For example, *d*-limonene from citrus juice can be absorbed by polymers such as LDPE, PP and EVOH, causing off-flavors (Sajilata, Savitha, Singhal, & Kanetkar, 2007). Although sensory evaluation of the MATS-processed foods is a key factor in shelf-life assessment, little is known about packaging effects on these qualities.

To address this issue, we conducted a storage study of vitamin C fortified sweet potato puree (SPP). We processed SPP by MATS and packaged in four types of pouches with coated-PET (3 types) and EVOH (1 type) as barrier materials. Sweet potato is a nutritious vegetable containing the highest carotenoids content of all foods (Truong & Avula, 2010). SPP fortified with vitamin C is usually served as commercial baby food, providing an attractive orange color and a sufficient daily nutrient supply (Gliemmo, Latorre, Gerschenson, & Campos, 2009). In this study, we analyzed the degradation reaction rates of SPP quality and nutritional indicators in various packaging pouches. Results reveal the oxygen and water vapor sensitivity of vitamin C and β-carotene in processed SPP. Therefore, findings will inform the appropriate design and selection of polymer packaging to improve retention of nutrients and other attributes for MATS processed or other thermally processed foods.

2. Materials and methods

2.1. Chemicals and reagents

Vitamin C (*L*-ascorbic acid, BioXtra, > 99%) and meta-phosphoric acid used for HPLC measurement were purchased from Sigma-Aldrich Co. (St. Louis, MO). Vitamin C (ascorbic acid, pure powder) used for food fortification was purchased from Now Foods Co. (Bloomingdale, IL). Potassium phosphate was purchased from Fisher Scientific Co. (Fair Lawn, NJ). Butylated hydroxytoluene (BHT) was purchased from ACROS Organics, Belgium. Hexane, ethanol, acetone, and phosphoric acid were purchased from Avantor Performance material (Center Valley, PA).

2.2. Preparation of sweet potato puree

Fresh Beauregard sweet potatoes were purchased from the local market. To prepare the puree, sweet potatoes were first washed and sliced to ˜0.8 cm thickness. Sliced potatoes were then aligned in a single layer and steam blanched for 15 min before peeling. Next, the flesh obtained was blended with additional water (sweet potato flesh: water = 2:1) for 1 min to obtain the puree. To fortify the formulation, vitamin C was added to the water at a concentration of 600 mg/L. All the blended puree was combined into a 12-L mixer for 20 min of constant speed mixture to ensure homogeneity.

2.3. Polymeric pouches and vacuum sealing

All packages were multi-layered polymeric pouches that were provided by Kuraray America, Inc. (Houston, TX), Toppan USA, Inc. (Rolling Meadows, IL) and KSM Enterprises (Gig Harbor, WA). They were labelled PF-X-Y, as noted in the list below. Note that X and Y are equal to 1–4, indicating the sequence of their measured average OTR and WVTR levels during storage from the lowest to the highest, respectively:

- PF-1-2: PET/coating 12 μm//nylon 15 μm//PP 60 μm
- PF-2–3: PET/oxide coating/organic coating 13 μm//nylon 15 μm//PP 50 μm
- PF-3-1: PET/coating 12 μm//nylon 15 μm//PP 50 μm
- PF-4-4: Nylon 15 μm//EVOH (27%mol ethylene) 15 μm//PP 60 μm
- PF-0-0: PET 12 μm//aluminum 9 μm//nylon 15 μm//PP 80 μm

All the pouches were tailored to the same dimension (185 mm × 130 mm). The sweet potato puree was vacuumed gently twice to remove the air inside of the food matrix. Next, 8 oz (227 g) of puree was poured into each polymer pouch and then sealed with a pressure of around 1.0 bar to minimize the residual air inside. The sealed pouches were kept at 4 °C overnight before processing. After processing, half of the PF-3-1 pouches were sealed again inside a foil pouch (PF-0-0, 230 mm × 190 mm) with the maximum vacuum level to serve as the barrier control (e.g., retort-processed product in foil pouches).

2.4. MATS processing and storage

A single-mode, microwave-assisted thermal sterilization pilot system (25 kW, 915-MHz) was utilized to process the puree. A full description of this system and technology can be found in a previous publication (Tang, 2015). The processing parameters and lethality measurement method followed those of Zhang et al. (Zhang, Bhunia et al., 2016). The processing procedure was set to 25 min for preheating at 61 °C, 3.7 min for microwave heating, and 3.8 min for holding at 124 °C. In the last step, the mixture was cooled for 5 min in tap water (around 20 °C). The obtained average lethality was F_0 = 7.6 min. After processing, a predetermined number of pouches was randomly divided into different storage incubators with temperatures of 35 °C, 23 °C and 4 °C for 9 months, 18 months, and 18 months, respectively. Triplicate pouches were sampled at each measurement to obtain instrumental analysis and sensory panel data.

2.5. Oxygen and water barrier properties

The OTRs and WVTRs of the films were measured with an Ox-Tran 2/21 MH model (Modern Control, Minneapolis, MN) and a Permatran 3/33 MG model (Modern Control, Minneapolis, MN), respectively. For the OTR measurements, conditions were set at 55% RH, 23 °C and 1 atm. Tests were conducted according to the ASTM F 1927 standard method. WVTR measurements were conducted at 100% RH and 38 °C, according to the ASTM standard method F 372-99. Film specimens with a surface area of 50 cm^2 were cut from the polymeric pouches and mounted inside the testing chambers. Triplicate film samples were measured before, after MATS processing, and after 3 months of storage at both 23 °C and 35 °C. The percentage of water loss (w/w%) was also calculated based on the changes in sample (n = 3) weight and was plotted against the storage time.

2.6. Color

The color of the puree was measured with a CM-5 spectrophotometer (Konica Minolta, Ramsey, NJ). The puree was poured into a

plastic petri dish (Ø = 60 mm, H = 15 mm). Three measurements were conducted at separate locations from each circular area (Ø = 8 mm) at the bottom of the petri dish. For each sample, three replicates from different pouches were collected. Results were reported based on the CIE color system: lightness (L^*), redness (a^*), and yellowness (b^*), and then further calculated to obtain the total color difference ΔE and Chrome (C):

$$\Delta E = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \quad (1)$$

$$C = \sqrt{a^{*2} + b^{*2}} \quad (2)$$

2.7. Vitamin C

Vitamin C content was determined based on a previous method, with some modifications (Scherer et al., 2012). Each 3 g puree was extracted in 10 ml 3% (w/v) meta-phosphoric acid solution. The mixture was vortexed, homogenized at 7000 rpm for 1 min, and then extracted for 2 h at room temperature. Next, the sample was placed in a centrifuge at 8000g for 5 min. The obtained supernatant was filtered through a 13 mm nylon syringe filter (0.45 μm pore size). Each 10 μl of sample was injected into an Agilent 1100 HPLC system (Agilent Technology, Santa Clara, CA) through a 250 mm 5 μm XTerra C18 column (Waters Corporation, Milford, MA) equipped with a diode array detector. The separation was a 25-min isocratic elution procedure in 0.01 mol/L KH_2PO_4 mobile phase solution (pH = 2.6 adjusted with o-phosphoric acid), with a flow rate of 0.5 ml/min and a column temperature of 25 °C. The detecting wavelength was set at 250 nm.

2.8. Total β-Carotene

The total β-carotene content was determined with a spectrometer (Ultraspec 4000, Pharmacia Biotech Inc., Piscataway, NJ) based on Leong and Oey's method (Leong & Oey, 2012). Each 5 g of SPP was homogenized in 30 ml solvent (50% hexane, 25% acetone, 25% ethanol, with 0.1% BHT w/v) at 7000 RPM for 5 min. The mixture was vacuum filtered through Whatman No.1 filter paper (Ø50 mm). The remaining pellets were homogenized in 10 ml of the same solvent for another 1 min and then filtered again. The filtrate was combined into a separating funnel. Next, the upper organic layer was filtered again using Whatman No.4 filter paper through a regular funnel. The final yellow solution was collected and diluted in a 50-ml volumetric bottle with the same extraction solvent before measurement. The absorption of solvent was measured at 450 nm against the blank (pure extraction solvent). The β-carotene content was calculated using the extinction coefficient of 2560 L/mol·cm. The entire procedure was conducted in the absence of light, and three replicated readings were obtained for each treatment.

2.9. Sensory evaluation

The sensory evaluation of SPP was conducted at the sensory lab at Washington State University. Each panel consisted of 48 untrained consumers who were recruited from the Washington State University community (approximately 60% females and 40% males, with an average age of 35 years). One day before the sensory evaluations, 10 ± 1 g of sample for each treatment (n = 5) were pre-portioned into 2 oz. soufflé cups, covered with lids and placed in a 4 °C refrigerator. Samples were brought back to room temperature 1 h before testing. Consumers were required to evaluate the color intensity (orange, yellow and red), flavor intensity and consistency. They also reported preferences regarding flavor, texture, and overall acceptance. Intensity was measured using a 9-point intensity scale and three anchors where 1 = extremely low, 5 = moderate and 9 = extremely high. For intensity of thickness/consistency, the scale anchors used were 1 = thin, 5 = moderate and 9 = thick. Acceptance was measured using a 9-point hedonic scale (1 = dislike extremely, 2 = dislike very much, 3 = dislike moderately, 4 = dislike slightly, 5 = neither like nor dislike, 6 = like slightly, 7 = like moderately, 8 = like very much and 9 = like extremely). Consumers were provided with crackers and water for rinsing between samples.

2.10. Data analysis

Sensory data were collected by Compusense-at-hand software (Compusense Inc., Guelph, ON). ANOVA tests using GLM procedure (SAS 9.2, SAS Institute Inc., Cary, NC, USA) were conducted. Tukey's HSD method was used to compare quality, nutrition, sensory attributes in different pouches and with different storage times at the significance levels of $p < 0.05$ and $p < 0.001$. Chemical degradation kinetics were calculated by general rate law (Eq. (3)) (Peng et al., 2017), where t is the reaction time, k is the rate constant, n is the order of reaction and A is the quality or nutrition index.

$$-\frac{dA}{dt} = kA^n \quad (3)$$

3. Results and discussion

3.1. Oxygen and water barrier properties

Table 1 displays changes in the OTRs and WVTRs of the pouches before and after MATS, as well as during storage. After MATS processing, the OTRs of all the pouches and the WVTRs of PF- 2-3 and PF-3-1 increased. However, the WVTR of PF-1-2 remained the same, and the WVTR of PF-4-4 decreased. After 3 months of storage, the OTRs of all 35 °C samples further increased, except for PF-4-4. The OTRs of PF- 2-3 and PF-3-1 at 23 °C/3-month also increased. The WVTRs for all pouches generally decreased or maintained during the storages at different temperature. Results were consistent with our previous studies of MATS influence on coated-PET and EVOH based pouches (Dhawan et al., 2014; Mokwena, Juming, Dunne, Yang, & Chow, 2009; Zhang et al., 2017; Zhang, Bhunia et al., 2016). Barrier properties changed mostly during thermal processing and within the first 2-3 months of storage

Table 1
Packaging oxygen and water barrier properties during MATS and following storage.

Pouch Films	OTR (cc/m^2 day)				WVTR (g/m^2 day)			
	PF-1-2	PF-2-3	PF-3-1	PF-4-4	PF-3-1	PF-1-2	PF-2-3	PF-4-4
Before MATS	0.018 ± 0.005^{bB}	0.016 ± 0.005^{bB}	0.039 ± 0.016^{bB}	1.404 ± 0.067^{aA}	0.126 ± 0.022^{bD}	1.353 ± 0.034^{aB}	0.345 ± 0.033^{bC}	3.572 ± 0.075^{aA}
Post MATS/ 0month	0.147 ± 0.045^{abB}	0.052 ± 0.033^{bB}	0.310 ± 0.162^{abB}	2.014 ± 0.133^{aA}	0.669 ± 0.268^{abB}	1.311 ± 0.103^{aB}	3.367 ± 0.721^{aA}	2.899 ± 0.199^{bA}
MATS 23 °C/ 3month	0.075 ± 0.021^{abB}	0.107 ± 0.067^{bB}	0.416 ± 0.267^{abB}	1.907 ± 0.300^{aA}	0.679 ± 0.318^{abB}	0.901 ± 0.029^{bB}	2.937 ± 0.087^{aA}	3.172 ± 0.086^{abA}
MATS 35 °C/ 3month	0.234 ± 0.100^{aB}	0.298 ± 0.061^{aB}	0.864 ± 0.337^{aB}	1.864 ± 0.369^{aA}	0.890 ± 0.159^{aB}	0.883 ± 0.028^{bB}	2.421 ± 0.359^{aA}	2.776 ± 0.053^{bA}

Data were expressed using means ± standard deviations, with superscript indicating differences within columns and rows for OTR and WVTR, respectively.

due to the changes of polymer crystallinity and surface coating morphology (Zhang et al., 2017). Based on this previously observed pattern, to quantitatively characterize the influence of packaging permeability, we use OTRs and WVTRs measured at 3rd month as the average values for gas barriers of packaging films during the storage.

As complementary information, the water loss was tracked to indicate a direct mass change in the processed samples. Fig. S1 displays consistent water loss rates with temperature dependence accorded with our previous findings (Zhang, Bhunia et al., 2016). The amount of water loss corresponded to the level of WVTR for a specific pouch. The highest amount of water loss reached 7.2% for the PF-4-4 at 35 °C/9-month and 4.3% at 23 °C/18-month. These losses were included to correct the vitamin C and total β-carotene content. However, since the original water content of the SPP was up to 90%, this indicates that WVTR may only have limited influence on SPP quality.

3.2. Color

Color plays an important role in consumer acceptance, especially for vegetable products (Peng et al., 2017). It was considered that the major form of degradation in high-carotenoid products is color fading, while colors tend to darken in starch-based and fruit products (Catauro & Perchonok, 2012). In our study, during MATS processing. L^* remained the same (from 48.3 ± 0.18 to 48.0 ± 0.34, $p > 0.05$), a^* decreased (from 24.1 ± 0.91 to 22.8 ± 0.39, $p < 0.05$), and b^* increased (39.2 ± 0.64 to 44.0 ± 0.36, $p < 0.001$). Similar color changes have occurred when SPP is aseptically processed over 110 °C to 140 °C (Coronel, Truong, Simunovic, Sandeep, & Cartwright, 2005). The increased yellowness may be due to heat-induced extraction of carotenoids from the cells (Vervoort et al., 2012).

Fig. 1 shows the color changes during the storage. The lightness (L^*) of SPP degraded significantly ($p < 0.001$) during the storage which indicated color darkening (Fig. 1A, D). After 3 months of storage, the L^* of PF-4-4 and PF-3-1 were lower than in other three pouches. There were no significant differences ($p > 0.05$) for PF- 2-3, PF-1-2 and PF-0-0. Results indicated that the effects of time and packaging were similar for both 35 °C and 23 °C storage. However, at 35 °C the L^* of PF-4-4 declined faster than PF-3-1 especially in the first 3 months. This did not occur at 23 °C indicating a more pronounced packaging effect at higher temperature. Chroma (C) and total color difference (ΔE) in SPP during the storage were shown in Fig. 1B, E and C, F, respectively. The reduction of chroma and increase of total color difference occurred quickly from 0-month to 3-month at 35 °C and 0-month to 6-month at 23 °C. Following that, the chroma of SPP in PF-4-4 and PF-3-1 were lower than the PF- 2-3, PF-1-2 and PF-0-0 ($p < 0.001$), and the ΔE were higher. Similarly, the differences of C and ΔE between PF-4-4 and PF-3-1 with PF- 2-3, PF-1-2 and PF-0-0 were more distinguished at 35 °C compared to at 23 °C, highlighting the effect of temperature. At the end of 9 months of storage at 35 °C, the ΔE of SPP in PF-4-4 and PF-3-1 reached 12.8 and 11.7 which was considered a different color from the sensory point of view (Zhang, Bhunia et al., 2016).

Statistically, color changes (L^*, C, ΔE) in SPP were affected significantly by all factors: temperature, packaging, storage time, and their interactions (F and p values shown in Table S1). Color changes were affected by packaging because of their different oxidation levels controlled by oxygen permeability, i.e. OTRs (Table 1). However, proportional changes were not found. PF- 2-3 and PF-1-2 had similar color protection capacity to a foil pouch (PF-0-0). These results accorded with previous findings, in which a high barrier polymeric pouch with less than 0.3 cc/m^2·day offered similar color protection as foil pouches (Zhang, Bhunia et al., 2016). It is likely that when OTR was below a critical limitation value, the total accessible oxygen in pouches for reactions causing color degradation was unchanged. Thus, reaction rates did not differ significantly between pouches PF-1-2, PF- 2-3 and the foil pouch, since their OTRs were all below 0.3 cc/m^2·day. In addition, The OTR (0.864 cc/m^2·day) and WVTR (0.890 g/m^2·day) of PF-3-1 is less than 50% and 35% of PF-4-4 at 35 °C, respectively. But these samples displayed little color difference during storage. Perhaps the oxygen diffusion rates into the food matrix reached a maximum, so that excessive oxygen could not further accelerate the color degradation.

3.3. Vitamin C

Degradation of vitamin C during storage of various vegetables is reported to be from 8% to 90% of their original content after the canning process (Howard et al., 1999; Jiratanan & Liu, 2004; Peng et al.,

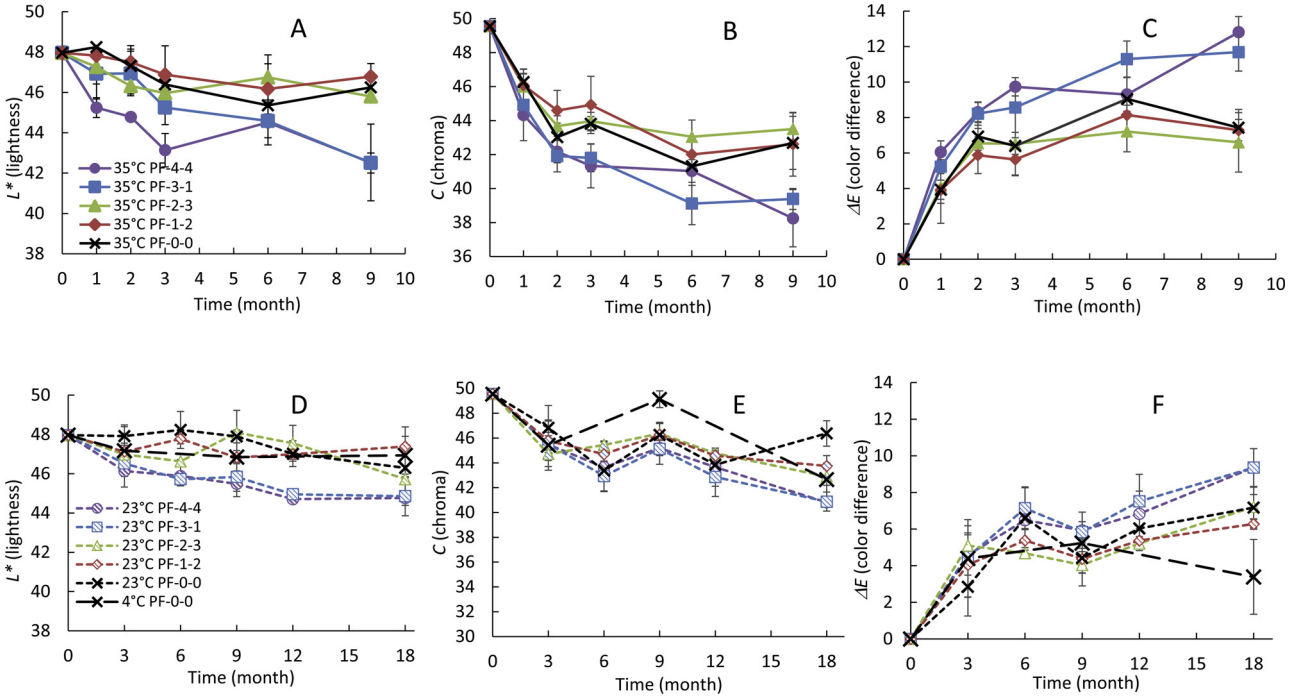

Fig. 1. Color changes (L^*, C, and ΔE) in MATS processed SPP during storage at 35 °C (A, B, C), 23 °C and 4 °C (D, E, F) in different pouches.

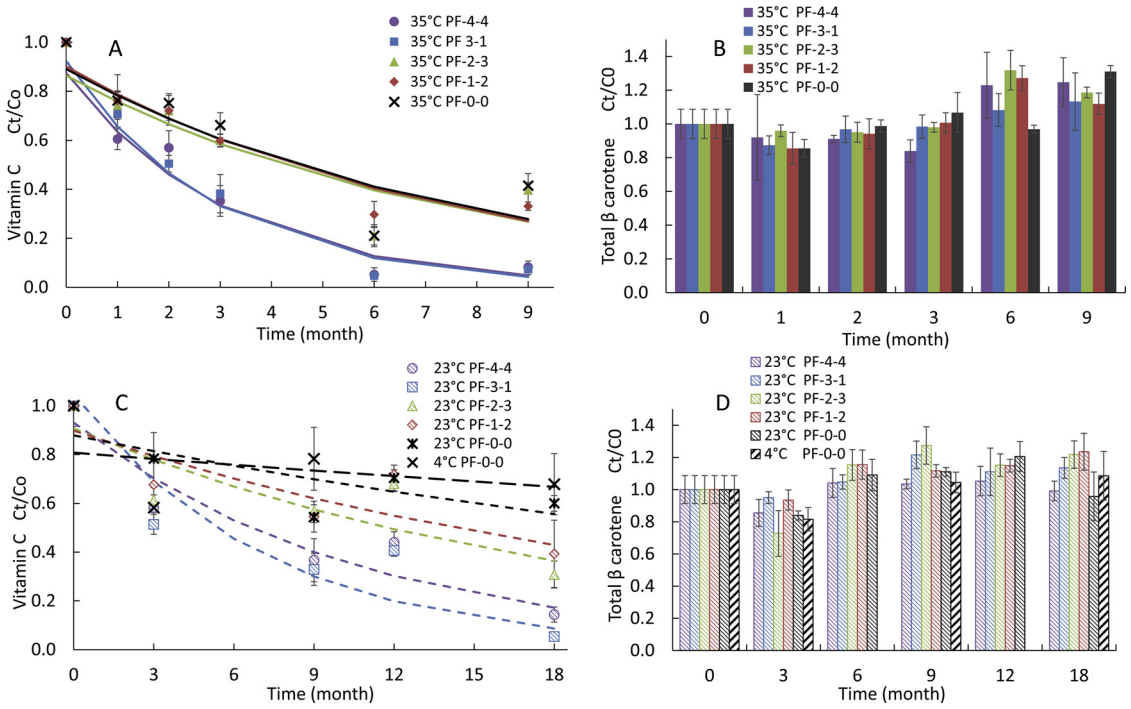

Fig. 2. Changes in relative content (C_t/C_0) of vitamin C and total beta-carotene in MATS processed SPP during storage at 35 °C (A, B), 23 °C and 4 °C (C, D) in different pouches. The initial concentration of vitamin C and total β-Carotene at 0-month is 185.8 ± 15.6 and 71.9 ± 6.2 mg/ 100 g dry mass, respectively. First order fitting curves for vitamin C degradation were also shown with the same color as each package.

2017; Rickman et al., 2007). In our study, the average vitamin C content in sweet potato puree decreased from 201.7 ± 4.7 to 185.8 ± 15.6 mg/100 g puree by dry mass ($p > 0.05$) after MATS processing. The lower change in vitamin C content after MATS processing vs. conventional sterilization can be attributed to the short processing time. Only 7.4 min of sterilization time was applied to achieve the same lethality as conventional processing, which typically requires more than 60 min (Tang, 2015). Another principal factor was the minimum residual air in pouches just after sealing. Studies show that the vitamin C degradation rate is strongly affected by initial dissolved oxygen concentration, even at 90 °C (Dhuique-Mayer et al., 2007). Our findings demonstrate that MATS caused only minor thermal reduction of vitamin C in vegetables, resulting in good initial quality.

Fig. 2A and C displays the change in vitamin C content during storage. At 35 °C, up to 172 mg/100 g of vitamin C (92% of original content) was lost for SPP packed in PF-3-1 and PF-4-4. Comparatively, less than 125 mg/100 g of vitamin C loss (79% of original content) was observed for PF-1-2 and PF- 2-3 after 9 months of storage at 35 °C, which is comparable to PF-0-0. At 23 °C, there was a 175 mg/100 g (94% of original content) and 158 mg/100 g (85% of original content) loss of vitamin C in SPP packaged in PF-3-1 and PF-4-4 at end of the storage. More than 57 mg/100 g of vitamin C in PF-1-2 and PF- 2-3 were still retained after the same storage time. ANOVA analysis showed significant temperature, packaging, storage time effects on vitamin C changes, as well as significant interactions between each two factors (Table S1). Many studies show that degradation of vitamin C in different thermally processed vegetables during storage (less than 20%) is less than during processing (Peng et al., 2017; Rickman et al., 2007). However, Talcott et al. found that ascorbic acid content decreased by 25% of the original content in fortified passion fruit juice after pasteurization (85 °C for 30 min). After another 14 days of storage at 37 °C, no vitamin C was detected (Talcott, Percival, Pittet-Moore, & Celoria, 2003). A recent NASA study found that vitamin C is one of the most sensitive nutrient in 109 foods of the space food menu. These foods are processed and packaged in foil pouches during 3 years of storage at 21 °C. Findings showed that in most fruit products, the degradation of vitamin C was from 32% to 83% of the initial content (Cooper et al., 2017). Our findings also reveal more vitamin loss during storage than during processing. Obviously, elevated temperatures, longer storage time, and food characterization itself are major reasons for these losses. On the other hand, the high degradation rates of vitamin C during storage indicate an even significant effect of packaging. Few studies had focused on the packaging effects on vitamin C during storage, yet to our knowledge no research had correlated gas barrier properties with nutrition after long term storages for sterilized ready-to-eat vegetables (Ayhan, Yeom, Howard Zhang, & Min, 2001; Polydera, Stoforos, & Taoukis, 2003). Out of the four pouches used, PF-1-2 and PF- 2-3 retained vitamin C in the same level with PF-0-0 ($p > 0.05$) at 35 ºC. At ambient conditions, there were no significantly differences between PF-1-2 and PF-0-0 ($p > 0.05$). Fig. 2A and C indicate that at both storage temperatures, the same first-order prediction lines fitted well. In fact, at 35 °C, there was a clear distinction between the two groups of pouches. Prediction lines for Group 1 (PF-1-2, PF- 2-3 and PF-0-0), and Group 2 (PF-3-1 and PF-4-4) nearly overlapped. At 23 °C, there was a clearer distinction between all pouches, including the foil control of 4 °C.

Clearly, the oxygen barrier of the pouches had a more significantly ($p < 0.001$) protective effect against vitamin C degradation than color change especially at room temperature. At 35 ºC, temperature effect dominant the vitamin C degradation so only the group of packages with OTR above 0.864 cc/m^2·day and the group of packages with OTR below 0.3 cc/m^2·day were differentiated. After storage at 23 °C for 18 months, 111.5 ± 5.9, 73.0 ± 25.6, 57.2 ± 10.3, 26.7 ± 5.8, and 10.0 ± 0.3 mg/100 g vitamin C were present in SPP packed inside PF-0-0, PF-1-2, PF- 2-3, PF-4-4, and PF-3-1, respectively. The stability of vitamin C was generally controlled by OTR but still no proportional changes were observed. In fact, PF-3-1 with an OTR higher than PF-4-4 had a less retention of vitamin C indicating that there might be other factors affected the stability of vitamin C. These results proved the high sensitivity of vitamin C to oxygen barrier during the storage. High-barrier polymeric pouches with limited OTR (< 0.3 cc/m^2·day) shows promise for providing MATS-processed foods with vitamin C stability (less than 50% loss of original content) of 1 year at ambient

Table 2
Sensory scores of MATS processed SPP packaged in different pouches during storage.

Attributes	Time/month	PF-1-2	PF-2-3	PF-3-1	PF-4-4	PF-0-0	PF-0-0 4 °C	*F* values
Orange	0	7.13 ± 1.31^{A}	7.17 ± 1.34	7.21 ± 1.32^{A}	7.24 ± 1.12^{A}			*0.07*
	3	6.88 ± 1.10^{AB}	7.08 ± 1.16	6.77 ± 1.22^{A}	6.75 ± 1.19^{AB}	6.81 ± 1.30	6.85 ± 1.07	*0.50*
	9	6.83 ± 1.19^{AB}	6.77 ± 1.37	6.63 ± 1.21^{AB}	6.42 ± 1.43^{B}	6.63 ± 1.48	6.67 ± 1.63	*0.51*
	18	6.40 ± 1.55^{B}	6.81 ± 1.18	6.00 ± 1.56^{B}	6.31 ± 1.22^{B}	6.67 ± 1.51	6.58 ± 1.25	*2.09*
	F values	*2.87*	*1.06*	*7.16*	*5.05*	*0.23*	*0.52*	
Yellow	0	4.30 ± 1.62	4.26 ± 1.58	4.33 ± 1.84	4.37 ± 1.68			*0.03*
	3	3.90 ± 1.65	4.00 ± 2.05	4.10 ± 1.63	4.02 ± 1.58	4.10 ± 1.68	4.00 ± 1.82	*0.10*
	9	4.27 ± 1.62	3.98 ± 1.94	4.06 ± 1.58	4.25 ± 1.88	4.38 ± 1.81	4.63 ± 1.79	*0.81*
	18	4.10 ± 1.67	4.13 ± 1.78	3.79 ± 1.66	4.15 ± 1.75	4.73 ± 1.95	4.42 ± 1.65	*1.60*
	F values	*0.62*	*0.25*	*0.83*	*0.33*	*1.43*	*1.58*	
Red	0	3.65 ± 1.90	3.43 ± 1.72	3.63 ± 1.83	3.80 ± 1.82			*0.32*
	3	3.54 ± 1.91	3.48 ± 1.98	3.38 ± 1.91	3.58 ± 1.99	3.23 ± 1.78	3.29 ± 1.84	*0.26*
	9	3.56 ± 1.64	3.56 ± 1.62	3.69 ± 1.82	3.33 ± 1.39	3.50 ± 1.65	3.02 ± 1.49	*1.05*
	18	3.52 ± 2.04	3.67 ± 1.94	3.94 ± 2.12	3.67 ± 2.09	3.29 ± 1.83	3.23 ± 1.92	*0.84*
	F values	*0.06*	*0.11*	*0.71*	*0.43*	*0.31*	*0.31*	
Consistency	0	5.63 ± 1.78	5.78 ± 1.48	5.48 ± 1.87	5.59 ± 1.65			*0.18*
	3	5.54 ± 1.70	5.71 ± 1.57	5.48 ± 1.66	4.88 ± 1.73	5.13 ± 1.88	5.35 ± 1.67	*1.51*
	9	5.65 ± 1.60	5.54 ± 1.56	5.27 ± 1.50	5.15 ± 1.46	5.33 ± 1.42	5.02 ± 1.52	*1.17*
	18	5.46 ± 1.70	5.44 ± 1.20	5.38 ± 1.35	5.46 ± 1.40	5.56 ± 1.58	5.35 ± 1.38	*0.13*
	F values	*0.11*	*0.58*	*0.14*	*2.17*	*0.86*	*0.76*	
Texture liking	0	5.91 ± 1.40	5.93 ± 1.44	6.00 ± 1.40	5.96 ± 1.35			*0.03*
	3	6.15 ± 1.34	5.98 ± 1.64	5.73 ± 1.43	5.67 ± 1.49	5.27 ± 1.61	5.65 ± 1.56	*1.91*
	9	5.96 ± 1.43	5.85 ± 1.30	6.13 ± 1.06	5.98 ± 1.59	5.79 ± 1.24	5.79 ± 1.47	*0.44*
	18	5.58 ± 1.37	6.23 ± 1.31	5.83 ± 1.49	6.08 ± 1.37	5.83 ± 1.49	5.88 ± 1.66	*1.21*
	F values	*1.43*	*0.59*	*0.75*	*0.80*	*2.23*	*0.26*	
Flavor intensity	0	5.78 ± 1.75	5.96 ± 1.73	5.89 ± 1.45	5.87 ± 1.44			*0.09*
	3	5.85 ± 1.61	5.90 ± 1.61	5.50 ± 1.57	5.60 ± 1.47	5.88 ± 1.70^{A}	5.73 ± 1.54	*0.50*
	9	5.33 ± 1.58	5.58 ± 1.49	5.71 ± 1.35	5.73 ± 1.45	5.65 ± 1.28^{AB}	5.21 ± 1.56	*1.04*
	18	5.54 ± 1.53	5.50 ± 1.60	5.65 ± 1.34	5.75 ± 1.58	5.00 ± 1.82^{B}	5.50 ± 1.54	*1.30*
	F values	*0.91*	*0.56*	*0.78*	*0.23*	*3.78*	*1.37*	
Flavor liking	0	5.46 ± 1.96^{AB}	5.22 ± 1.70^{B}	5.96 ± 1.37	5.96 ± 1.80			*2.14*
	3	6.08 ± 1.62^{A}	5.96 ± 1.75^{A}	5.83 ± 1.51	6.02 ± 1.38	5.19 ± 1.68^{B}	5.77 ± 1.49	*2.05*
	9	5.52 ± 1.57^{AB}	5.67 ± 1.45^{AB}	5.71 ± 1.35	6.02 ± 1.45	6.06 ± 1.31^{A}	5.27 ± 1.67	*2.00*
	18	4.85 ± 1.64^{bB}	6.29 ± 1.41^{Aa}	5.77 ± 1.55^{a}	6.13 ± 1.41^{a}	5.52 ± 1.61^{ABab}	5.73 ± 1.44^{ab}	*5.38*
	F values	*4.17*	*4.98*	*0.18*	*0.10*	*3.93*	*1.56*	
Overall acceptance	0	5.21 ± 1.85^{B}	5.41 ± 1.60^{B}	5.87 ± 1.47	6.02 ± 1.42			*2.58*
	3	6.13 ± 1.55^{Aa}	5.90 ± 1.59^{ABa}	5.75 ± 1.52^{ab}	5.83 ± 1.26^{ab}	4.96 ± 1.68^{Bb}	5.81 ± 1.42^{ab}	*3.36*
	9	5.60 ± 1.43^{AB}	5.58 ± 1.43^{AB}	5.83 ± 1.33	5.98 ± 1.34	5.81 ± 1.23^{A}	5.29 ± 1.71	*1.41*
	18	4.94 ± 1.56^{Bb}	6.31 ± 1.21^{Aa}	5.71 ± 1.41^{ab}	6.13 ± 1.33^{a}	5.65 ± 1.56^{ABab}	5.79 ± 1.43^{a}	*5.36*
	F values	*4.97*	*4.13*	*0.11*	*0.39*	*4.36*	*1.79*	

Data were expressed using means ± standard deviations. For each attribute, the data were denoted with lower − case superscript to indicate differences within the rows and uppercase superscript to indicate differences within the columns.

temperature. Efforts are still need for extending the shelf life of foods used in special missions considering the vitamin C.

3.4. Total β-carotene

β-carotene served as the important pro-vitamin A, and largely determines vegetable color. Total β-carotene was not affected by MATS processing (from 67.7 ± 3.0 to 71.9 ± 6.2 mg/100 g puree by dry mass, $p > 0.05$). Studies show that β-carotene can be destroyed by thermal processing due to oxidation or isomerization (Chandler & Schwartz, 1988; Knockaert, Lemmens, Van Buggenhout, Hendrickx, & Van Loey, 2012). Chandler and Schwartz found a 20% β-carotene loss in sweet potatoes after canning at 116 °C for 90 min (Chandler & Schwartz, 1988). Vervoort et al. compared the thermal process and high-pressure process at different conditions for carotene retention. Results show that at sterilization conditions (117 °C, 23 min), there was 31% reduction of β-carotene, but no significant changes at pasteurization and high pressure conditions (Vervoort et al., 2012).

It was not surprised that β-carotene is more stable than more sensitive nutrients such as vitamin C. In our study, the total β-carotene in MATS processed SPP increased, probably due to the shorter process time. It is well known that the extractability of β-carotene can be enhanced by thermal processes due to disruption to the food protection matrix (Peng et al., 2017; Vervoort et al., 2012). The loss of β-carotene is less than the β-carotene released from plant cells, explaining why β-carotene content can increase after processing. In addition, the fortified level of vitamin C can also work as an antioxidant to prevent oxidation of carotenes. Other studies found vitamin C protection on carotenoids in various food systems (Gliemmo et al., 2009; Stephen T. Talcott et al., 2003). Although the isomers of β-carotene were not identified in our study, their relative amount in the total β-carotene would be small, especially in less severe processing conditions (Knockaert et al., 2012).

Fig. 2B and D indicate that during initial storage at 35 °C/1-month and 23 °C/3-month, β-carotene content declined. However, over extended storage, the β-carotene content remained steady ($p > 0.05$) or increased again ($p < 0.05$) after 6 months at both 35 °C and 23 °C. The initial reduction of β-carotene content in SPP may be due to the relatively high residual oxygen content in pouches during initial storage. Therefore, quick degradation of total β-carotene content was observed. As the remaining oxygen inside the pouches decreased there was no further degradation of β-carotene. Increments of total β-carotene content were observed again from the third to the sixth month. Similar to processing impact, carotene content can be increased by further improvement of extractability during storage (Peng et al., 2017; Vervoort et al., 2012). Howard et al. found a 10% increase of trans-β-carotene content during the first two weeks of storage for canned carrots. After 21 days, the concentration decreased slightly, followed by an increase after 6 weeks (Howard et al., 1999). Additional, carotenoids in vegetables can migrate into the brine when released from binding proteins. However, previous studies only measured solid vegetables (Howard

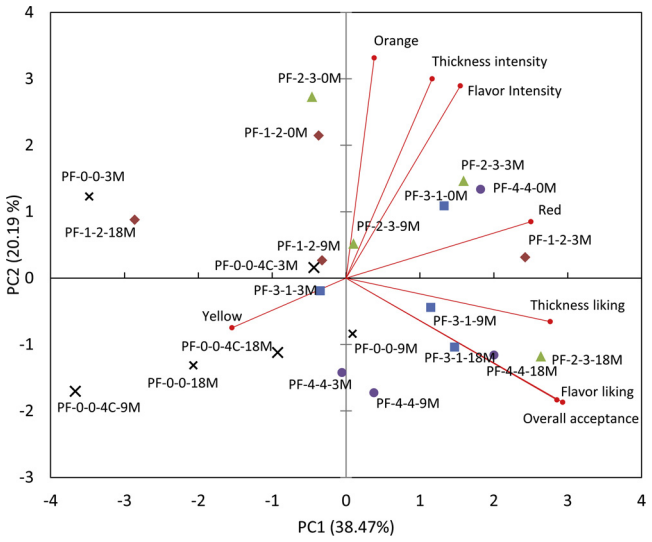

Fig. 3. PCA biplot for sensory attributes of MATS processed SPP packaged in different pouches: PF-0-0 (×), PF-1-2 (◆), PF- 2-3 (▲), PF-3-1 (■), and PF-4-4 (●) during storages.

et al., 1999) thus resulting in a lesser measured content. After 6 months, the β-carotene content did not further change. This suggests that the amount of β-carotene extracted was similar to the amount oxidized. Throughout storage, the total β-carotene content in SPP for all types of packages had no significant differences with the β-carotene content right after processing. However, significant main effects of temperature, package and storage time, and significant interaction between package and storage time were still observed (Table S1).

Ayvaz et al. explored the effect of three polymer package types on quality changes in pressure-assisted thermally processed carrots during storage. Findings showed that after 12 weeks of 37 °C storage, only one of three selected packages Nylon/EVOH/EVA retained 7.19 mg/100 g of β-carotene compared to 11.13 mg/100 g of fresh raw carrots (Ayvaz et al., 2012). Gliemmo et al. studied the effect of packaging, potassium sorbate, and ascorbic acid on the color stability of pumpkin puree. They concluded that high-barrier package retained more color (reds and yellows) because less carotene was oxidized. The effects of packaging on β-carotene retention in MATS-processed foods could be higher if no antioxidants such as vitamin C are added (Gliemmo et al., 2009).

3.5. Sensory attributes and correlations

Table 2 lists sensory scores for different attributes (intensity or liking) of processed SPP packaged in all five types pouches during 18 months of storage at 23 °C, as well as foil pouches stored at 4 °C. The ANOVA analysis showed a significant decrease ($p < 0.001$) in orange color, as well as significant changes in ($p < 0.05$) liking of flavor and overall acceptance for PF-1-2, PF- 2-3 and PF-0-0 during storage. Other sensory attributes did not change significantly or affected by packaging. Significant main effects of packaging for flavor liking and overall liking were also observed with interactions between packaging and storage time (Table S2).

Our instrumental analysis indicated a reduction in both the red and yellow color of SPP. The color different ΔE reached to above 9 for PF-3-1 and PF-4-4. Although these were characterized as having a "strong difference" in a prior study (Zhang, Bhunia et al., 2016), consumers did not perceive this difference in our study. Scores for yellow and red were lower than those for orange color, further confirming that consumers identified the orange color better as for the SPP. Consumers' liking of flavor and texture were more fluctuated than intensity of flavor and texture (consistency) during storage. There were obvious differences in water loss for different polymer pouches and between polymer and foil pouches. However, there were no significant ($p > 0.05$) difference in consumer reports of intensity or texture liking linked to water loss over storage time. For the SPP inside PF- 2-3 and PF-4-4 with high WVTRs, consumers reported higher texture liking scores at 18 months of storage than at the beginning of storage. Flavor liking score for SPP packed in PF-1-2 first increased, and then decreased to as low as 4.85 at the end of storage. Fluctuations in consumers' flavor liking were also observed for PF- 2-3 and PF-0-0. However, scores for PF-3-1 and PF-4-4 remained stable. The same pattern was observed in consumers' score of overall acceptance.

Few differences between packaging types were observed for consumers' flavor preference at 18 months' storage and for overall acceptance at 3 months and 18 months. Generally, packaging barrier properties impacted the flavor liking score of MATS-processed SPP. This further affected overall acceptance. However, there were significant interactions between packaging and storage time. Additionally, a slight increase in the *F*-value was also observed during storage for other attributes revealing the packaging effects in extended time. Unlike instrumental results, there were no differences in color between SPP samples in different pouches over 18 months of storage. Sensory evaluation of color and texture did not reveal differences though color and water loss between PF-1-2, PF- 2-3 with PF-3-1 and PF-4-4 differed. There were also no differences for polymeric pouches comparing with PF-0-0 at both 23 °C and 4 °C.

Fig. 3 shows that the principle components analysis (PCA) described a total of 58.7% of the sample variation, including 38.5% from PC1 and 20.2% from PC2. The attributes contributing most to PC1 were intensity of red, yellow, liking of flavor, liking of texture and overall liking. Attributes contributing most to PC2 were orange color, flavor and thickness/consistency intensity. Consumers' overall acceptance was closely tied to flavor liking and thickness liking rather than intensity. As storage time increase, intensity scores generally declined, while liking scores increased. At the end of the 18-month storage, SPP packed in the PF-3-1 and PF-4-4 was scored 5.71 and 6.13. This was higher ($p < 0.05$) than the PF-1-2, which was only scored 4.94 (Table 2). Although the greatest degradation of color and vitamin C were observed in PF-3-1 and PF-4-4 during the storage, consumers still liked the product.

Variations of flavor and overall acceptance scores for PF-1-2, PF- 2-3 and PF-0-0 shall be associated with packaging properties. The polymeric materials fabricating PF-1-2 and PF- 2-3 are more likely to cause flavor changes due to interactions between packaging materials and the food matrix. Thermally processed packaged foods have been long criticized for "scalping of flavor". Some polymers absorb flavor compounds or develop undesirable flavors after storage due to migration of small molecular compounds such as monomers. additives, plasticizers or inks (Guillard, Mauricio-Iglesias, & Gontard, 2010; Sajilata et al., 2007).

In our study, some consumers complained of a bitter or undesired aftertaste, especially for PF-1-2 after 18 months of storage, as well as for PF-1-2 and PF- 2-3 immediately after MATS processing. A few consumers also noted a sour taste. Hence, it is possible that packaging and food interactions influenced the consumer's liking scores. Nevertheless, most consumers deemed that the SPP possessed a natural sweet potato flavor, which was bland but comparable to a baby food. Consumers also commented that the texture was too "watery" or "runny," especially for PF-0-0. This may explain why final scores of texture-liking for SPP in PF- 2-3 and PF-4-4, which had high water loss, were slightly higher ($p > 0.05$) than for the other pouches. Overall liking scores may be increased by further optimizing the ratio of sweet potato and water in the formulation.

Few studies have explored the impact of packaging oxygen barriers on the sensory attributes of thermally processed foods. Low oxygen barrier pouches (oxygen permeability > 920 g·μm/m^2·day) led to less acceptance ($p < 0.05$) of retorted salmon due to lipid oxidation (Byun et al., 2010). Umme et al. studied the effects of different storage

conditions on pasteurized soursop puree sensory qualities, and found that puree packed in aluminum foil scored higher than that packed in a lacquered can or HDPE bottle (Umme, Bambang, Salmah, & Jamilah, 2001). Our consumer panel gave comparable scores for all attributes after 18 months of storage at ambient condition as for the 4 °C control. This suggests that the polymer pouches used had sufficient barriers (maximum OTR value 1.8 cc/m^2·day, maximum WVTR value 3.2 g/m^2·day) to maintain sensory qualities as well as the foil packaging. Some packaging materials may have influenced the flavor of processed SPP, affecting overall acceptance scores. We recommend that manufacturers design packaging for such products with materials that have high barriers as well as minimal food interactions.

3.6. Kinetic reaction rates and shelf life prediction

Degradation reaction rate constants were calculated based on the best fitting model for water loss, color and vitamin C (Table S3). The water loss and ΔE fitted with a zero order reaction for all pouches corresponded with those of a previous study (Zhang, Bhunia et al., 2016). Other color indices and vitamin C degradation fit better with the first order (Peng et al., 2017). Fitting correlation coefficients (R^2) were generally above 0.6, but were low in PF-1-2, PF- 2-3 and PF-0-0. The less goodness of the modelling indicated slow chemical reaction rates at low oxygen and low temperature conditions. Notably, the faster rates at 35 °C than 23 °C were attributed to the temperature as well as higher OTR values. Catauro and Perchonok reported that for most of vegetables or starch-based space food products, quality loss was due to color change and flavor change via Maillard browning (Catauro & Perchonok, 2012). However, for vegetable products such as SPP, there may be additional reactions, such phenolic condensation and changes in pH values especially at temperature lower than the ambient environment (Gliemmo et al., 2009; S T Talcott & Howard, 1999).

Fig. 4 displays reaction rates of water loss (Fig. 4A), ΔE (Fig. 4B) and vitamin C (Fig. 4C), plotted against both OTRs and WVTRs as a bubble graph. These graphs show the integrated effects from both WVTR and OTR in the same packaging. Results confirm that the water loss was highly correlated to WVTR. However, color change and vitamin degradation rates were not correlated to the WVTR. When the OTR changed from approximately 0.3 to 0.8 cc/m^2·day at 35 °C or from 0.1 to 0.4 cc/m^2·day at 23 °C, both reaction rates for color and vitamin C increased. These sensitive ranges of OTR values inform the packaging properties that are more likely to affect qualities and shelf life. Findings show that high oxygen barrier pouches, especially with OTRs below 0.2 cc/m^2·day had comparable color and nutrient retention capacity as the foil pouch.

Shelf life of SPP was extrapolated based on degradation of vitamin C and color (Table S4). The end-points of shelf life based on instrumental analysis were set as 20% or 50% loss of vitamin C, 20% loss of L^* or C values (Catauro & Perchonok, 2012) and $\Delta E = 6$. Results indicate very different shelf life lengths, whereas almost all the Q_{10} values fall into the reported range (1-4) of thermal-stabilized products (Zhang, Bhunia et al., 2016). At both temperatures, packaging effects on the estimated shelf life can be observed: Group 1, i.e., PF-0-0, PF-1-2 and PF- 2-3 provided much longer shelf life than Group 2, i.e., PF-3-1 and PF-4-4. The shelf life obtained for vitamin C with 50% loss (PF-0-0: 22.2 month, PF-1-2: 14.3 month, PF- 2-3 : 11.7 month, PF-3-1: 5.3 month, and PF-4-4: 6.6 month at 23 °C) were comparable to those for $\Delta E = 6$ (PF-0-0: 11.6 month, PF-1-2: 16.7 month, PF- 2-3 : 14.6 month, PF-3-1: 6.5 month, and PF-4-4: 7.3 month at 23 °C), but shelf life obtained for vitamin C with 20% loss were much shorter than 20% loss of L^* or C values. Nevertheless, in this study, no consumers rejected the food samples at the end of 18 months of storage at 23 °C. In addition, 77%–95% of the consumers reported that MATS processed SPP would be a suitable baby food throughout the storage. From the sensory point of view, the shelf life end-point of SPP was not observed within 18 months.

4. Conclusion

Microwave-assisted thermal sterilization had limited impact on color, vitamin C and total β-carotene content of vitamin C-fortified sweet potato puree. During the following storage, significant degradation of color and vitamin C were observed that are dependent on storage temperature and packaging. Packaging also influenced the flavor liking and overall acceptance of the food samples. To the opposite, the total β-carotene content was increased because of the enhanced extractability by thermal process and storage. Reaction rates of color and vitamin C loss remained comparable to the foil pouch when the OTRs of pouches were under 0.3 cc/m^2·day at 35 °C or 0.1 cc/m^2·day at 23 °C. Consumers considered the SPP as qualified baby food till the end of 18-month, however, the effects of barrier properties on consumer sensory evaluation results are not correlated with those for quality indicators. Findings show that extremely high oxygen barrier package can provide similar shelf life lengths as foil package for MATS processed SPP. Further research may explore the influence of packaging on other vitamins, as well as other innovative packaging strategies for stabilize nutrients in MATS processed or other thermally processed foods for over 3 years.

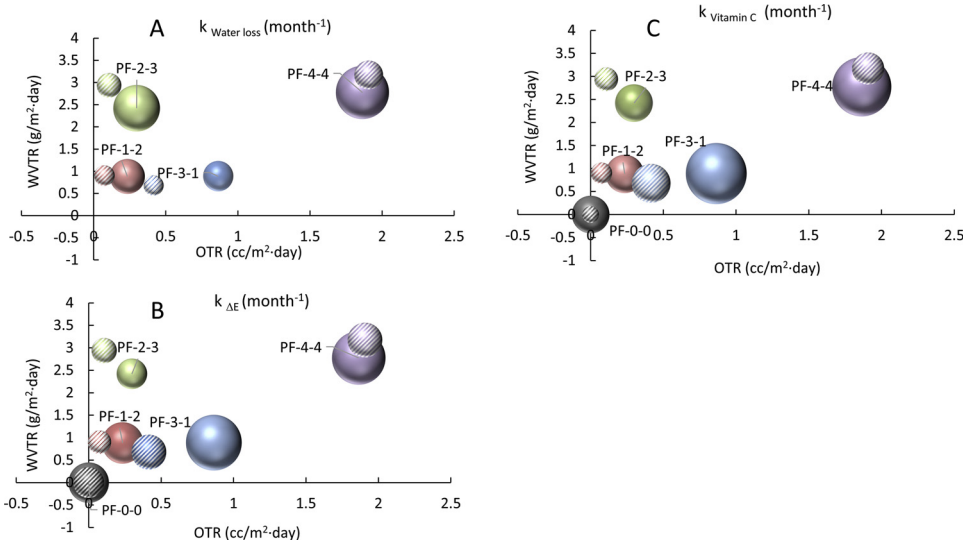

Fig. 4. Correlation of packaging barrier properties (OTRs and WVTRs) with reaction rate constants (k) of water loss (A), total color difference (B) and vitamin C (C). The areas of the bubbles represent values of each reaction rate constant, while the solid and slanted filling balls represent reaction rates at 35 °C and 23 °C, respectively.

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Appendix A. Supplementary data

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