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Shelf-life modeling of microwave-assisted thermal sterilized mashed potato in polymeric pouches of different gas barrier properties

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ABSTRACT

This study investigated how the shelf-life of foods processed with microwave-assisted thermal sterilization (MATS) is affected by temperature and package gas barrier properties. We conducted accelerated shelf life testing of a mashed potato-based model food processed with MATS. The model food was processed to a lethality of $F_0 = 9.0$ min, packaged in four pouch materials with different oxygen transmission rate (OTR) and water vapor transmission rate (WVTR), and then stored at 23 °C, 37 °C and 50 °C for up to 12, 6, and 2.8 months, respectively. Findings showed that there were significant temperature effects and the combined effects of OTR and WVTR on the food color (ΔE). Moisture loss and lipid oxidation were also affected by package over the storage periods. Shelf-life predictions were based on the model at different temperatures and OTRs (23 °C storage) using $\Delta E = 12$ as the end point for acceptable quality, with Q_{10} values ranged from 2.85 to 3.15. The results provide valuable information for selecting packaging materials for MATS and other thermally processed foods.

1. Introduction

Microwave-assisted thermal sterilization (MATS) has the potential to produce food with a higher quality and longer shelf-life. Fast volumetric heating created by microwave reduces the time for the product to reach desired processing temperature and the overall processing time (Guan et al., 2003). Process validation has been conducted using a 10-kW 915-MHz microwave sterilization system and single-mode cavity for 7-oz to 13-oz food trays or 8-oz pouches (Tang et al., 2006). Subsequently, the MATS has been accepted by the Food and Drug Administration (FDA) for prepackaged commercial sterilization of homogeneous and non-homogeneous foods (Tang, 2015). MATS has also received a non-objection notification from the Food Safety and Inspection Service (FSIS) of the USDA for production of shelf stable foods (Tang, 2015).

Several studies on system design and validation studies show that MATS can produce safe shelf stable food. Early studies focused on how quality was influenced by MATS vs. retort processing under the same lethality conditions (Sun et al., 2007; Guan et al., 2002). More extensive work had been conducted to obtain kinetic information through isothermal treatment conditions for various food products: salmon (Kong et al., 2007a, 2007b), green asparagus (Lau et al., 2000), carrots (Peng et al., 2014), blue mussels (Ovissipour et al., 2013), and spinach (Aamir et al., 2014). These studies showed that shorter processing times resulted in higher quality, which were primarily judged based on reduced shrinkage, less loss of texture and greater retention of fresh-like appearance. However, research is needed to determine how long-term storage affects food quality (Tang, 2015). A shelf-life study has been conducted by the U.S. Army Natick Soldier Center compared MATS-treated chicken breast in 10.5-oz EVOH based trays to chicken retort processed at the same lethality as the control in the aluminum pouch. Results of the sensory study revealed that the MATS-sterilized product had an overall higher quality and flavor than the retort control before and after storage at 100 °F (37.8 °C) over 6 months. In a recent study on commercially sterile chicken and dumplings in 8-oz polymer pouches, storage at 120 °F (48.9 °C) for 4 weeks was conducted to simulate storage of 3 years in 80 °F (26.7 °C). Sensory scores of MATS-processed chicken and dumplings showed a slight decrease in overall quality, but a higher score than the retort control (Tang, 2015). However, only sensory attributes were evaluated, no instrumental quality data was collected that can be used to predict shelf-life.

Packaging is an important factor determining the shelf-life of

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thermally processed foods. Polymer materials are suitable choices for MATS, providing advantages of flexibility, transparency (in some cases), heating efficiency, and most importantly, microwave penetrability (Zhang et al., 2016). But high gas barrier properties in polymer packages may deteriorate after undergoing high temperature and moisture processes. Our previous work has reported the effect of MATS on oxygen transmission rates (OTR) and water vapor transmission rates (WVTR) for selected polyethylene terephthalate (PET) and ethylene vinyl alcohol (EVOH) package films (Mokwena et al., 2009; Dhawan et al., 2014). The performance of polymer packages requires validation during shelf life studies of MATS foods. Recently, the Advanced Food Technology (AFT) Project of the National Aeronautics and Space Administration (NASA) evaluated the stability of 13 representative retort processed foods in pouches for use on space flights. Findings showed that the main mechanisms of quality loss were color and flavor changes via Maillard reactions, as well as texture changes via moisture migration (Catauro and Perchonok, 2012). Lipid oxidation can also alter original food color and flavor in storage, especially for high lipid meats or seafoods (Zhang et al., 2016). Consequently, it is important to optimize packaging for MATS processing, especially in terms of the barrier properties, to achieve the required shelf life of 1 year for the retail market, 3 years for U.S. Army ready-to-eat meals and 5 years for NASA space missions at room temperature (Tang, 2015).

This study investigated quality changes in a mashed potato model food processed by MATS during storage at different temperatures. We evaluated the kinetics of color, moisture loss, and lipid oxidation, and characterized the effects of packaging barrier properties on quality changes. Findings can be used to predict the shelf-life of MATS foods or other thermally-processed foods. These results can also be used to inform necessary improvements to food packaging.

2. Materials and methods

2.1. Chemicals

Trichloroacetic acid (TCA) and 2-Thiobarbituric acid (TBA) were purchased from Avantor Performance Materials, Inc. (Center Valley, PA), butylated hydroxyanisole (BHT) was purchased from Fisher Scientific USA (Pittsburgh, PA), and malondialdehyde (MDA) standard was purchased from Enzo Life Science (Farmingdale, NY). Hexanal standard (GC level, purity > 95%) was obtained from TCI Chemical (Portland, OR).

2.2. Packaging

The structures and thickness of selected three polymer pouches used as model food packages, named as MFA, MFB and MFC and the foil pouch (named as MF0) were listed in Table 1. All polymer pouches were tailored to the same dimensions (181 mm × 133 mm) before processing. The MF0 pouch (230 mm × 190 mm) was used to double-seal the MFA pouches after processing, and served as the control. The oxygen transmission rates (OTR) and water vapor transmission rates (WVTR) of these pouches were measured with a Mocon Ox-Tran 2/21 MH and a Mocon Permatran 3/33 permeability instrument, following the method of Dhawan et al. (2014). After MATS processing, the OTRs (23 °C, 65% RH, 1 atm) and The WVTRs (38 °C, 100% RH, 1 atm) were also listed in Table 1, they were used as barrier properties during storage.

2.3. Model food preparation

Mashed potato model food was prepared fresh for each experiment. The following ingredients were added to each 100 g of mashed potato model food: 11 g potato flakes (Oregon Potato Company, Pasco, WA), 4.3 g vegetable oil (flaxseed oil: olive oil = 1:1), 4.7 g whey protein, 1.3 g glucose, and 0.5 g salt, in this order, into 78.2 ml of hot water (70 °C). The model food was designed with a simple, homogeneous formulation that is sensitive to color changes according to our former study (Zhang et al., 2016). Air was removed from the mixture by vacuum-treatment using a UV 250 sealing machine (KOCH Equipment, Kansas City, MO, USA). Next, 230 g of mashed potato was added to each pouch and sealed at a vacuum pressure of 0.8 bar. The control pouch (MF0) was made by sealing the processed MFA pouch inside it with a pressure of 1.0 bar to reach a complete vacuum.

2.4. MATS processing and accelerated storage

Processing of the packaged foods was conducted with a single-mode microwave-assisted thermal sterilization pilot system (10 kW, 915-MHz). A description of this system can be found in Tang et al. (2006). The general processing procedure general followed that of Dhawan et al. (2014). To ensure sufficient lethality, the $F_0 = 9$ min for MFA pouch was adopted. The process protocol was established for pouches of the same shape and dimensions. The processing time was set to 26 min for preheating at 61 °C, 7.4 min for microwave heating, and then 4 min for holding at 124 °C, with a final step of 4 min cooling in tap water (around 20 °C). After processing, pouches were randomly divided into three groups to be stored at different temperatures: 50 °C, 37 °C, and 23 °C for 12 weeks (2.8 months), 6 months, and 12 months, respectively. Duplicate pouches were taken out at each time interval, with at least 5 measurements conducted for each treatment.

2.5. Moisture loss

Moisture loss was calculated as the percentage weight loss divided by the filled pouch weight to show the quantity of water migration from the inside to the outside of the pouch. Triplicate pouches (n = 3) were measured at each interval during the storage period.

Table 1
Parameters of the pouch materials used as model food packages.

Pouch[a]	Material structure[b]	Thickness (μm, n = 5)	OTR[c] (cc/m^2·day)	WVTR[d] (g/m^2·day)
MFA	CNC 1 μm/PET 12 μm/CNC 1 μm/Nylon/PP	96.4 ± 1.8	0.20 ± 0.03	8.73 ± 0.01
MFB	Nylon 15 μm/27% EVOH 15 μm/CPP 60 μm	91.8 ± 2.2	2.11 ± 0.09	4.48 ± 0.26
MFC	HB-PET 12 μm/Nylon 15 μm/CPP 70 μm	107.6 ± 0.9	0.07 ± 0.01	0.70 ± 0.13
MF0	PET12 μm/Al 9 μm/BOPA 15 μm/RCPP 80 μm	114.8 ± 1.8	–	–

[a] Pouch names stand for model food pouch A, B, C and 0.
[b] BOPA: biaxially oriented nylon; CNC: composite nano coating; CPP: cast polypropylene; HB-PET: hyper-branched polyester; PP: polypropylene; RCPP: retort cast polypropylene.
[c] Oxygen transmission rate.
[d] Water vapor transmission rate.

2.6. Color measurement

Visual observations of color changes were recorded by a SLR camera system (EOS 60D, Canon Inc., NY). The CIE color values of the mashed potato model food: lightness L^*, redness a^*, and yellowness b^* were obtained using a Minolta CR-200 colorimeter (Konica Sensing America, NJ). In each pouch, measurements were conducted twice at five predetermined pouch locations: the top surface, edge, geometric center, reverse side hot region and cold region, as previously described (Zhang et al., 2016). The general average color values were calculated from 20 measurements taken over two pouches. The total color difference ΔE and the Browning index (BI) were calculated based on the general average. Equations (1) and (2) for the calculation are as follows (Wang et al., 2013):

$$\Delta E = \sqrt{\left(L^* - L_0^*\right)^2 + \left(a^* - a_0^*\right)^2 + \left(b^* - b_0^*\right)^2} \quad (1)$$

where L_0^*, a_0^*, and b_0^* stand for the initial values of L^*, a^*, and b^* immediately after process.

$$BI = [100(x - 0.31)]/0.172 \text{ where } x = \frac{(a^* + 1.75L^*)}{(5.645L^* + a^* - 3.012b^*)} \quad (2)$$

2.7. Thiobarbituric acid related substances (TBARS) measurement

TBARS were measured following procedures described by Sun et al. (2001), with modifications. A 2.5 g sample was taking from the pouch top surface layer, since there was no significant effect on the TBARS result of the sampling locations according to our previous study (Zhang et al., 2016). Next, the sample was mixed with 10 ml 50 g/L TCA and vortexed for 1 min. The homogenate was centrifuged at 10,000 rpm (13,000g, VWR Galaxy 14D Microcentrifuge, Radnor, PA) for 10 min. The obtained supernatant (250 μL) was used for the TBA reaction with a 2.5 ml TBA buffer solution (5 g/L TBA: 50 g/L TCA = 1:1) in a 15 ml test tube, with 20 μL 1% (w/w) BHT added to prevent further oxidation during heating. Subsequently, the test tubes were incubated for 60 min in a water bath at 90 °C, cooled in ice water for 10 min, and then centrifuged at 10,000 rpm for 5 min before measurement by a spectrometer (Ultraspec 4000, Pharmacia Biotech Inc., Piscataway, NJ) at 532 nm. Triplicated measurements were tested, and results were expressed as mg MDA/kg sample.

2.8. GC-volatile analysis

Identification and quantification of volatiles were carried out with HS-SPME-GC, following Iyer et al. (2010). The SPME fiber applied was a 65 μm polydimethylsiloxane/divinylbenzene (PDMS/DVB) fiber (Fused Silica 24 Ga, Supelco, Bellefonte, PA). SPME extraction lasted for 60 min at room temperature (23 °C ± 1 °C). Volatiles were thermally desorbed for 4 min using a SPME liner and set in the splitless mode into the injection port of a HP5890/5970 GC/FID (Agilent, Avondale, PA) equipped with a DB-1 column (60 m × 0.32 mm i.d., 0.25 μm film thickness, J&W Scientific, Folsom, CA). Hexanal was then quantified using the external standard method. Triplicate measurements were tested for samples taken from the top surface layer. In our prior work, we found that hexanal content was influenced by sampling location. The top surface was selected for sampling because of its direct contact with the package film exposed to oxygen.

2.9. Data analysis

In terms of the kinetic analysis of the quality index (denoted as A), changes at constant temperature generally followed Equation (3) below (Robertson, 2012):

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

where k is the reaction rate constant and n is the reaction order. The integrated forms zero- and first-kinetic models were used as Equations (4) and (5) (Kong et al., 2007a), where A_0 is the initial value of the quality index and A is the value at time t:

$$\text{Zero} - \text{order}: \ A_t = A_0 - k \cdot t \quad (4)$$

$$\text{First} - \text{order}: \ \ln(A_t) = \ln(A_0) - k \cdot t \quad (5)$$

The Arrhenius equation was applied to describe the temperature effects on the deterioration rate. The relationship can be expressed in the form of Equation (6):

$$k = k_0 e^{\frac{-E_a}{RT}} \quad (6)$$

where k_0 is the pre-exponential factor, E_a is the activation energy (J/mol), R is the ideal gas constant (8.314 J/K·mol), and T is the absolute temperature (K). The activation energy can thus be determined from the slope of a straight line plotted using the rate constant (Y-axis) on semi-logarithmic scale, with reciprocal absolute temperature as the variable (X-axis).

Prediction for shelf life was based on the linear model described in the following equation:

$$\theta_i = \theta_0 e^{-b(T_i - T_0)} \text{ and } b = \frac{lnQ_{10}}{10} \quad (7)$$

where θ_i is the shelf life at temperature T_i, θ_0 is the shelf life at temperature T_0, b is the slope of the linear plot of the log shelf life vs. temperature, and Q_{10} is the temperature quotient equal to the ratio of the shelf life between any two temperatures that are 10 °C apart. (Robertson, 2012)

One-way ANOVA tests using GLM procedure (SAS 9.1, SAS Institute Inc., Cary, NC, USA) were conducted. At least three replicates were used to compare temperature, storage time, and packaging barrier properties with significance levels of $p < 0.05$ and $p < 0.001$.

3. Results and discussion

3.1. Kinetics of model food color change

The top views of the model food in four pouches after MATS processing, at 37 °C storage for 1 month, 2 months and 6 months are shown in Fig. 1 as an example. The color became darker and the concentration of browning increased with storage time at 37 °C. The same trend was observed in 23 °C and 50 °C storage. The instrumental data L^*, a^*, b^* values were obtained and plotted against storage time in Fig. 2a–c. The brightness (L^*) of model food dropped, while redness (a^*) and yellowness (b^*) increased over the storage time. Similar color change patterns were reported in long-term storage study of potato flakes, with a decrease in the L^* value and increase in the a^* and b^* values (Neilson et al., 2006). The formation of darker and brown color components is similar to that of the model foods for kinetic analysis of thermal processes, in which the sugar reacted with amine through non-enzymatic browning reactions (Pandit et al., 2006). The effect of

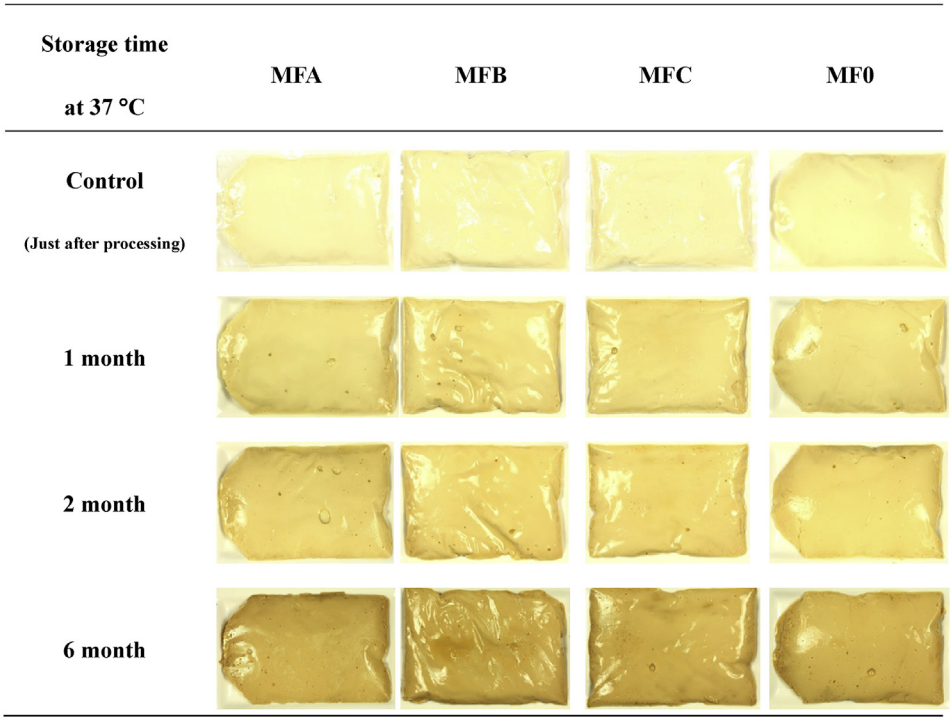

Fig. 1. Example of visual color change of mashed potato model food after MATS and during 37 °C storage. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

temperature during thermal processing was reported by Rattan and Ramaswamy (2014). This study revealed color changes in canned potato using different thermal processing methods, with a significant influence by heating temperature. It appears that long-term storage at temperatures under 50 °C exert a similar influence on color changes as brief heating at above 100 °C due to browning reactions.

The color changes (L^*, a^* and b^*) of the processed sample had followed similar patterns for each temperature storage. Thus, to further characterize the overall color change, we calculated the total color difference (ΔE) with Equation (1). The browning index (BI) was also calculated using Equation (2) to show the purity of brown color. The model food just after processing was used as the starting point. Color difference and browning index values were plotted against storage time, as shown in Fig. 3a,b, respectively. The highest color change was found for MFA, with a ΔE value equal to 19.6 after 2.8 months storage at 50 °C. The lowest ΔE value was MF0, which reached to 5.9 after 12 months of storage at 23 °C. Significant effects of both temperature and storage time were found for all color parameters (L^*, a^*, b^*, ΔE and BI, $p < 0.001$). A significant relationship ($p < 0.001$) between temperature and time was also found.

Kinetic analysis indicates that L^* fits with the first order reaction (Equation (5)), and a^* and b^* fit with the zero order reaction (Equation (4)). However, based on correlation factor (R^2), a better zero order correlation was observed for ΔE and BI comparing with L^*, a^* or b^*. The zero order ΔE and BI agreed with report for the browning phase of salmon fillet (Kong et al., 2007a) and non-enzymatic browning for dehydrated potato (McMinn and Magee, 1997). Hence, further data analyses and prediction of color changes were based on ΔE and BI. Zero order reaction parameters are shown in Table 2, with activation energy E_a obtained through an Arrhenius plot (Equation (6)). The E_a for ΔE and BI fall into the range of 70–90 kJ/mol and 70–80 kJ/mol for our model food. This lies within the range cited (60–120 kJ/mol) for food quality changes and chemical marker formation (Kong et al., 2007a).

Overall, both the ΔE and BI values correlated to large color changes in all types of packaged mashed potato. At the end of storage, the total color difference of MFA had the highest value, followed by MFB, MFC and MF0 at 50 °C. During storage at 37 °C and 23 °C, the highest ΔE value was MFB, followed by MFA, MFC and MF0. Although ANOVA analysis demonstrated significant effects ($p < 0.001$), there were no significant interactions for time and temperature ($p > 0.05$). The largest color change was observed in packages with the greatest oxygen permeability. Both lipid oxidation and Maillard reactions contribute to color formation (Zamora and Hidalgo, 2005). Maillard browning may be the reason for similar or higher color values for MFA pouch samples in 37 °C or 50 °C at the end of the storage. The same pattern was observed for the zero order model reaction rate.

3.2. Kinetics of model food moisture loss

Results for moisture loss fit well with the zero order model ($R^2 > 0.9$). The loss rate constant k of MFA, MFB and MFC pouches at three storage temperatures was used for the Arrhenius plot (Fig. 4a). They were also plotted vs. WVTR, as shown in Fig. 4b. Correlation factors R^2 for both Arrhenius plots and the linear correlation were above 0.9. As expected, there was no moisture loss in the control pouch. Therefore, k_{MF0} was considered to be zero and was not included in the plot. For the polymer pouches, the MFA had the fastest moisture loss rate, followed by the MFB and then the MFC. Temperature was found to significantly influence the moisture loss rate ($p < 0.001$). The activation energy (E_a) of MFA, MFB and MFC were calculated based on Fig. 4a to be 62.8 kJ/mol, 70.8 kJ/mol, and 47.6 kJ/mol, respectively.

Fig. 4b indicates that the moisture loss rate had good linear correlation with WVTR in each temperature. Comparing with MFA

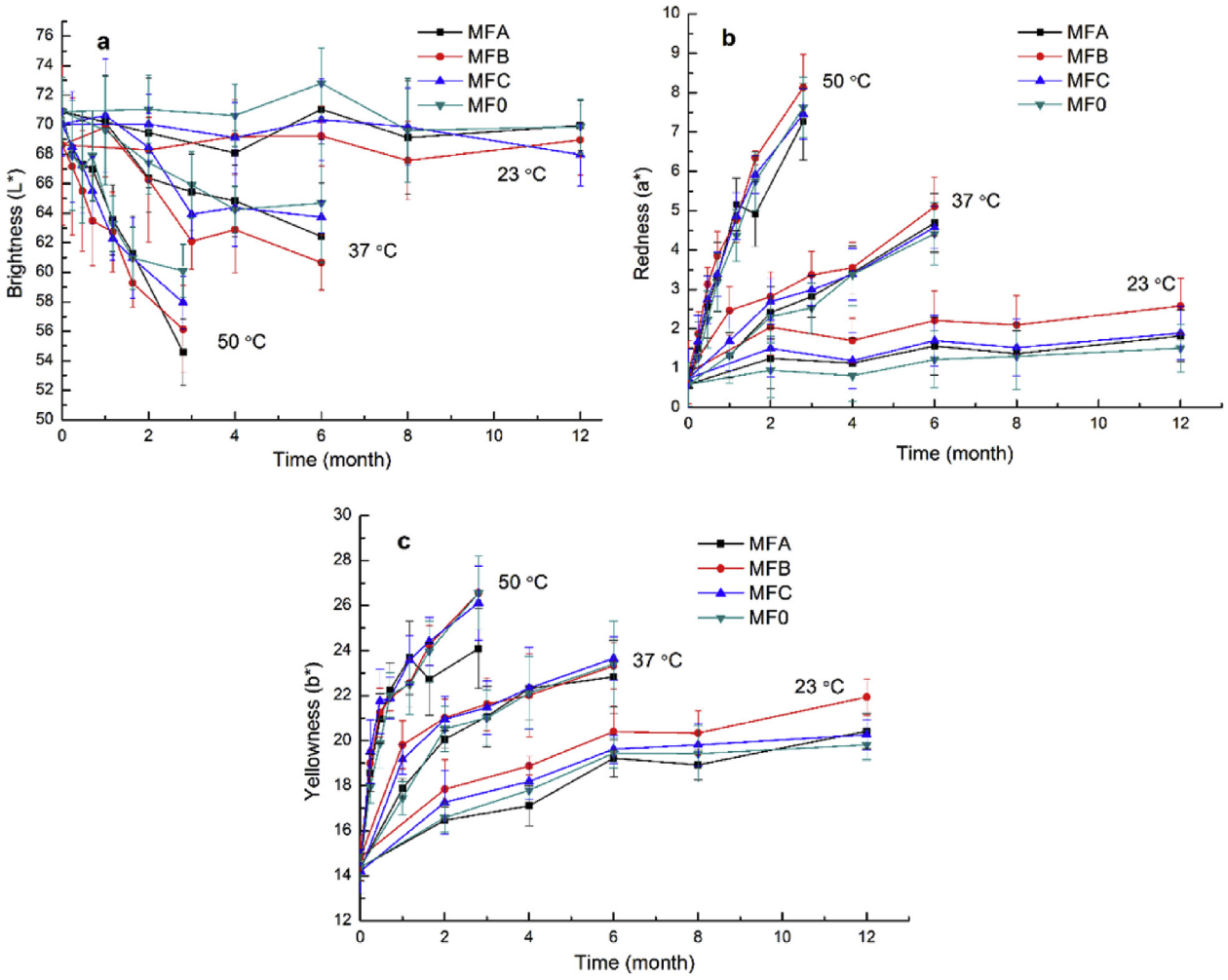

Fig. 2. Color changes in L^*, a^*, b^* (a, b, c) at three temperatures during storage. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

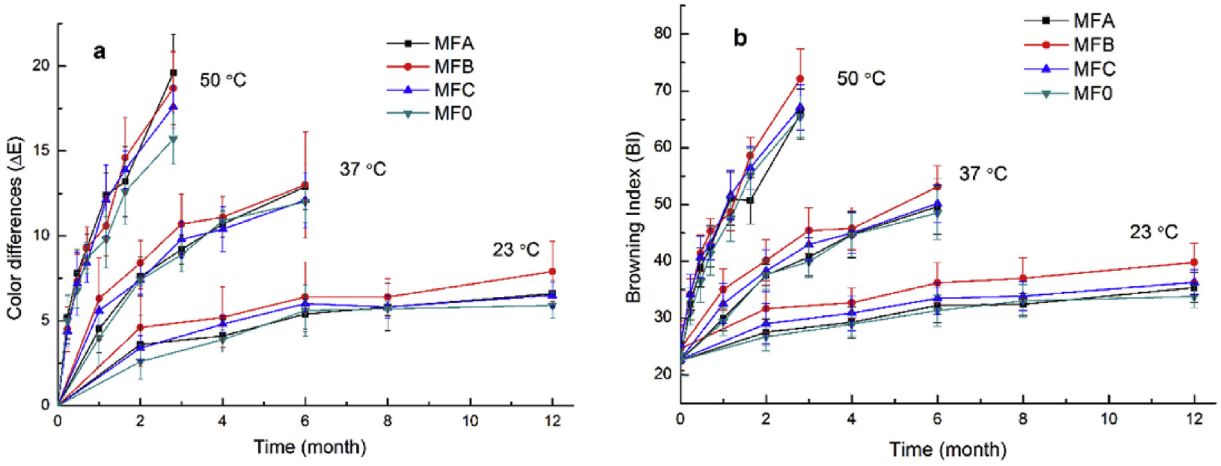

Fig. 3. Color changes expressed by total color difference (ΔE) and browning index (BI). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and MFC, MFB got higher E_a. Moisture loss for MFB was the most temperature-dependent, which may be due to the EVOH content in the MFB pouch. The EVOH provides a higher barrier for oxygen, but is more moisture-sensitive than PET material. Change in temperature combined with change in RH% in the storage condition could influence the WVTR of MFB (Mokwena et al., 2009). The highest

Table 2
Zero-order kinetic parameters for color differences (ΔE) and browning index (BI) of MATS processed mashed potato model food at 3 storage temperatures.

Temperature	$k_{(\Delta E\ MFA)}$ ($month^{-1}$)	R^2	$k_{(\Delta E\ MFB)}$ ($month^{-1}$)	R^2	$k_{(\Delta E\ MFC)}$ ($month^{-1}$)	R^2	$k_{(\Delta E\ MF0)}$ ($month^{-1}$)	R^2
50 °C	5.28	0.975	5.32	0.962	4.97	0.942	4.03	0.960
37 °C	1.62	0.949	1.29	0.929	1.28	0.929	1.54	0.891
23 °C	0.31	0.940	0.33	0.958	0.29	0.802	0.32	0.733
$Ea_{\Delta E}$ (kJ/mol)	83.9	0.998	82.1	0.997	83.5	0.999	75.0	0.992
Temperature	$k_{(BI\ MFA)}$ ($month^{-1}$)	R^2	$k_{(BI\ MFB)}$ ($month^{-1}$)	R^2	$k_{(BI\ MFC)}$ ($month^{-1}$)	R^2	$k_{(BI\ MF0)}$ ($month^{-1}$)	R^2
50 °C	13.88	0.913	15.55	0.957	14.03	0.932	14.50	0.951
37 °C	4.45	0.938	4.39	0.912	4.34	0.908	4.30	0.924
23 °C	0.99	0.905	1.16	0.879	1.02	0.852	0.93	0.884
Ea_{BI} (kJ/mol)	78.4	0.999	73.9	0.999	75.0	0.999	79.6	0.999

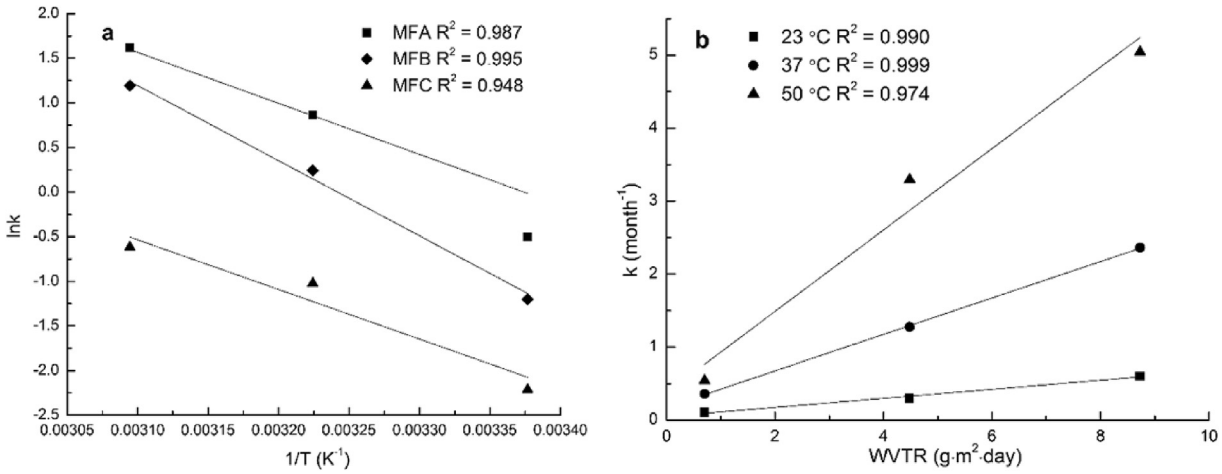

Fig. 4. Arrhenius plots of moisture migration (a) and its correlation with WTVR (b).

moisture loss was 14.17% for MFA after 12 weeks storage at 50 °C, and 14.19% for MFA after 6 months storage at 37 °C. Therefore, an important factor in selecting barriers for packaging used for shelf stable foods is probably whether water loss will affect the taste or overall acceptance of consumers.

3.3. Kinetics of model food lipid oxidation

In this study, both the hexanal content and the TBARS value were used as indicators of lipid oxidation for the mashed potato model food. The trend for hexanal formation differed for each type of packaging and at different temperatures (shown in Fig. 5). The initial loss of hexanal for processed food is temperature-dependent (Viljanen et al., 2011). For MF0 at 23 °C, there was an initial drop in the first 2–4 months, after which it remained constant. At higher temperatures, there was a large initial drop with the apparent formation of hexanal after 1 month at 50 °C. For MFA, hexanal levels dropped, with the greatest decrease observed at the highest temperature. For MFB, hexanal levels dropped at 23 °C and 37 °C for the first 2 and 4 month and then increased. At 50 °C, the results were less clear, but an initial drop was observed within the first month, followed by increased levels. For MFC, the hexanal levels at 23 °C and 37 °C dropped, but those at 50 °C initially decreased and then increased at later storage periods. These results are linked to levels of oxidation anticipated from the oxygen transmission rate of the different packages. For packaging with a higher OTR, the likelihood of increased oxidation indicated by hexanal formation during storage increased, compared to packages with lower OTR. TBARs show an initial drop in TBA values, followed by an increase at each temperature after long-term storage (Fig. 6).

Our ANOVA results demonstrate significant effects of temperature, storage time, and pouch influences ($p < 0.001$). However, the interactions between all factors were also significant ($p < 0.05$), expect for the interaction of time and temperature ($p > 0.05$). There is a combined effect of Maillard reaction and lipid oxidation. NASA conducted shelf-life studies for foods processed in retort pouches. Flavor changes were largely due to Maillard browning, and to a lesser extent, lipid oxidation (Catauro and Perchonok, 2012). The complexity of lipid oxidation and Maillard reactions has received much study. Both can produce volatiles, and with a contribution of reaction products from lipid oxidation participating in Maillard reaction and vice versa, this is particularly significant at higher temperatures (Zamora and Hidalgo, 2005). For example, aldehydes produced by lipid oxidation can further react with amino acids and proteins. These aldehydes can also react with MDA and produce a pink color when reacting with TBA (Díaz et al., 2008). This may explain our result of variation of hexanal and TBA values during storage. Medina et al. (1995) found a decrease of TBA for canned fish due to dilution of secondary products in a liquid medium. In our study, a similar diffusion of TBA reactive substances may have occurred from the top layer to the inner food matrix.

Rancidity in real food products usually must be confirmed by sensory evaluation. Hexanal often gives a grassy, tallow and fat odor, the odor may contribute to an off-flavor in high concentrations (Viljanen et al., 2011). Jensen et al. (1999) reported that the odor threshold for hexanal in mashed potato is around 38 μg/kg.

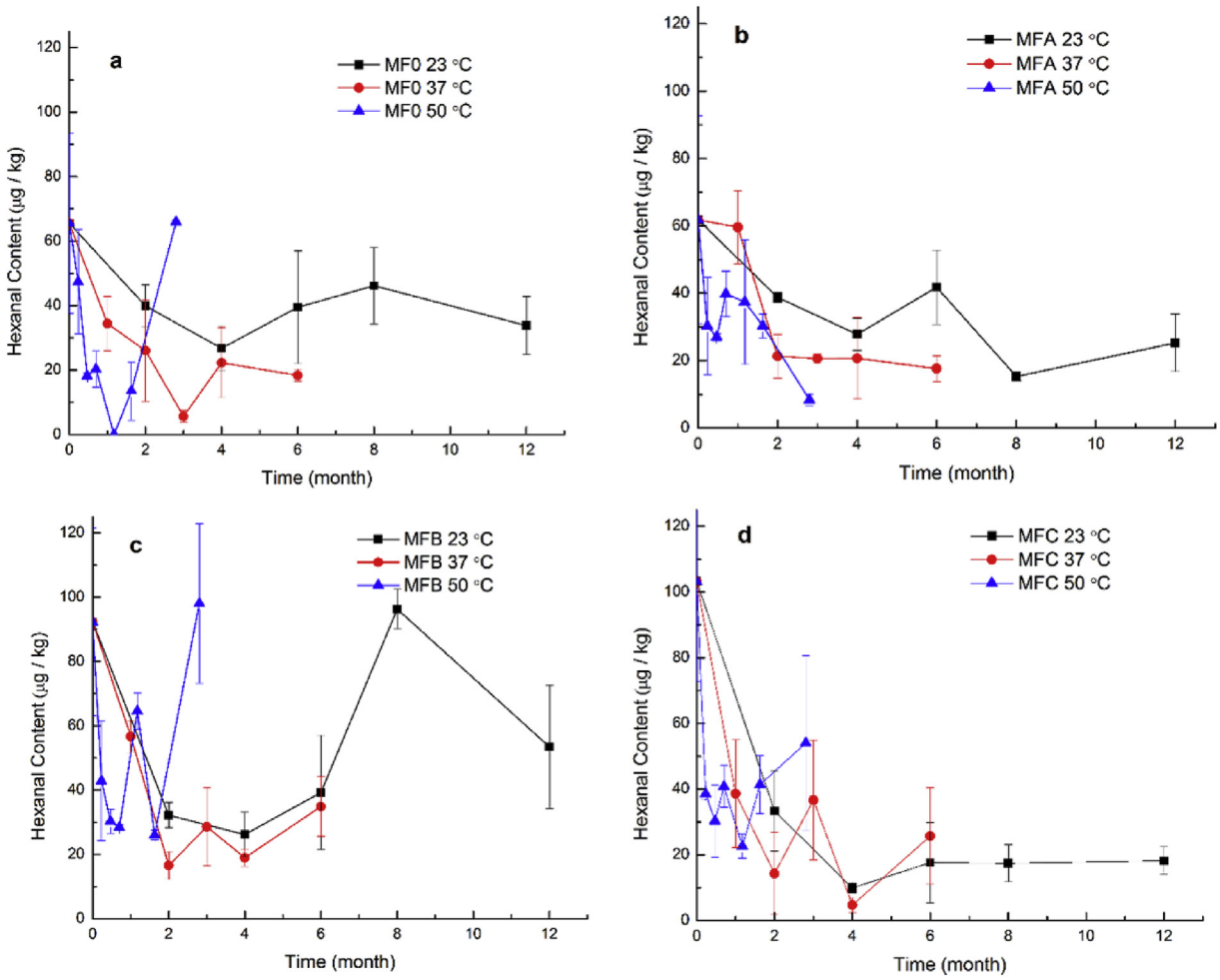

Fig. 5. Hexanal content in the mashed potato model food in four pouches at three temperatures.

According to this limit value, the hexanal content in our model food should be detectable at this level. For similar potato products (Neilson et al., 2006), meat products such as cooked pork (Díaz et al., 2008) and chicken (Mukprasirt et al., 2001), a positive correlation between the oxidation values and the sensory score are not always correlated, while adverse flavor changes can take a long time to materialize. According to a NASA space food study, a flavor change does not appear to drive the overall sensory acceptability in most tested foods until at least 16 months of storage at ambient conditions (Catauro and Perchonok, 2012).

3.4. Shelf life prediction

In our study, color changes in the model food were considered as the main form of degradation. Lipid oxidation provided less clear results, and the moisture loss was usually not main issue for shelf stable foods. However, changes in both lipid oxidation and moisture content affected color changes. Total color difference ΔE was used to represented the overall color change, and the end point of shelf life for our model food was set as $\Delta E = 12$, at which point the food was considered to have changed color (Wang et al., 2013).

Table 3 shows that each predicted shelf life (θ) was calculated based on zero-order kinetic information for ΔE. The Q_{10} value for each pouch was obtained through the slope of the shelf life plot (see Equation (7)) with a logarithm shelf life (θ, Y axis) vs. temperature (T, X axis). The higher oxygen barrier packages (MFC and MF0) provided a longer shelf life for samples than lower barrier packages (MFA and MFB) at the three storage temperatures. The largest difference in shelf life was observed for MFB in 23 °C, at almost 5 month less than that of MFC. The MFC pouch had a similar or longer predicted shelf life, due to its lowest level of OTR and WVTR. The Q_{10} value for all samples fitted in the range of 1.1–4 as reported for thermally processed foods (Robertson, 2012). The highest Q_{10} value was for the MFA pouch, followed by MFC, MFB and MF0. The shelf life of MFA was more temperature-dependent, which was less than MFB at 50 °C.

Derived from Equation (7), models in Fig. 7 was used to predict the shelf-life of MATS-processed model food as a function of the OTR at the temperature of 23 °C. The control foil pouch was also included for prediction, with a measured average OTR of 0.0083 cc/m^2 day. Both the linear and polynomial relationship can be applied for this prediction ($R^2 > 0.99$). However, these prediction equations have poor correlations at 37 °C and 50 °C (data not shown). This result further confirms the influence of temperature on color change. Hence, this model can be further validated by applying to any oxygen-sensitive model food product that might give uniform results in different temperatures. Since the barrier properties of both OTR and WVTR are fixed after package processing, they should always be taken into account as a combined effect. OTR influenced more profoundly in the case of MATS processed model food, while water loss of up to 15% should be taken into consideration for color change.

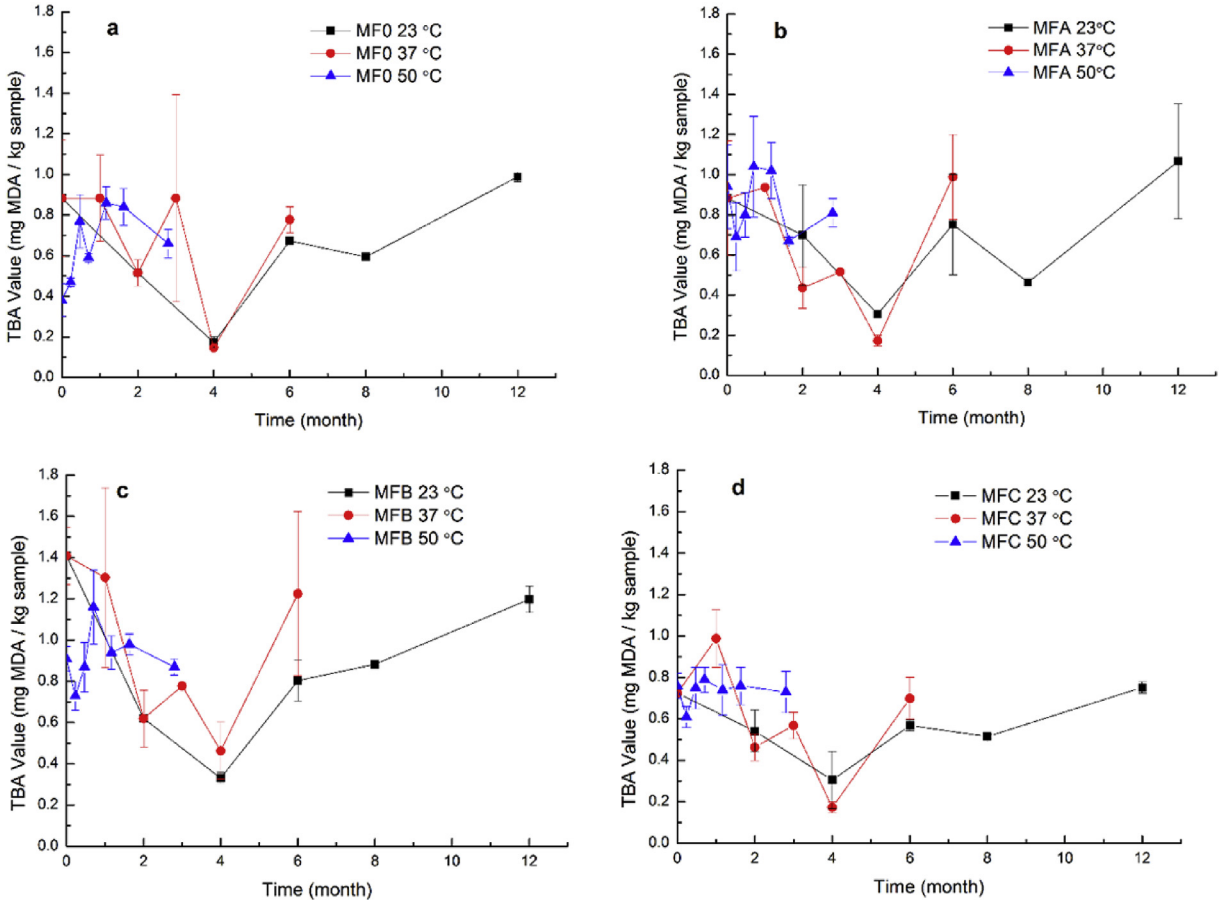

Fig. 6. TBA value change for four pouches at three temperatures.

Table 3
Shelf life prediction of model food using $\Delta E = 12$ as end point.

Storage temperature	$\theta_{(MFA)}$ (month)	$\theta_{(MFB)}$ (month)	$\theta_{(MFC)}$ (month)	$\theta_{(MF0)}$ (month)
50 °C	1.31	1.39	1.45	1.72
37 °C	5.07	4.83	5.50	5.37
23 °C	28.8	24.5	29.4	29.0
Q_{10} value	3.15	2.90	3.06	2.85

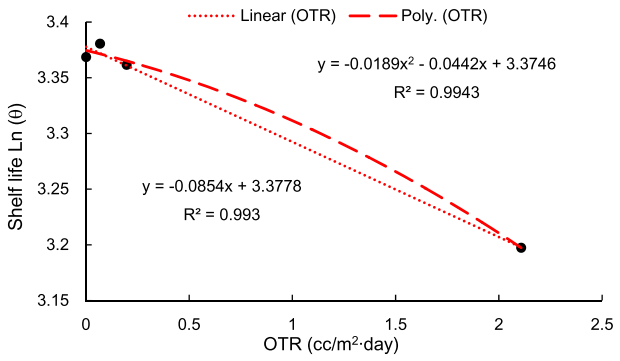

Fig. 7. Modeling of shelf-life as a function of OTR in ambient temperature.

4. Conclusions

In this study, we developed a systematic approach to identifying quality changes during thermal processing and storage. We investigated the kinetics of color change, lipid oxidation and moisture migration for a mashed potato model food processed by microwave-assisted thermal sterilization (MATS). We examined the effects of packaging barrier properties, i.e. oxygen transmission rate and water vapor transmission rate on shelf life, and predicted shelf-life as a function of OTR. The dominant degradation mechanism in the mashed potato model food was Maillard browning, which was enhanced by lipid oxidation and possibly moisture loss.

The ΔE (main quality indicator) changes in model food packaged in four types of pouches were zero-order reactions, with an activation energy ranging from 74 to 85 kJ/mol. Findings show that temperature and packaging barrier properties had a significant ($p < 0.001$) impact on color change. The Q_{10} values were 2.85–3.15, using $\Delta E = 12$ as the end point. Low oxygen-barrier MFA and MFB showed overall higher ΔE and $k_{\Delta E}$ values than those of MFC and the MF0 control. Our further research may measure more quality attributes for shelf life, including consumer response for various MATS foods. Regarding long-term storage, package barriers for both oxygen and water vapor are critical for ensuring food quality.

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References

Aamir, M., Ovissipour, M., Rasco, B., Tang, J., Sablani, S., 2014. Seasonality of the thermal kinetics of color changes in whole spinach (*spinacia oleracea*) leaves under pasteurization conditions. Int. J. Food Prop. 17, 2012–2024.

Catauro, P.M., Perchonok, M.H., 2012. Assessment of the long-term stability of retort pouch foods to support extended duration spaceflight. J. Food Sci. 77, S29–S39.

Dhawan, S., Varney, C., Barbosa-Cánovas, G.V., Tang, J., Selim, F., Sablani, S.S., 2014. The impact of microwave-assisted thermal sterilization on the morphology, free volume, and gas barrier properties of multilayer polymeric films. J. Appl. Polym. Sci. 131, 40376.

Díaz, P., Nieto, G., Garrido, M.D., Bañón, S., 2008. Microbial, physical–chemical and sensory spoilage during the refrigerated storage of cooked pork loin processed by the sous vide method. Meat Sci. 80, 287–292.

Guan, D., Gray, P., Kang, D.H., Tang, J., Shafer, B., Ito, K., Younce, F., Yang, T.C.S., 2003. Microbiological validation of microwave-circulated water combination heating technology by inoculated pack studies. J. Food Sci. 68, 1428–1432.

Guan, D., Plotka, C.F.V., Clark, S., Tang, J., 2002. Sensory evaluation of microwave treated macaroni and cheese. J. Food Process. Preserv. 26, 307–322.

Iyer, S., Mattinson, D.S., Fellman, J.K., 2010. Study of the early events leading to cassava root postharvest deterioration. Trop. Plant Biol. 3, 151–165.

Jensen, K., Petersen, M.A., Poll, L., Brockhoff, P.B., 1999. Influence of variety and growing location on the development of off-flavor in precooked vacuum-packed potatoes. J. Agric. Food Chem. 47, 1145–1149.

Kong, F., Tang, J., Rasco, B., Crapo, C., 2007a. Kinetics of salmon quality changes during thermal processing. J. Food Eng. 83, 510–520.

Kong, F., Tang, J., Rasco, B., Crapo, C., Smiley, S., 2007b. Quality changes of salmon (*Oncorhynchus gorbuscha*) muscle during thermal processing. J. Food Sci. 72, S103–S111.

Lau, M., Tang, J., Swanson, B., 2000. Kinetics of textural and color changes in green asparagus during thermal treatments. J. Food Eng. 45, 231–236.

Medina, I., Sacchi, R., Aubourg, S., 1995. A 13C NMR study of lipid alterations during fish canning: effect of filling medium. J. Sci. Food Agric. 69, 445–450.

McMinn, W.A.M., Magee, T.R.A., 1997. Kinetics of ascorbic acid degradation and non-enzymatic browning in potatoes. Food Bioprod. Process. 75, 223–231.

Mokwena, K.K., Tang, J., Dunne, C.P., Yang, T.C.S., Chow, E., 2009. Oxygen transmission of multilayer EVOH films after microwave sterilization. J. Food Eng. 92, 291–296.

Mukprasirt, Herald, Tang, J., Boyle, D.L., Boyle, E., 2001. Physicochemical and microbiological properties of selected rice flour-based batters for fried chicken drumsticks. Poult. Sci. 80, 988–996.

Neilson, A.P., Pahulu, H.F., Ogden, L.V., Pike, O.A., 2006. Sensory and nutritional quality of dehydrated potato flakes in long-term storage. J. Food Sci. 71, S461–S466.

Ovissipour, M., Rasco, B., Tang, J., Sablani, S.S., 2013. Kinetics of quality changes in whole blue mussel (*Mytilus edulis*) during pasteurization. Food Res. Int. 53, 141–148.

Pandit, R.B., Tang, J., Mikhaylenko, G., Liu, F., 2006. Kinetics of chemical marker M-2 formation in mashed potato—a tool to locate cold spots under microwave sterilization. J. Food Eng. 76, 353–361.

Peng, J., Tang, J., Barrett, D.M., Sablani, S.S., Powers, J.R., 2014. Kinetics of carrot texture degradation under pasteurization conditions. J. Food Eng. 122, 84–91.

Rattan, N.S., Ramaswamy, H.S., 2014. Comparison of free/bi-axial, fixed axial, end-over-end and static thermal processing effects on process lethality and quality changes in canned potatoes. LWT Food Sci. Technol. 58, 150–157.

Robertson, G.L., 2012. Shelf life of foods. In: Food Packaging: Principles and Practice, third ed. CRC Press, Florida, USA, pp. 329–363.

Sun, Q., Faustman, C., Senecal, A., Wilkinson, A.L., Furr, H., 2001. Aldehyde reactivity with 2-thiobarbituric acid and TBARS in freeze-dried beef during accelerated storage. Meat Sci. 57, 55–60.

Sun, T., Tang, J., Powers, J.R., 2007. Antioxidant activity and quality of asparagus affected by microwave-circulated water combination and conventional sterilization. Food Chem. 100, 813–819.

Tang, J., 2015. Unlocking potentials of microwaves for food safety and quality. J. Food Sci. 80, E1776–E1793.

Tang, J., Liu, F., Patfiak K., & Eves, E.E., 2006. Apparatus and method for heating objects with microwaves. U.S. patent 7119313 B2.464.

Viljanen, K., Lille, M., Heiniö, R.L., Buchert, J., 2011. Effect of high-pressure processing on volatile composition and odour of cherry tomato purée. Food Chem. 129, 1759–1765.

Wang, S., Lin, T., Man, G., Li, H., Zhao, L., Wu, J., Liao, X., 2013. Effects of anti-browning combinations of ascorbic acid, citric acid, nitrogen and carbon dioxide on the quality of banana smoothies. Food Bioprocess Technol. 7, 161–173.

Zamora, R., Hidalgo, F.J., 2005. Coordinate contribution of lipid oxidation and maillard reaction to the nonenzymatic food browning. Crit. Rev. Food Sci. Nutr. 45, 49–59.

Zhang, H., Bhunia, K., Kuang, P., Tang, J., Rasco, B., Mattinson, D., Sablani, S.S., 2016. Effects of oxygen and water vapor transmission rates of polymeric pouches on oxidative changes of microwave-sterilized mashed potato. Food Bioprocess Technol. 9, 341–351.