Stability of vitamin C, color, and garlic aroma of garlic mashed potatoes in polymer packages processed with microwave-assisted thermal sterilization technology

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Abstract: The U.S. Army and NASA need ready-to-eat meals with extended shelf-life for military operations and future manned space missions. For traditional heat sterilization methods, aluminum foil laminated pouches are used to achieve a shelf-life of 3 to 5 years at room temperature. However, those packages are not suited for advanced thermal processing technologies based on microwave energy. This research investigated the effect of polymeric packaging materials on storage stability of garlic flavor, vitamin C, and color of garlic mashed potatoes processed with microwave-assisted thermal sterilization (MATS) technology. Three types of high-barrier metal oxide-coated polymer pouches were used for MATS process, designed to achieve lethality approximately $F_0 = 6$ min. Aluminum foil-based pouches were used for retort process as control. Results demonstrated that both oxygen and water vapor barrier properties (oxygen transmission rate [OTR] and water vapor transmission rate [WVTR]) of the polymer pouches were affected by MATS processing. OTR increased by three to nine times, while WVTR increased by 5 to 20 times after processing. The MATS process resulted in 13% to 16% vitamin C loss, while retort process resulted in 18% loss in garlic mashed potato. The kinetics of vitamin C indicated that metal oxide-coated high-barrier packages (after processing OTR <0.1 cc/m^2.day; WVTR <1.0 g/m^2.day) could replace aluminum foil-based pouches for MATS processed shelf-stable ready-to-eat garlic mashed potatoes.

Keywords: garlic aroma, kinetic analysis, metal oxide-coated polymeric pouches, microwave sterilization, shelf-life, vitamin C

Practical Application: Garlic mashed potatoes in polymer packages processed in a microwave-assisted thermal sterilization (MATS) system had better retention of vitamin C compared to samples packaged in aluminum laminated pouches and processed in retort. Polymer packages combined with MATS processing could potentially provide safe, better quality, and nutritious shelf-stable food products for military and space missions.

1. INTRODUCTION

Thermal processing is an effective method to extend the shelf-life of food products. Traditional thermal processes, such as canning, have long processing time and therefore, can reduce the overall sensory quality and nutritional content of the final product (Peng et al., 2017; Rickman, Barrett, & Bruhn, 2007). Advanced thermal processing technologies are needed to fulfill the increasing demand for shelf-stable ready-to-eat (RTE) meals that are convenient, high quality, and nutritious for consumers.

With the advent of advanced thermal processing methods, such as microwave-assisted thermal sterilization (MATS), food products can be processed in shorter times while attaining a similar lethality (Tang, 2015; Zhang, Tang, Rasco, Tang, & Sablani, 2016). This improves food safety, helps retain quality attributes, and extends shelf-life. Studies show that MATS-processed products have higher overall texture, color, and nutrient retention than retort-processed products for the similar target lethality (Patel et al., 2019; Tang, 2015; Zhang et al., 2019). This creates a unique possibility for producing safe and shelf-stable RTE products with superior quality. MATS processing shows promise for preparing RTE meals for extended duration space missions and military purposes. However, MATS is a relatively new method and hence, research is needed to analyze the effects of processing on various nutrients, food quality attributes, packaging materials, and shelf-life.

MATS processing relies on a 915 MHz frequency that delivers microwave radiation to multiple single-mode cavities to attain the target lethality in the prepackaged food (Tang, 2015). Traditional high-barrier packaging materials containing aluminum foil are not suitable for MATS, as they block microwave energy from reaching the food product to achieve the targeted lethality value. High barrier polymer packaging materials are, therefore, used for in-package thermal sterilization in MATS systems (Dhawan et al., 2014; Parhi, Tang, & Sablani, 2020; Zhang et al., 2017). Several polymer-based structures can provide high barrier to water vapor, and most

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A Publication of the Institute of Food Technologists
Journal of Food Science

doi: 10.1111/1750-3841.15366

importantly, to oxygen. For example, polymeric films coated with AlO_x or SiO_x can be used as high barrier packaging for thermal sterilization. Also, multilayer films with oxygen scavengers can be used as high barrier materials for such applications.

All these packaging materials are exposed to relatively high temperature during thermal processing. Therefore, their barrier properties can be adversely affected, which may lead to deterioration in the food texture, color, and nutrients during storage. Zhang et al. (2017, 2019) studied the effect of metal oxide and Ethylene Vinyl Alcohol (EVOH) based packaging and MATS processing on food quality parameters, such as lipid oxidation, vitamin C loss, color degradation, β-carotene content, and sensory analysis in mashed potato and sweet potato puree baby food. Patel et al. (2019) looked into the effects of metal oxide and oxygen scavenger-based packaging on MATS processed mac and cheese by performing vitamin A and E analysis, macaroni texture, color degradation, and sensory analysis to estimate the shelf-life of the recipe. Similarly, Sonar et al. (2020) researched effects of thermal processing and barrier properties of packages on encapsulated vitamin C. Al-Ghamdi, Sonar, Patel, Albahr, and Sablani (2020) investigated the effects of high pressure-assisted thermal sterilization on low acid fruit and vegetable purees by looking into betalains, chlorophyll and anthocyanin pigments, ascorbic acid, and color change quality parameters. Hence, systematic investigation of the effects of MATS processing and high barrier packaging materials is needed on other food quality parameters, such as flavor and aroma retention.

Therefore, for the first time through this study, the effects of thermal processing as well as packages' barrier properties were studied on garlic aroma retention in the recipe. A total of three different metal oxide-coated polymer pouches, including one oxygen scavenger-based pouch, were subjected to MATS processing for sterilization of the garlic mashed potatoes. Aluminum foil-based pouch was used in retort processing for comparison. We also evaluated the kinetics of selected quality parameters of garlic mashed potato during storage for one polymer pouch and the foil pouch at three temperatures, 25, 37.8, and 45 °C. Three replicates of each kind of pouch were analyzed for changes in the vitamin C content, garlic aromatic compound (diallyl sulphide [DAS] content), color, and weight loss. We determined the oxygen and water vapor transmission rates (WVTRs) of film pouches before and after thermal sterilization and at the end of storage.

2. MATERIALS AND METHODS

2.1 Food ingredients, reagents, and chemicals

Potato flakes (Idahoan Original Mashed potato, Idaho Falls, ID, USA) and garlic paste (Shan brand, NW Halal Meats Store, Pullman, WA, USA) were used in the garlic mashed potatoes recipe. Other ingredients, such as white ground pepper and parsley flakes, were procured from McCormick & Company Inc. (Hunt Valley, MD, USA). Kraft Philadelphia cream cheese, Mortan noniodized salt, and Crisco vegetable oil were purchased from a local Walmart store. This recipe was fortified with vitamin C (ascorbic acid, pure powder, Now Foods Co., Bloomingdale, IL, USA).

Other chemicals for analysis, such as vitamin C (L-ascorbic acid, BioXtra, >99%), DAS (>96.5%), polydimethylsiloxane/divinylbenzene (PDMS/DVB)-coated fiber, and metaphosphoric acid, were purchased from Sigma-Aldrich Co. (St. Louis, MO, USA). Potassium phosphate was purchased from Fisher Scientific Co. (Fair Lawn, NJ, USA). Butylated hydroxytoluene was obtained from Acros Organics (Geel, Belgium). Hexane, ethanol, acetone, and phosphoric acid were purchased from Avantor Performance Materials (Center Valley, PA, USA).

2.2 Preparation of garlic mashed potato

The recipe was developed and provided by the U.S. Army Natick Soldier Center (Natick, MA, USA). At first, salt and vitamin C were mixed thoroughly in the 12 L water for 5 min at a constant speed of 107 rpm using A200 Hobart mixer in 20 L stainless steel bowl using a flat beater (Hobart GmbH, Offenburg, Germany). Next, cream cheese and white pepper were added to form a smooth slurry. After the cream, cheese was mixed properly in the water, the oil and garlic paste were added, followed by the potato flakes. Flakes were added slowly into the mixture and mixed for 10 min. Finally, parsley flakes were added and mixed thoroughly for another 5 min. The recommended dietary allowance of vitamin C is 90 mg/day for men (Institute of Medicine, 2000). Since vitamin C is very susceptible to temperature and degrades easily due to the oxidation during storage, this recipe was fortified with 600 mg vitamin C per kg of the garlic mashed potato (wet basis) to retain at least 50% of initial vitamin C content in the food by the end of shelf-life.

2.3 Packaging in high gas barrier pouches

Three multilayer polymer packages (P1, P2, and P3) were used for MATS processing and one aluminum foil-based package (AL) for the retort processing. All polymer packages had a metal oxide-coated polyethylene terephthalate as an oxygen barrier layer. P1 was a clear (transparent to visible light) pouch, while pouch P2 had printed label on the outer surface and pouch P3 was opaque. P3 had an oxygen scavenging layer in addition to the metal oxide coating (Patel et al., 2019; Mitsubishi Gas Chemical America, New York, NY, USA). As polymer packages do not provide zero permeation of gases and water vapor, aluminum foil-based packaging was used as a control to compare the performance of polymer pouches during storage.

The thickness of the multilayer films was measured with an electronic disk micrometer (Model 15769, Flexbar Machine Co., Islandia, NY, USA) at three different positions (center, side, and bottom). Details are listed in Table 1 for the multilayer packages studied. Before processing, pouches P1, P2, P3, and AL were filled with 227 ± 1 g of garlic mashed potato and degassed two to three times at 0.6 bar for 8 to 9 s prior to sealing to remove the entrapped air. Vacuum sealing was conducted using Easy-Pack (UltraSource. LLC, Kansas, MO, USA), with a sealing time of 2.5 to 5 s and temperatures of 180 to 200 °C, depending on the type and thickness of the package.

The oxygen transmission rate (OTR) and WVTR of the polymeric films were measured using an oxygen permeation analyzer (Mocon Ox-Tran 2/21 MH, Modern Control, Minneapolis, MN, USA) at 23 °C, 55% RH, and 1 atm and a water vapor permeation analyzer (Mocon Permatran 3/33, Modern Control) at 100% RH and 38 °C, respectively, following the method of Dhawan et al. (2014). Duplicate film samples were measured before and after MATS processing, and at the end of storage at 37.8 °C.

2.4 Thermal processing and storage

The single-mode MATS pilot system (25 kW and 915 MHz) at Washington State University was used to process the food samples. A detailed description of MATS is provided in Tang (2015). In this study, the MATS processing conditions for the garlic mashed potato recipe were developed by measuring the temperature at the cold spots using precalibrated mobile temperature sensors. The

Table 1–Details of package label, structure, dimension, and thickness of multilayer pouches used.

Package	Structure	Dimensions (L x W)(mm)	Total thickness (µm)
P1	PET//AlO_x//GL coating 12 µm//OPA 25 µm//CPP 50 µm	185 × 130	110
P2	AlO_x PET12 µm//OPA15 µm//CPP70 µm	180 × 140	112
P3	PET//PA//AlO_x//MXD6//EVOH//Iron-based oxygen absorbent agents//PP	185 × 130	114
AL	PET 12 µm//aluminum 9 µm//nylon 15 µm//PP 80 µm	210 × 120	120

(//) indicates a tie layer in between.

processing conditions were: preheating at 60 °C for 25 min; microwave heating for 3.7 min at 121 °C; holding time in circulation water for 3.8 min at 121 °C; cooling in tap water for 5 min at 20 °C; and system pressure at 35 psig. The average lethality obtained at the cold spot was found to be $F_o = 8.26 \pm 2.38$ min. A total of 200 pouches of garlic mashed potato were processed using the MATS system.

Since the MATS system is not compatible with aluminum foil packages, a retort system (Gentle Motion, 38, AllPax Products LLC, Covington, LA, USA) with a water-spray mode was used to sterilize the garlic mashed potatoes in the aluminum foil (AL) pouches, which served as control in this study. A total of 75 AL pouches containing garlic mashed potatoes were processed at the U.S. Army Natick Soldier Research, Development and Engineering Center (NSRDEC) at Natick, MA, USA. The processing conditions were: come-up time of 11 min; cooking time of 50 min at 116.6 °C; pressure cooling time of 42 min till 20.4 °C and system pressure at 22 psig. The average calculated lethality at the cold spot was $F_o = 10.5 \pm 3.3$ min.

The processed pouches (P1, P2, P3, and AL) were stored in a closed incubator, KB055 (Darwin Chambers, Saint Louis, MO, USA), set at 37.8 ± 0.2 °C for the accelerated shelf-life study for 6 months to simulate the storage at 25 °C for 3 years (Robertson, 2016). Pouches P1 and AL were also stored at 25 °C for 12 months and 45 °C for 2 months to obtain data for kinetic analysis of color and vitamin C, and to predict the shelf-life.

2.5 Weight loss

Since polymeric pouches have a finite water vapor barrier property, some weight loss in the packages was expected during storage. The weight of the pouches ($n = 3$) was measured each month during storage using a simple balance scale (model GK703, Sartorius, Goettingen, Germany).

2.6 Quantification of vitamin C

Quantification of vitamin C was performed using an Agilent 1100 high-performance liquid chromatography system (HPLC; Agilent Technology, Santa Clara, CA, USA) with a 250 mm 5 µm XTerra C18 column (Waters Corporation, Milford, MA, USA) and a diode array detector. The vitamin C content was determined following the method of Zhang et al. (2019), with no modifications. This was measured at a 250 nm wavelength.

2.7 Garlic volatile analysis: DAS

Garlic is a common flavoring agent with antioxidative properties. To identify the major volatile components of garlic in the garlic mashed potato, headspace solid-phase microextraction and gas chromatography (HS-SPME-GC) with mass spectrometry technique was used. Agilent HP 6890, fitted with 0.32 mm × 60 m, 1 µm thickness DB-1MS column (Phenomenex, Torrence, CA, USA) coupled to an HP 5973 Mass Selective Detector was used to analyze the samples. Volatile compounds were extracted using a 65 µm PDMS/DVB fiber and then identified by comparing the MS spectra against an NIST 129K-NBS library. DAS compound was detected in the sample. This compound comes from the decomposition of allicin under heat treatment. DAS was then quantified with a flame ionization detector using the external standard method (Ettre, 1993).

The sample was prepared by mixing the pouch well before opening and then taking 3 g of garlic mashed potato sample in a 15 mL headspace glass vial with a screw top and Teflon-faced silicon septa. Next, 1 g sodium chloride and 3 mL DI water were added to the glass vial. A magnetic stirrer was used to constantly vortex the solution at 3,000 to 4,000 rpm for 60 min to obtain a maximum absorption of garlic volatiles on the fiber. Fiber was desorbed for 3 to 4 min at 250 °C in the injection inlet operating on the splitless mode. Helium was used as a carrier gas flowing at 0.7 mL/min. The oven temperature was programmed to hold at 33 °C for 5 min, increase at 2 °C/min to 50 °C, and then at 5 °C/min to 250 °C. The mass spectrometer operated at a 70 eV (150 °C ion source) electron impact mode. Values reported were obtained from the average of three analyses ($n = 3$).

2.8 Color measurement

Color parameters ($L^\star$ lightness, $a^\star$ +Red to − Green, $b^\star$ + Yellow to − Blue) were measured using a CM-5 spectrophotometer (Konica Minolta, Ramsey, NJ, USA) to detect color change in the garlic mashed potato after thermal processing and during storage. The browning index (BI) value is defined as brown color purity and is a common indicator of browning in food products (Buera, Lozano, & Petriella, 1986). The total color difference (ΔE) indicates the magnitude of color difference between stored and control samples (Patras, Brunton, Tiwari, & Butler, 2011). The ΔE and BI values were calculated using $L^\star$, $a^\star$, and $b^\star$ values (Subhashree, Sunoj, Xue, & Bora, 2017), as follows:

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

$$BI = [100\,(x - 0.31)]\,/0.172 \tag{2}$$

where:

$$x = \frac{a^* + 1.75L^*}{5.645L^* + a^* - 3.012b^*} \tag{3}$$

Approximately 50 to 60 g sample was taken in a petri-dish, and the spectrophotometer was set to the reflectance mode, with Specular Component Excluded (SCE).

2.9 Data analysis

Data were analyzed with OriginPro8 (OriginLab, Inc., Northampton, MA, USA) and JMP 13.0.0 (SAS Institute Inc., Cary, NC, USA) using pairwise Tukey's honestly significant difference method between the means at $\alpha = 0.05$. Chemical degradation kinetics were performed using the general rate law (Eq. 4), 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 (Robertson, 2016):

$$-\frac{dA}{dt} = kA^{n} \tag{4}$$

The shelf-life extrapolation of garlic mashed potato was based on nutrition degradation. Depending on the reaction order identified through Eq. 4, the reaction rate at 25, 37.8, and 45 °C and corresponding Q_{10} values were determined using the following equation (Labuza & Schmidl, 1985):

$$Q_{10} = \left(\frac{k_2}{k_1}\right)^{\frac{10}{T_2 - T_1}} \tag{5}$$

where k_1 and k_2 are reaction rate constants at temperatures T_1 and T_2 (°C), respectively.

3. RESULTS AND DISCUSSION

3.1 Oxygen and water vapor transmission rates

The OTRs of packages P1 and P2 were 0.04 and 0.01 cc/m^2·day, respectively, before MATS processing. After MATS processing, the OTR increased by three to five times. The OTR of P3 (oxygen scavenger package) was not measured before and after processing due to the presence of active oxygen scavenging elements that absorb oxygen upon permeation. During storage at 37.8 °C for 6 months, the OTR of pouch P1 increased by three times and OTR of P2 increased by four times compared to the after MATS processing values. For P3, the OTR was measured only after the storage period, and was the highest of all pouches (Table 2).

All polymeric pouches with a barrier layer of aluminum oxide coating developed defects, such as cracks and pinholes, due to thermal and mechanical stresses. The change in OTR may be due to a higher permeation of oxygen through these defects, leading to an overall increase in OTR of these films. Similar results have been reported by others (Byun, Bae, Cooksey, & Whiteside, 2010; Parhi, Bhunia, Rasco, Tang, & Sablani, 2019; Struller, Kelly, & Copeland, 2014; Zhang et al., 2017).

The WVTR for all three polymeric pouches significantly increased ($P < 0.05$) because of thermal processing. However, the moisture barrier properties of pouches P2 and P3 recovered (WVTR decreased) at the end of the 6-month storage, while the WVTR of P1 showed no significant change ($P > 0.05$). The moisture barrier properties in polymeric films possibly deteriorated due to the defects in the metal oxide coating (Zhang et al., 2017), as well as the interaction between the water molecules and coating (Henry et al., 2001). The presence of the hydrophobic polypropylene (PP) layer and the properties of packaged food may also have contributed to the moisture barrier properties of the films (Zhang et al., 2017).

Table 2–Oxygen transmission rate (OTR) and water vapor transmission rate (WVTR) of polymer pouches before and after MATS processing (n = 3).

Package	OTR(cc/m^2.day)			WVTR(g/m^2.day)		
	Before processing	After processing	After storage @37.8 °C/6 months	Before processing	After processing	After storage @37.8 °C/6 months
P1	0.04 ± 0.00^a	0.12 ± 0.01^b	0.35 ± 0.04^c	0.21 ± 0.00^a	0.83 ± 0.08^b	0.69 ± 0.05^b
P2	0.01 ± 0.00^a	0.05 ± 0.01^b	0.20 ± 0.03^c	0.25 ± 0.02^a	0.81 ± 0.00^b	0.48 ± 0.08^c
P3	N.A.	N.A.	0.48 ± 0.10*	0.31 ± 0.05^a	7.19 ± 0.32^b	6.26 ± 0.32^c

Values with the same small subscription letter are not significantly different from each other at ($P > 0.05$) comparing process influence between columns. N.A. = not applicable because of the oxygen scavenging elements present in the package.
*This value is taken after oxygen scavenging elements were saturated.

3.2 Weight loss

The weight loss in the samples packaged in all the polymer pouches increased with storage time at 37.8 °C (Figure 1). The

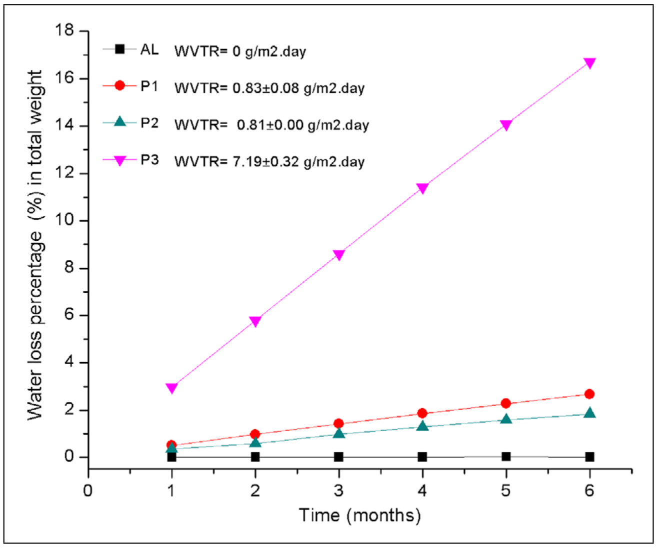

Figure 1–Weight loss in all the pouches during the storage time at 37.8 °C ($n = 3$).

samples in the aluminum foil pouch (AL) showed no significant ($P > 0.05$) weight loss, while the sample in pouches P1 and P2 lost 2.7% and 1.9% of their weight, respectively. The highest weight loss (16.7%) was observed in pouch P3. Over the 6 months of storage, pouches with high WVTR lost more weight during storage due to moisture migration from the food to the atmosphere (Dhawan et al., 2014). At the end of storage, the weight loss percentage in the P3 differed significantly ($P < 0.05$) from the other pouches. Patel et al. (2019) also reported a weight loss of around 16% in pouches (WVTR of 7.19 g/m^2.day) stored at 37.8 °C for 6 months. For pouch P1, stored at 25 and 45 °C, there was 2.5% weight loss at both the temperatures. This indicates that to preserve food texture and color and to minimize weight loss in the packaged foods, a high-water vapor barrier (lower WVTR) in the pouches may be essential.

3.3 Vitamin C

Vitamin C is prone to degradation during processing and storage since it is highly susceptible to heat treatment and oxidation. In this study, the vitamin C content in garlic mashed potato before processing was 172 ± 15.5 mg/100g d.b., after retort processing, it was reduced to AL (141 ± 2.43 mg/100g d.b.), and after MATS, it was reduced to: P1 (150 ± 1.00 mg/100g d.b.), P2 (144 ± 0.99 mg/100g d.b.), and P3 (144 ± 1.30 mg/100g d.b.) (Table 3). The average loss in vitamin C was 13% to 16% after MATS processing and 18% after retort processing. Vitamin C loss depends highly on food matrix. Zhang et al. (2019) reported an 8% loss in vitamin C in sweet potato puree after MATS processing for an average lethality of 7.6 min.

Vitamin C content decreased significantly ($P < 0.05$) in all the pouches at the end of the storage including control. During the first 3 months of storage, the vitamin C content did not change significantly in MATS processed pouches, except P1 ($P > 0.05$) (Table 4). This can be attributed to the protective effect of sulfur compounds in the garlic due to their antioxidant activity (Horita et al., 2016; Petropoulos et al., 2018). At the end of 6 months of storage at 37.8 °C, there was an average 25% to 35% loss of initial vitamin C (compared to month 0) in all the pouches with no significant difference ($P > 0.05$) between the polymer and AL pouches. According to Zhang et al. (2019), high barrier polymer pouches (OTR = 0.23 and 0.29 cc/m^2.day at 35 °C) lost 70% and 79% of the original content of vitamin C in sweet potato puree, respectively, compared to 79% loss in the AL pouch after 6 months of storage at 35 °C. At 23 °C after 12 months storage, the same polymer pouches lost 29% to 32% vitamin C, compared to a 30% loss in AL pouch.

In a study, Cooper, Perchonok, and Douglas (2017) found a 32% to 83% of vitamin C loss in different fruit products, processed and packaged in aluminum foil pouches, and stored at 21 °C for 3 years. In this study, at 25 °C after 12 months storage, the AL pouch and P1 pouch lost almost similar quantity (approximately25%) of vitamin C and (approximately21% to 27%) at 45 °C after 2 months of storage. There was no significant difference ($P > 0.05$) among the polymer and AL pouches at both the temperatures at the end of the storage. This indicates that the vitamin C degradation rate is highly dependent on the food matrix and storage temperature.

3.4 Garlic volatile analysis: DAS

The garlic volatile content, DAS, decreased by 58% after thermal processing, regardless of the processing method. There was no significant difference ($P > 0.05$) in the DAS concentration of MATS and retort processed garlic mashed potato. Figure 2 depicts the changes in DAS content in processed pouches over a 4-month storage at 37.8 °C. No quantification was conducted at 25/45 °C for this quality parameter.

The initial content of DAS in pouches AL, P1, P2, and P3 was 40.53 ± 9.8 μg/kg, 26.0 ± 2.93 μg/kg, 25.62 ± 4.41 μg/kg, and 34.78 ± 4.91 μg/kg, respectively. This initial content differed significantly ($P < 0.05$) from the content at 1 month's storage at 37.8 °C but was stable during the remaining storage time. The highest loss of this sulfur compound occurred during the initial

Table 3–Vitamin content and food quality attributes of garlic mashed potato before and after processing at 37.8 °C ($n = 3$).

Attributes	Before process(Fresh)	Retort F_o = 10.5 min	Microwave-assisted thermal sterilization (MATS) F_o = 8.26 min		
		AL	P1	P2	P3
Vitamin C (mg/100 g mash potato on dry basis)	172 ± 15.5^a	141 ± 2.43^b	150 ± 1.00^c	144 ± 0.99^b	144 ± 1.30^b
Diallyl sulfide (μg/kg)	62.7 ± 3.09^a	40.5 ± 7.01^b	26.0 ± 2.39^b	25.6 ± 3.60^b	34.8 ± 4.01^b
Lightness (L^*)	69.7 ± 0.19^a	67.7 ± 0.37^{bc}	68.7 ± 0.60^{ab}	65.9 ± 2.69^c	69.2 ± 0.08^{ab}
Redness (a^*)	−3.12 ± 0.04^a	−2.10 ± 0.05^b	−2.24 ± 0.04^b	−1.81 ± 0.39^c	−2.36 ± 0.08^b
Yellowness (b^*)	5.29 ± 0.31^a	9.16 ± 0.31^b	8.20 ± 0.52^b	8.98 ± 0.47^b	8.43 ± 0.42^b
Browning index (BI)	4.33 ± 0.78^a	11.7 ± 0.65^b	9.85 ± 0.62^c	12.1 ± 1.04^b	10.0 ± 0.60^c

Values with small letters subscription in the same column are not significantly different from each other at ($P > 0.05$) and values after ± sign indicate standard deviation

Table 4–Vitamin C content (mean ± standard deviation) in garlic mashed potato in different pouches during 6-month storage at 37.8 °C (n = 3).

Time (months)	Vitamin C Content (mg/100 g garlic mashed potato dry basis)			
	AL	P1	P2	P3
0	141 ± 2.43^{aA}	150 ± 1.00^{bB}	144 ± 0.99^{aA}	144 ± 1.30^{aA}
1	143 ± 1.73^{aA}	157 ± 21.7^{aABC}	138 ± 31.3^{aABC}	152 ± 20.8^{aAB}
2	132 ± 7.83^{bA}	157 ± 1.13^{aA}	143 ± 11.4^{abA}	139 ± 5.14^{bA}
3	125 ± 7.18^{aAB}	140 ± 7.82^{aAB}	136 ± 9.77^{aAB}	118 ± 26.9^{aAB}
5	84.8 ± 1.21^{aC}	81.0 ± 7.89^{aD}	85.7 ± 1.77^{aC}	88.9 ± 20.8^{aAB}
6	106 ± 3.50^{aB}	98.9 ± 4.07^{aCD}	103 ± 5.52^{aBC}	93.6 ± 5.51^{aB}

Values with the same capital letter subscription letter are not significantly different from each other at (P > 0.05) comparing time influence between rows, small letters are comparing between packages in each column at (P > 0.05), and ± sign indicates standard deviation.

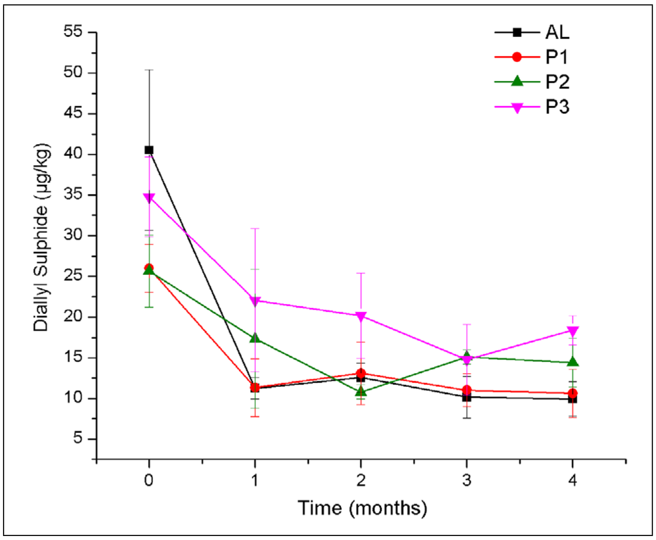

Figure 2–Changes in diallyl sulphide content in different packages during 4-month storage at 37.8 °C (n = 3).

storage period. This may be due to degradation in the antioxidative properties of the DAS by the residual air in the headspace of each pouch. This may also be due to the interaction of the DAS and vitamin C's antioxidative properties, which inhibited early decomposition of vitamin C during storage. In a study, authors evaluated the concentration of sulfur compounds in irradiated samples in polyethylene bags (OTR = 2,300 mL/m^2/24 hr at 22.7 °C) during the 7-day storage period, stored at 4 °C. They found that within 7 days of storage, 66% of the DAS was lost (Yang et al., 2011). In another study, Arora, Hansen, and Armagost (1991) studied the sorption of aldehydes, methyl ketones, methyl esters, alkylpyrazines, and sulfur compounds by PP. Round PP disks were immersed in a buffer solution containing flavor compounds for 24 hr at room temperature. Then, the flavor compound retention in the buffer was quantified using GC. Sulfur compounds absorbed by the PP ranged from 38% to 48%. All the pouches used in this study have a PP layer as the food contact layer. The sorption of garlic aromatic compound, DAS, was also quite possible during the storage.

Statistical analysis showed that the DAS content in AL pouches at the end of storage was similar (P > 0.05) to the samples in P1, P2, and P3 pouches. This suggests that the polymeric pouches tested in this study were effective in retaining the DAS compound, similar to that of AL packaging.

3.5 Color

The lightness L^* of fresh garlic mashed potato (69.7 ± 0.19) decreased significantly (P < 0.05) after retort processing in AL (67.7 ± 0.37). There was no significant change (P > 0.05) in P1 (68.7 ± 0.6) and P3 (69.2 ± 0.08). However, a significant difference (P < 0.05) was noted in P2 (65.9 ± 2.69) after MATS processing (Table 3). The lightness in pouch P2 showed a higher standard deviation, possibly due to poor mixing of the sample before opening the package. The redness a^* and yellowness b^* of the garlic mashed potato changed significantly (P < 0.05) after both thermal processes in all pouches. There was reduction in the a^* value of the sample, but an increase in b^*. This may be due to nonenzymatic browning during thermal sterilization. Figure 3 displays acquired images of all pouches just after processing and at the end of 6 months of storage.

Figure 4 shows changes in the BI and total color difference ΔE in garlic mashed potato during storage at 37.8 °C for 6 months. BI for each pouch changed significantly (P < 0.05) after 6 months. In pouch P1, BI changed from 9.84 to 17.71, while in P2, it increased from 12.21 to 18.22. Similarly, in P3, BI changed from 9.99 to 22.5 and lastly in AL 11.7 to 18.59. At the end of storage, the sample in pouch P3 showed a significantly higher BI than all the other pouches (P < 0.05). This could be due to higher OTR and WVTR of the pouch, leading to an increased oxidation and water loss in the packaged food product. This in turn may have led to browning. The BI values in P1 and P2 were not significantly different (P > 0.05) compared to AL at the end of 6-month storage. At 45 °C, pouch P1 had a significantly (P < 0.05) lower (14.7) BI than AL (17.9) after 2 months, whereas at 25 °C after 12 months, the BI values were 15.54 and 14.63 for P1 and AL, respectively.

The ΔE showed a significant difference (P < 0.05) in its value at the end of the accelerated shelf-life storage at 37.8 °C (Figure 4). The ΔE value reached 3.2, 4.5, 5.7, and 3.7 for pouches P1, P2, P3, and AL, respectively. According to the scale adapted from Wang et al. (2014), $3 < \Delta E < 6$ is considered as a perceptible difference, while $6 < \Delta E < 12$ is considered as a strong difference. The color difference values were less than 6 in all pouches, which indicated that the color of the food sample did not change much over the storage time. This may be due to the addition of vitamin C, which acted as an antibrowning agent (Gunes & Lee, 1997), and phenolic compounds from the garlic puree, which inhibited oxidation and prevented nonenzymatic browning of garlic mashed potato during initial storage time. At 25 °C, color difference values (2.24 and 2.42) of both P1 and AL, respectively, were similar (P > 0.05), whereas at 45 °C, there was significant difference (P < 0.05) in P1's ΔE value (2.72) compared to AL (3.12). Zhang, Bhunia, et al. (2016) observed a similar trend of color change and

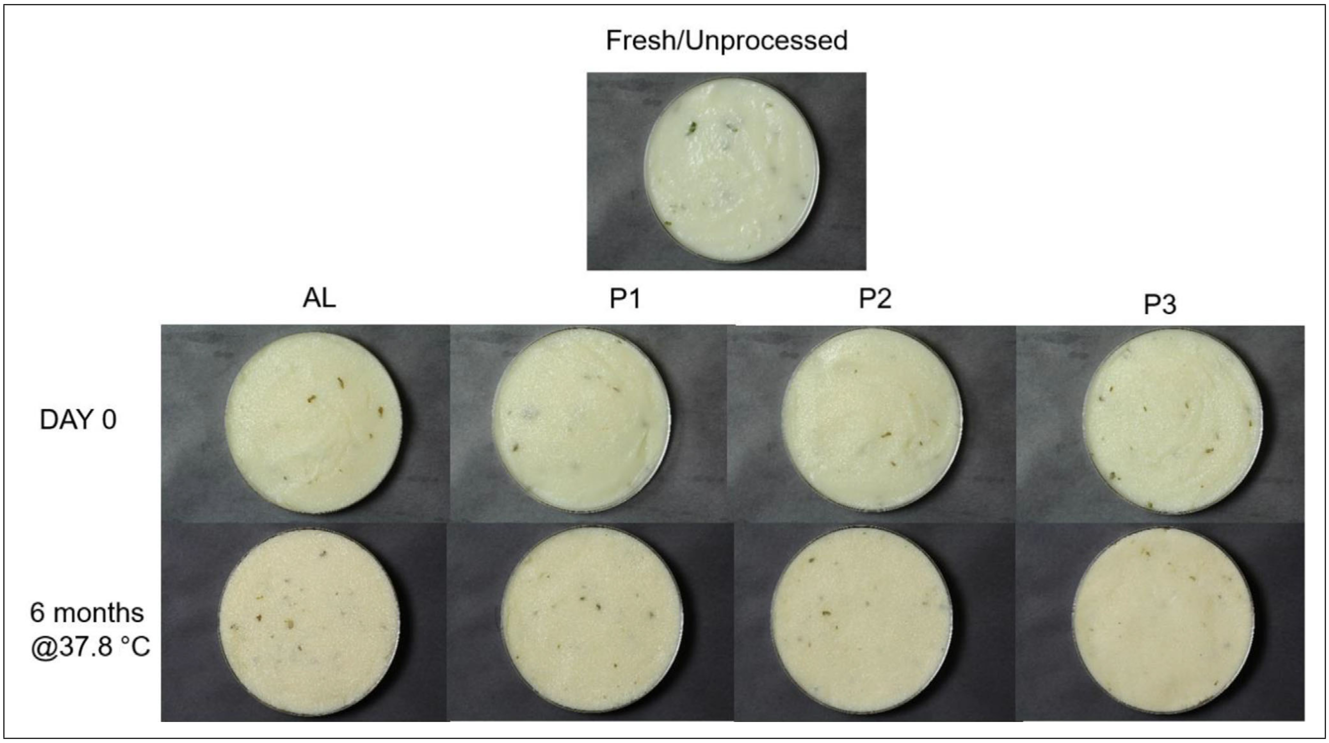

Figure 3–Color of garlic mashed potato before process (fresh), after process (day 0), and after 6-month storage at 37.8 °C in all the pouches.

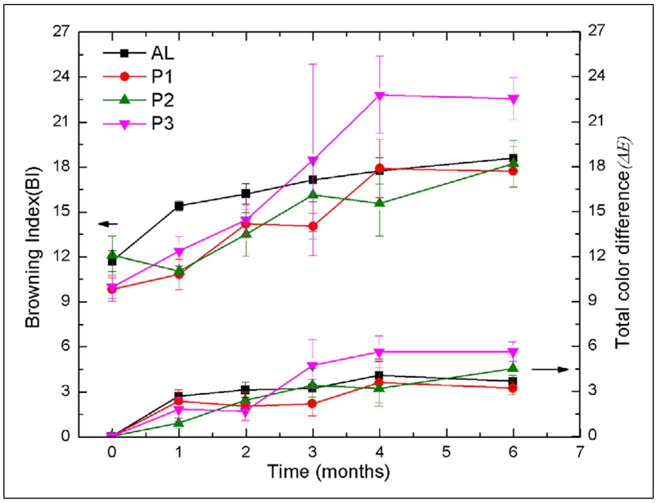

Figure 4–Changes in total color difference (ΔE) and browning index (BI) in garlic mashed potato during 6 months of storage at 37.8 °C ($n = 3$).

browning in MATS processed mashed potatoes in polymeric pouches with an OTR of 0.07 to 2.11 cc/m^2.day and stored at 50 °C for 2.8 months.

3.6 Kinetic analysis and shelf-life extrapolation

The reaction rate constants of the BI, vitamin C, and color parameters $a^\star$ and $b^\star$ were calculated based on the best fitting model (Table 5). Figure 5 and 6 display the changes in *BI* and vitamin C during storage in AL and P1 pouches at three temperatures. Vitamin C degradation was best fitted with the first-order model with a correlation coefficient (R^2) ranging from 0.86 to 0.98 for both AL and P1 pouches. A similar fit of the model for vitamin C was found for dehydrated potato (Mcminn & Magee, 1997) and sweet potato puree (Zhang et al., 2019). *BI*, $a^\star$, and $b^\star$ followed a zero-order reaction rate, which corresponded with a previous study conducted on mashed potatoes (Zhang, Tang et al., 2016). Table 5 indicates the poor fit of the zero-order model in the AL pouch at 25 °C for *BI*, $a^\star$, and $b^\star$. This may be because there was no permeation of oxygen and water vapor, and due to the lower storage temperature, leading to slower chemical reaction rates. Similar results were found by Zhang et al. (2019) in sweet potato puree packaged in high barrier pouches. As expected, higher reaction rates were obtained at 37.8 and 45 °C than at 25 °C.

Shelf-life extrapolation of this recipe was done using two quality indicators (*BI* and vitamin C, see Table 6). In this study, 50% vitamin C loss and BI_{max20} and BI_{max25} were set as endpoints. Several studies have considered color darkening in starch products as a parameter to determine shelf-life (Goddard, 1994). Catauro and Perchonok (2012) estimated the shelf-life of home-style potatoes as 48 months at 22 °C in aluminum foil pouch based on flavor change via oxidative degradation. $\Delta E = 6$ is considered as a strong difference in color and has been used as an endpoint in determining the shelf-life of vegetable-based puree (Zhang et al., 2019).

In this study, $\Delta E = 6$ was used as a reference to calculate *BI* values of both AL and P1 pouches at all three temperatures, ranging from 18 to 25. Therefore, the *BI* maximum values of 20 and 25 were set as shelf-life endpoints. Based on 50% loss of initial value of vitamin C in AL at 25 °C, the shelf-life of garlic mashed potato was estimated to be 24.1 and 24.2 months for AL and P1 pouches, respectively. At higher storage temperatures, the shelf-life of polymer pouch P1 was longer than the AL pouch. Since this may depend on properties of the food sample, further research is needed to determine why the vitamin C degradation rate is lower at high temperature storage in polymeric pouch than the aluminum foil-based pouch. The Q_{10} value reported in Table 6 is between 25 and 45 °C and represents the reported range of

Table 5–Degradation reaction rates of browning index, vitamin C, a^* and b^* in garlic mashed potato during storage.

			k (R^2) month^{-1}	
Quality indicator	**Fitting model**	**Storage temperature**	**AL**	**P1**
Browning index	Zero order	25 °C	0.169 (0.291)	0.445 (0.881)
		37.8 °C	0.914 (0.724)	1.379 (0.915)
		45 °C	3.123 (0.981)	4.392 (0.697)
Vitamin C	First order	25 °C	−0.029 (0.964)	−0.030 (0.911)
		37.8 °C	−0.100 (0.864)	−0.078 (0.900)
		45 °C	−0.182 (0.910)	−0.111 (0.980)
Color a*	Zero order	25 °C	0.063 (0.338)	0.071 (0.739)
		37.8 °C	0.264 (0.839)	0.235 (0.945)
		45 °C	0.031 (0.957)	0.030 (0.856)
Color b*	Zero order	25 °C	0.084 (0.355)	0.231 (0.838)
		37.8 °C	0.432 (0.632)	0.694 (0.870)
		45 °C	1.194 (0.950)	1.131 (0.431)

*Values in brackets indicated the correlation coefficient R^2 for each model fitting for different treatments.

Table 6–Shelf-life extrapolation based on vitamin C loss and browning index.

		Shelf-life (months)			
		Vitamin C loss Browning index			
Package	**Storage temperature (°C)**	**20%**	**50%**	**BI_{max20}**	**BI_{max25}**
AL	25	7.83	24.1	38.0	63.63
	37.8	2.91	7.62	6.61	12.08
	45	1.22	3.80	2.57	4.18
	Q_{10}	*2.50*		*4.29*	
P1	25	8.30	24.2	23.4	34.63
	37.8	3.71	9.74	7.15	10.78
	45	2.00	6.24	2.01	3.16
	Q_{10}	*1.94*		*3.14*	

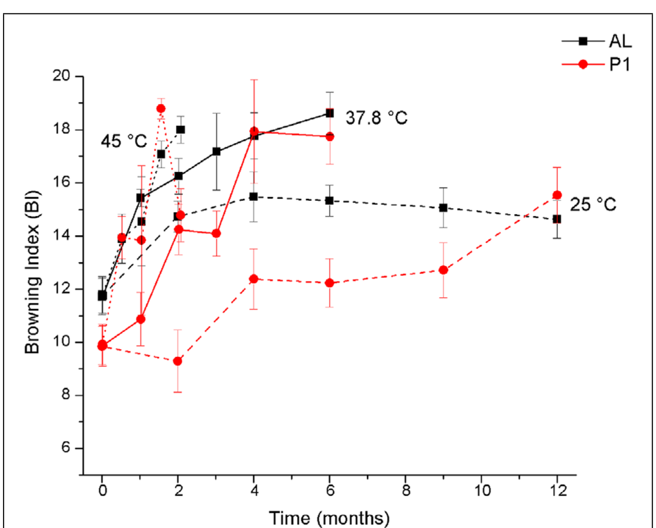

Figure 5–Browning index changes in aluminum foil (AL) and polymer (P1) packages at three temperatures during storage.

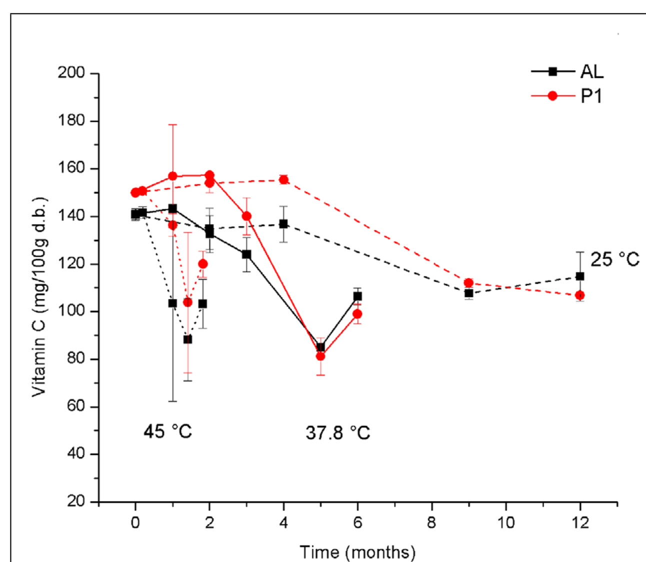

Figure 6–Vitamin C changes in aluminum foil (AL) and polymer (P1) packages at three temperatures during storage.

thermal stabilized products (Robertson, 2016), except for the *BI* in the AL pouch. This is due to a poorer fit of the zero-order model, as explained above. The higher Q_{10} value in AL than P1 indicates that temperature plays a key role in degradation of vitamin C and color since there is no permeation in aluminum foil-based pouches. This indicates that polymer pouches with high barrier properties could replace aluminum foil pouches for a similar shelf-life.

4. CONCLUSION

In this study, we found that thermal sterilization increased the OTR and WVTR of metal oxide-coated polymeric packages, while oxygen scavenging packaging had the highest OTR and WVTR of all packages studied. The weight loss in garlic mashed potato samples during storage correlated well with the WVTR of pouches. Thermal processing resulted in a 13% to 18% loss in vitamin C and more than a 50% loss in DAS concentration. The retention of garlic aroma (i.e., concentration of DAS) in polymeric pouches was similar to that of foil packaging. The total color change (ΔE) of recipe in high barrier pouches (P1 and P2) during storage was similar to the AL pouch, but the higher OTR and WVTR of pouch (P3) resulted in a higher ΔE. The vitamin C degradation rate in the food sample was higher in AL pouch than the polymeric pouch (P1) when stored at 45 °C. The shelf-life of this recipe based on a 50% loss of processed vitamin C at 25 °C was similar for the AL and polymeric pouch (P1), that is, 24 months. This study's findings indicate that high barrier pouches with initial OTR <0.1 cc/m^2.day; WVTR < 1.0 g/m^2.day are a promising alternative to foil pouches to extend the shelf-life of garlic mashed potato recipe. For future, focus could be on testing two or three metal oxide-coated layer packages with MATS technology. These coatings could provide extra protection to flavor and aroma retention during thermal processing and storage.

ACKNOWLEDGMENTS

This work was supported by the USDA National Institute of Food and Agriculture Research grants #2016-67017-24597 and #2016-68003-24840, and Hatch project #1016366. The authors would like to thank Dr. Zhongwei Tang for his technical help. In addition, the authors would like to thank Toppan Printing Co, LTD. (Japan) and Mitsubishi Gas Chemical America (NY) for providing packaging materials.

AUTHORS CONTRIBUTIONS

All authors participated in designing the research. J. Patel and A. Parhi performed the experiments and drafted first draft of the manuscript. S. Al-Ghamdi, C. Sonar, and D. Mattinson participated in analyzing the data and interpretation of the results. T. Yang, J. Tang, and S. Sablani participated in editing the manuscript. All authors approved the final manuscript.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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