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Development of Vitamin C-Enriched Lentil Hummus With Innovative Microwave Technologies

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ABSTRACT

Hummus, a nutrient-dense food rich in dietary fiber, plant-based proteins, and various micronutrients, is widely consumed in many countries worldwide. However, its preparation methods can pose a risk of microbial contamination and foodborne outbreaks. This study aimed to evaluate the use of innovative technologies of microwave-assisted thermal sterilization (MATS) technologies and microwave-assisted pasteurization system (MAPS) in the production of microbially safe ready-to-eat hummus. Experimental studies provided data on the lipid oxidation, color, pH, and vitamin C content in microwave-processed lentil hummus during the storage process. The lipid oxidation value of the lentil hummus was found to be below the acceptable threshold. By the end of the storage period, the retention of vitamin C was measured at 76% in MAPS-treated samples and 33.5% in MATS-treated samples. MAPS-treated samples showed stable color properties throughout storage, whereas MATS-treated samples exhibited a decrease in L^* values. Both MAPS and MATS methods initially increased the pH of the hummus samples, followed by a gradual decline during storage. These technologies ensure the safety of mass-produced hummus without chemical preservatives.

1 | Introduction

Recently, there has been a global rise in plant-based diets, with human nutrition research demonstrating that such diets have the potential to enhance health and lower the risk of chronic diseases (Wang et al. 2023). Legumes, rich in protein and dietary fibers, are a fundamental component of plant-based diets across many regions. Hummus, a Middle Eastern dip made from chickpeas, is gaining popularity in the United States and Europe, emerging as one of the most favored ready-to-eat options (Klug et al. 2018). Traditionally, hummus is prepared by blending boiled and mashed chickpeas with tahini (sesame paste), olive oil, garlic, lemon juice or citric acid, and salt (Al-Qadiri et al. 2021). The hummus market in North America is projected to experience significant growth, with anticipated revenues reaching US $1559 million by 2027, up from US $601 million in 2019 (Market Research 2020).

Hummus is commonly prepared without undergoing additional thermal treatments beyond boiling the chickpeas. However, this presents a potential risk of cross-contamination with foodborne pathogens during the preparation and

MATS and MAPS technologies ensure the safety of mass-produced hummus without chemical preservatives.

packaging processes. Between 2000 and 2018, hummus was associated with 20 foodborne illness outbreaks in the United States (Olaimat et al. 2022). As a result, many commercial hummus products contain chemical preservatives like potassium sorbate and sodium benzoate to guarantee food safety and extend shelf life. Maintaining food safety without these chemical preservatives is a challenging task in high-volume commercial production of hummus. Despite this, there is very limited information in the literature regarding the pasteurization and sterilization of hummus.

To ensure the inactivation of microorganisms, two common thermal methods, pasteurization and sterilization, are used. Pasteurization, designed to achieve a 6-log reduction in nonproteolytic *Clostridium botulinum* for MAPS (ECFF 2006; Qu et al. 2021) allows the pasteurized food products within their packaging to be stored at refrigerated temperatures for 10–16 weeks (Zhang 2016). Sterilization aims at inactivating *C. botulinum*, which has the highest heat resistance in low-acid foods (pH > 4.6) and can grow in anaerobic conditions. This process targets a reduction of exotoxin-producing *C. botulinum* spores by more than 12 logs (Zhang et al. 2016). In-pack sterilized food products are shelf stable and can be stored unrefrigerated for up to 5 years depending upon the food product (Patel et al. 2020).

Traditional thermal processes use convection and conduction mechanisms (Khakbaz Heshmati et al. 2014). While ensuring food safety, these processes often result in quality losses due to prolonged holding times and come-up times, affecting nutritional content, appearance, and texture (Patel et al. 2020). Innovative technologies, such as microwave-assisted thermal sterilization (MATS) and microwave-assisted pasteurization system (MAPS), offer a solution. They combine microwave energy with water immersion for volumetric heating that minimizes edge heating and shortens heating time to enhance the product quality. MAPS and MATS both use a single mode 915 MHz microwave system, which penetrates food products more effectively and increases heating uniformity (Tang 2015). Given the importance of ensuring food safety without chemical preservatives, this study aimed to assess the use of MAPS and MATS for the preservation of hummus.

Lentil is a crucial crop used in rotation with wheat in the Pacific Northwest of the USA to maintain healthy soil conditions. But the domestic consumption of lentil is very small. According to the USDA Economic Research Service (ERS), between 75% and 80% of lentils produced in the USA are exported. Fluctuations in global demand dramatically influence farmers' incomes. It is desirable to expand the use of lentil for domestic consumption. Thus, in this study, red lentils were used as an alternative to chickpeas in hummus production. Red lentils are highly nutrient-dense, as per the FDA's naturally nutrient-rich (NNR) standards (Drewnowski 2005). Depending on the tahini and oil content, hummus contains an average of 19.7 g fat per 100 g (WHO 2008), including lipids rich in unsaturated fatty acids susceptible to oxidation. There is no existing data on lipid oxidation in hummus. Our study determined the oxidative stability of thermally processed hummus and monitored the retention of vitamin C in hummus enriched with vitamin C throughout the storage period.

2 | Materials and Methods

2.1 | Materials

The preparation of lentil hummus used lentils, tahini, soybean oil, lemon juice, garlic, salt, and cumin. Liposomal encapsulated vitamin C (sodium ascorbate) was added for vitamin C fortification. The fresh ingredients (garlic and lemon) used to prepare lentil hummus were obtained from local retail markets and stored at 4°C for up to 2 h before use. Lentils were obtained from a local grower in Pullman, WA, USA. Soybean oil was chosen in our study because it is one of the leading oils used in food-based applications in the United States and is generally found in commercially available hummus recipes (Lewis et al. 2015). Commercially prepared tahini (Krinos Foods LLC), soybean oil (Great Value, Walmart Inc.), iodized table salt (Morton Salt), and cumin (Great Value, Walmart Inc.) were also obtained from local retail grocers. Liposomal encapsulated (sodium ascorbate) vitamin C (LivOn Laboratories, Henderson, NV) was obtained from online retail stores. All the ingredients except garlic and lemon were stored at room temperature. Propyl gallate (98%), Sodium EDTA-Titriplex III, Ethanol, Trichloroacetic acid (TCA), 2-Thiobarbituric acid (TBA), Plate Count Agar (PCA), Potato Dextrose Agar (PDA), tartaric acid, and peptone water were purchased from Sigma-Aldrich.

2.2 | Preparation of Lentil Hummus

The hummus recipe was developed by comparing the ingredients and ingredient ratios in the recipes used in relevant articles (Alali et al. 2012; Pazlopez 2014; Doumani et al. 2020; Salazar et al. 2020). Preliminary experiments were conducted to optimize hummus recipes. Recipes with different water and lentil ratios were pre-trialed in order to obtain a product with a consistency after the process similar to commercially available hummus. As the temperature applied during the process increases, the swelling and water retention capacity of lentils increase (Ahmed et al. 2016). The recipe for lentil hummus samples to be sterilized included more water with a lesser amount of lentils, while all other ingredients used had the same amount in both pasteurized and sterilized recipes. In addition to water, oil and sesame paste both also contribute to the consistency of the hummus.

The recipe for lentil hummus to be pasteurized consisted of 65.6% (w/w) cooked lentil, 8.8% (w/w) water, 10.7% (w/w) tahini, 8.0% (w/w) soybean oil, 4.4% (w/w) lemon juice, 1.2% (w/w) garlic, 0.9% (w/w) salt, 0.1% (w/w) cumin, and 0.3% (w/w) liposomal-encapsulated Vitamin C. To enrich the lentil hummus samples, liposomal-encapsulated vitamin C was added to achieve 60 mg of vitamin C per 100 g of the product. The recipe for the sterilized lentil hummus was 54.0% (w/w) cooked lentil, 20.4% (w/w) water, 10.7% (w/w) tahini, 8.0% (w/w) soybean oil, 4.4% (w/w) lemon juice, 1.2% (w/w) garlic, 0.9% (w/w) salt, 0.1% (w/w) cumin, and 0.3% (w/w) liposomal-encapsulated Vitamin C. In the formulation, 1 kg of cooked lentils contained 0.65 kg of water.

Dried lentils were washed and boiled in water for 10 min. The boiled lentils were then combined with all of the other ingredients and blended for 1 min in a blender. At this stage, the lentil hummus

had a runny and smooth consistency, but after processing it reached a thicker, more recognizably hummus-like consistency. Rigid trays (Silgan Plastics, Chesterfield, MO) with a structure of PP/regrind/tie/EVOH/tie/regrind/PP (PP: polypropylene, EVOH: ethylene vinyl alcohol) were filled with 300 ± 2 g of the product. The inner dimensions of the trays were 140 × 95 × 30 mm. Air was removed from the product, and the trays were hermetically sealed using a vacuum sealer (Multivac T-200, Multivac Inc., Kansas City, MO) with a lid film composed of an outer barrier of polyethylene terephthalate (PET) and an inner layer of polypropylene, with multiple layers in between (Printpack., Atlanta, GA). The lid film consists of PET/BON/PP (BON: biaxially oriented nylon) layers. The oxygen transmission rate (OTR) of the film after processing is 0.13 cc/m^2 day and water vapor transmission rate (WVTR) after processing is 0.89 g/m^2 day. The sealing parameters were adjusted to 200°C for 8 s, with vacuum (6.5 kPa absolute pressure) and nitrogen flushing at 45 kPa (absolute pressure). The packages were stored at 4°C until processed on the same day.

2.3 | Microwave-Assisted Thermal Processes of Lentil Hummus

The pilot MAPS and MATS systems operating at 25 kW and 915 MHz, located at Washington State University (Pullman, WA, USA), were used for the pasteurization and sterilization processes (Tang 2015; Zhang 2016). Heat penetration studies were conducted to determine the process conditions. Preliminary experiments were performed to identify the temperature and position of the cold spot inside the trays using calibrated mobile temperature sensors (TMI Inc. Reston, VA). Hummus is in the low-acid food category (pH > 4.6). Pasteurization targets a minimum of 6 log reduction of the target pathogen psychrotrophic *C. botulinum* and sterilization targets a minimum of 12 log reduction of *C. botulinum* type A and B (proteolytic) spores.

Equation (1) was used to determine the thermal lethalities at the cold spots inside the food packages to ensure the desired reduction in the target bacterial population (Tang and Chan 2007; Peng 2014; Tang 2015).

$$F = \int_0^t 10^{\frac{T(t)-T_{\text{ref}}}{z}} dt \quad (1)$$

where F is the time in minutes that the food is exposed to the reference temperature T_{ref}, $T(t)$ is the temperature at the cold spots inside the food packages, and the z value, in °C, shows how the bacterium's resistance to heat.

The MAPS processing conditions included microwave powers of 5, 5, and 8.7 kW for the 1st, 2nd, and 3rd/4th microwave heating cavities, respectively; water temperatures of 51°C, 91°C, 91°C, and 23°C for preheating, heating, holding, and cooling, respectively; 35 min preheating; 3.35 min microwave heating; 12 min holding; and 8 min cooling. The average lethality achieved was $F_{90°C} = 16$ min. The photographs of hummus before and after the MAPS process can be found in Figure 1.

The following conditions were used for MATS processing of the lentil hummus: microwave powers of 11.7, 3.7, and 3.8 kW set for the 1st/2nd, 3rd, and 4th microwave heating cavities, respectively; pressure of 234.4 kPa (34 psig) set for the system; water temperatures of 61°C, 124°C, and 124°C set for preheating, heating, and holding, respectively; 35 min preheating; 5.2 min microwave heating; 5.35 min holding; and 5 min cooling in water. The average lethality achieved was $F_{121°C} = 9.7$ min. Figure 2 shows the photographs of hummus before and after the MATS process.

2.4 | Storage Conditions and Food Quality Analyses

The whole experiment was replicated two times. The pasteurized lentil hummus samples were stored at 4°C and used for quality analysis every 15 days for 4 months. The sterilized samples were stored at 38°C for 6 months in line with the accelerated shelf life testing (ASLT) protocol, equivalent to 3 years of storage at 23°C (Onwulata 2014; Tang 2015; Zhang et al. 2016;

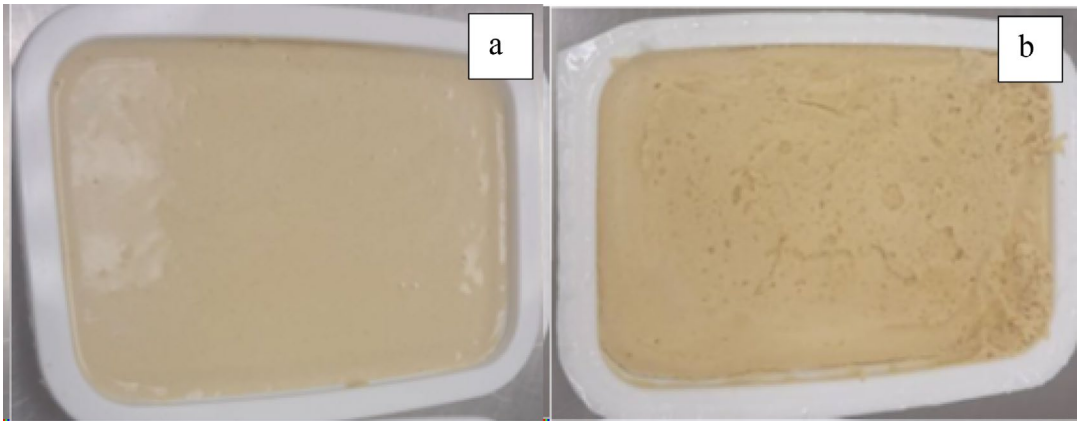

FIGURE 1 | Lentil hummus in trays (a) before and (b) after MAPS processing.

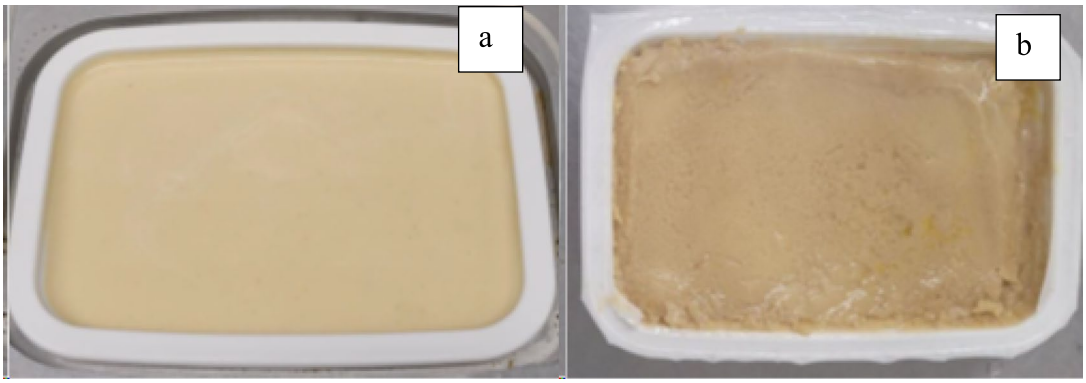

FIGURE 2 | Lentil hummus in trays (a) before and (b) after MATS processing.

Zhang 2016; Patel et al. 2020). Samples were subjected to analyses that included pH, color, weight loss, Vitamin C, TBARS, total plate count, yeast, and molds. Each of these analyses was performed on the samples before process, after process, and during the storage.

2.5 | Color Measurement

Colorimetric values of the samples were determined using a Minolta CR 200 colorimeter (Konica Sensing America Inc., Ramsey, NJ, USA). Prior to measurements, the instrument (45°/0° geometry, 10° observer) was calibrated using standard black and white references. The color profile was assessed in terms of lightness (L^*), redness (a^*), and yellowness (b^*) values according to the CIE color system (International Commission on Illumination) (8 mm, SCE, 10°/D65). The total color difference (ΔE) values were calculated from the average CIE L^*, a^*, and b^* values obtained from six sampling locations. The calculations for ΔE and the browning index (BI) were performed using the formulas provided in Equation (2) (Kong et al. 2007).

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

where ΔL^*, Δa^*, and Δb^* represent the differences between the corresponding color parameters of the processed sample and the unprocessed sample. The ΔE value represents the color difference between two samples, as defined by the following scale (Wang et al. 2013):

$\Delta E < 0.2$: no perceptible difference.

$0.2 < \Delta E < 0.5$: very small difference.

$0.5 < \Delta E < 2$: small difference.

$2 < \Delta E < 3$: fairly perceptible difference.

$3 < \Delta E < 6$: perceptible difference.

$6 < \Delta E < 12$: strong difference.

$\Delta E > 12$: different colors.

2.6 | Determination of Thiobarbituric Acid Reactive Substances (TBARS) Value

TBARS were measured in duplicate for each sample. When preparing samples for TBARS analysis, samples were randomly collected from the top and interior of each tray and then homogenized. The resulting mixture was used for analysis. This protocol includes the addition of EDTA and propyl gallate to the trichloroacetic acid (TCA) extraction solution to prevent TBARS formation during the analysis. A 2 g sample was blended with 12 mL of extraction solution and homogenized for 15 s. The homogenate was then filtered through Whatman No. 1 filter paper. One milliliter of the filtrate was combined with 1 mL of thiobarbituric acid (TBA) and vortexed. The mixture was heated at 100°C for 40 min, then cooled and centrifuged at 2000 × g for 5 min. Absorbance was read at 532 nm against a blank containing 1 mL of TCA extraction solution and 1 mL of TBA solution. TBARS values were reported as μg TBARS per gram of sample (Kılıç et al. 2014).

2.7 | Determination of Vitamin C Content

The titrimetric method utilizing 2,6-dichloroindophenol, as specified by AOAC Method 967.21, was utilized (Nielsen 2017). Within the scope of the method, indophenol solution (dye), ascorbic acid standard solution, and metaphosphoric acid–acetic acid solution were prepared. Before starting the analysis, the dye was standardized, and blanks were prepared and titrated. The obtained results were recorded for use in the calculation. The sample was titrated with indophenol solution in the presence of metaphosphoric acid–acetic acid solution. The amount of dye used was recorded. Calculations for Vitamin C were based on Equations (3) and (4). The concentration of ascorbic acid in the sample was determined and expressed in mg per 100 g.

$$\text{Titer} = F = \frac{\begin{matrix}\text{mg ascorbic acid in volume} \\ \text{of standard solution titrated}^{**}\end{matrix}}{\begin{pmatrix}\text{average mL dye used} \\ \text{to titrate standards}\end{pmatrix} - \begin{pmatrix}\text{average mL dye} \\ \text{used to titrate blank}\end{pmatrix}} \quad (3)$$

**mg ascorbic acid in volume of standard solution titrated:

$$= (\text{mg of ascorbic acid} / 50\ \text{mL}) \times 2\text{mL}$$

$$\text{mg ascorbic acid} / \text{mL} = (X - B) \times (F / E) \times (V / Y) \quad (4)$$

where:

X = mL for sample titration.

B = average mL for sample blank titration.

F = titer of dye (= mg ascorbic acid equivalent to 1.0 mL indophenol standard solution).

E = mL assayed (=2 mL).

V = volume of initial assay solution (=7 mL).

Y = volume of sample aliquot titrated (=7 mL).

2.8 | Measurement of pH, Microbiological Quality, and Weight Loss

The pH of the samples was measured using a pH meter (Oakton Instruments, Vernon Hills, Il) at room temperature (25°C). The microbiological quality of humus samples was determined by performing total plate count and yeast and mold count analyses before processing, after processing, and during storage. Under aseptic conditions, a 10 g sample was taken from each tray. The sample was transferred into a sterile stomacher bag, and 90 mL of sterile peptone water was added. The mixture was homogenized for 2 min. Serial dilutions were prepared. For total plate count, 0.1 mL of the sample was plated onto Plate Count Agar. The plates were incubated at 30°C ± 2°C for 48 h. For yeast and mold enumeration, 0.1 mL of the sample was plated onto acidified Potato Dextrose Agar after sterilization. The plates were incubated at 25°C ± 2°C for 5 days. At the end of the incubation period, typical colonies were counted. The results were expressed as $\log_{10}$ CFU/g (BAM 1998). Weight loss ($n = 2$) was determined as the percentage of weight reduction (%) for treated trays after processing and at various storage intervals using a GK703 balance (Sartorius, Goettingen, Germany).

2.9 | Statistical Analysis

Data were reported as means ± standard deviation based on duplicate determinations. Statistical analyses were conducted using One-Way Analysis of Variance (ANOVA) and Duncan's New Multiple Range Test (DMRT) via SPSS software. A p-value < 0.05 was considered statistically significant (Cheenkaew et al. 2020).

3 | Results

3.1 | Color

The color values of lentil hummus samples before and after thermal processing are listed in Tables 1–3. After MAPS and MATS treatments, the L^* and a^* values of the samples decreased, while the b^* values increased. During the entire storage period, the a^* and L^* values of MAPS samples remained

TABLE 1 | Quality characteristics of lentil hummus prior to MAPS and MATS treatments.

Treatment	pH	L^*	a^*	b^*	Ascorbic acid content (mg/100 g)	MDA (μg/g)
MAPS	5.35 ± 0.01	72.0 ± 0.19	3.58 ± 0.07	22.6 ± 0.22	35.0 ± 0.86	0.060
MATS	5.25 ± 0.01	72.3 ± 0.17	2.99 ± 0.05	21.7 ± 0.18	33.6 ± 0.72	0.060

TABLE 2 | Quality characteristics of lentil hummus after MAPS treatment.

Storage time (days)	pH	L^*	a^*	b^*	ΔE	Ascorbic acid content (mg/100 g)	MDA (μg/g)
0	5.72 ± 0.01^{a}	69.3 ± 0.65^{ab}	2.65 ± 0.16^{abc}	23.3 ± 0.27^{bcd}	3.18 ± 0.56^{bcd}	52.4 ± 0.71^{a}	0.078 ± 0.008^{e}
15	5.65 ± 0.01^{b}	70.4 ± 0.23^{a}	2.25 ± 0.15^{de}	22.9 ± 0.78^{cd}	2.25 ± 0.14^{d}	46.5 ± 0.78^{b}	0.123 ± 0.024^{bcd}
30	5.48 ± 0.01^{c}	69.1 ± 0.61^{ab}	2.64 ± 0.24^{bc}	26.1 ± 0.98^{a}	4.67 ± 1.05^{a}	44.5 ± 1.04^{bc}	0.238 ± 0.035^{a}
45	5.44 ± 0.01^{d}	69.8 ± 0.19^{ab}	2.57 ± 0.04^{bcd}	24.3 ± 0.15^{b}	2.99 ± 0.19^{cd}	44.2 ± 0.93^{c}	0.155 ± 0.014^{b}
60	5.42 ± 0.01^{ef}	69.6 ± 0.19^{ab}	2.39 ± 0.06^{cde}	22.5 ± 0.40^{d}	2.69 ± 0.17^{cd}	36.7 ± 1.30^{e}	0.152 ± 0.021^{b}
75	5.43 ± 0.00^{de}	68.7 ± 0.28^{b}	2.96 ± 0.21^{a}	24.2 ± 0.81^{b}	3.78 ± 0.37^{abc}	29.3 ± 1.05^{g}	0.113 ± 0.023^{cde}
90	5.42 ± 0.01^{ef}	70.2 ± 0.15^{a}	2.21 ± 0.06^{e}	22.5 ± 0.36^{d}	2.23 ± 0.10^{d}	32.7 ± 0.91^{f}	0.150 ± 0.014^{bc}
105	5.40 ± 0.01^{f}	69.9 ± 1.93^{ab}	2.77 ± 0.25^{ab}	23.8 ± 0.70^{bc}	2.75 ± 1.70^{cd}	35.2 ± 1.00^{e}	0.105 ± 0.014^{de}
120	5.41 ± 0.01^{f}	69.2 ± 0.28^{ab}	2.84 ± 0.26^{ab}	25.9 ± 0.79^{a}	4.41 ± 0.37^{ab}	39.8 ± 1.65^{d}	0.120 ± 0.011^{bcd}

Note: The superscript letters (a, b, c, d) was indicate statistically significant differences among the mean values within each row, based on the results of the statistical analysis.

TABLE 3 | Quality characteristics of lentil hummus after MATS treatment.

Storage time (days)	pH	L^*	a^*	b^*	ΔE	Ascorbic acid content (mg/100 g)	MDA (μg/g)
0	5.42 ± 0.02^{b}	64.8 ± 0.81^{bc}	2.29 ± 0.37^{bc}	23.7 ± 0.72^{a}	8.20 ± 0.80^{b}	50.5 ± 0.76^{a}	0.242 ± 0.017^{c}
30	5.34 ± 0.01^{c}	63.6 ± 0.53^{d}	2.07 ± 0.08^{cd}	21.6 ± 0.57^{c}	8.71 ± 0.52^{b}	42.0 ± 1.17^{b}	0.330 ± 0.036^{b}
60	5.34 ± 0.01^{c}	66.1 ± 0.11^{a}	1.97 ± 0.05^{d}	21.8 ± 0.23^{c}	6.22 ± 0.11^{c}	34.7 ± 0.82^{c}	0.340 ± 0.045^{b}
90	5.33 ± 0.01^{c}	65.6 ± 0.61^{ab}	2.51 ± 0.22^{b}	22.7 ± 0.83^{b}	6.81 ± 0.56^{c}	21.3 ± 0.90^{d}	0.327 ± 0.014^{b}
120	5.33 ± 0.02^{c}	64.5 ± 0.51^{cd}	2.26 ± 0.59^{c}	22.4 ± 0.09^{bc}	7.89 ± 0.50^{b}	19.6 ± 1.34^{d}	0.387 ± 0.012^{a}
180	5.49 ± 0.02^{a}	62.0 ± 0.48^{e}	2.99 ± 0.21^{a}	22.8 ± 0.37^{b}	10.4 ± 0.50^{a}	16.9 ± 0.99^{e}	0.218 ± 0.013^{c}

Note: The superscript letters (a, b, c, d) was indicate statistically significant differences among the mean values within each row, based on the results of the statistical analysis.

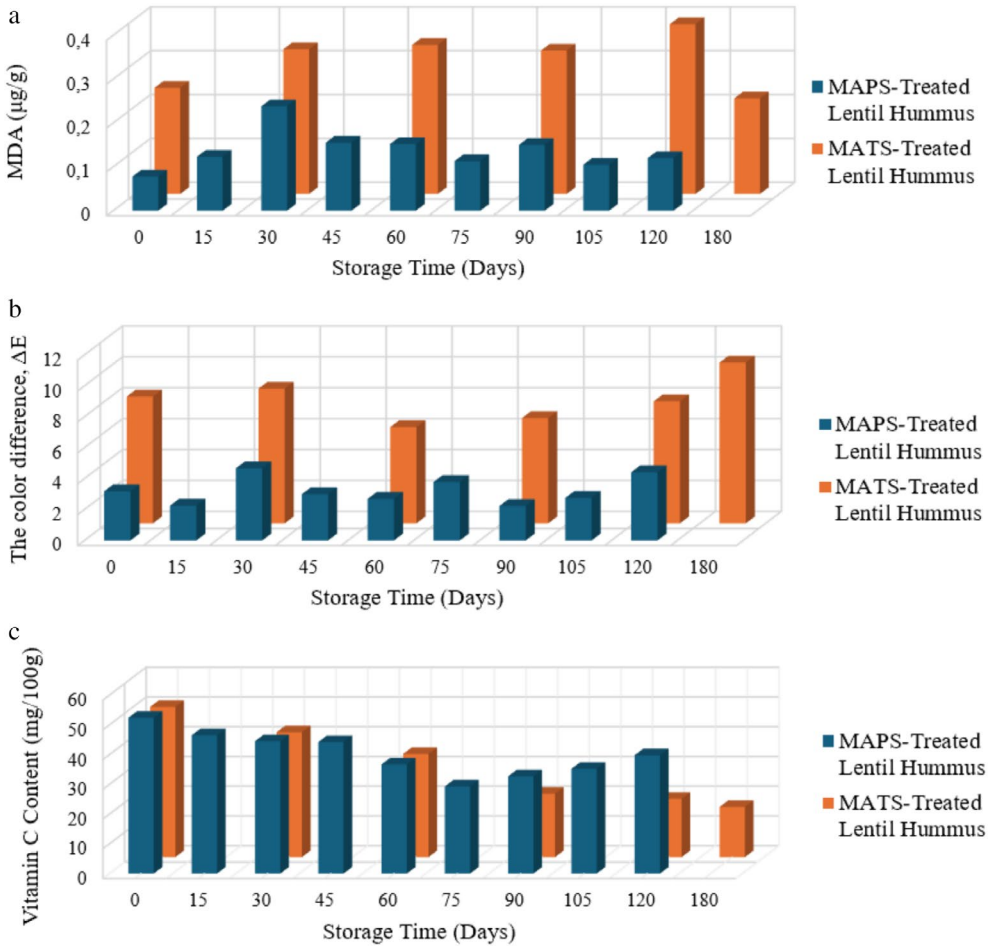

FIGURE 3 | Quality characteristics of lentil hummus after MAPS and MATS treatments. (a) TBARS values, (b) ΔE values, and (c) Vitamin C content.

statistically stable. On the other hand, reduction in a^* and L^* values was noted in MATS samples over the storage period. The color difference, ΔE, was found to be higher in MATS samples compared to MAPS samples (Figure 3). On the 120th day of storage, the ΔE value of MAPS-treated lentil hummus reached 4.41, as there were no differences in ΔE values between the first and last day. MATS-treated lentil hummus exhibited ΔE value of 10.4 on the 180th day, with differences observed in the ΔE values from the initial to the final day. According to the ΔE scale table, hummus samples treated with MAPS were observed to fall within the range of "fairly perceptible difference" to "perceptible difference" throughout the storage period. The ΔE values of hummus samples treated with MATS were determined to be within the "strong difference" range throughout the storage period.

Makhloufi and Yamani (2024) in their study prepared various dip samples using not only chickpeas but also red lentils, white

beans, green lentils, and green peas. They reported that the dip made with red lentils was the most preferred in terms of taste and appearance compared to the chickpea-based dip (hummus). In their findings, the red lentil-based dip had the same a^* and b^* values as the chickpea-based dip, but the L^* value was higher in the chickpea-based dip. They indicated that the L^*, a^*, and b^*values of the chickpea dip were 74.47, 5.57, and 30.66, respectively. The L^*, a^*, and b^* values of the red lentil dip (hummus) were 71.70, 6.35, and 30.65, respectively. In their studies examining the rheological properties, Alvarez et al. (2017) reported the L^*, a^*, and b^* color values of commercially available plain hummus produced in Spain as 75.3 ± 0.12, 0.29 ± 0.04, and 14.3 ± 0.09, respectively. When this is compared with their results, our product is darker (low L^*), less red (low a^*), and less yellow (low b^*). In our study, the color values of the samples were 69.3, 2.65, and 23.3 after MAPS treatment, while 64.8, 2.29, and 23.7 after MATS treatment.

Son et al. (2022) investigated the effect of microwave processing on the microbial decontamination level and quality of hummus purchased from a local market in Turkey. They reported L^*, a^*, and b^* color values as 76.3 ± 1.53, -0.25 ± 0.16, and 25.0 ± 0.69, respectively, after 5 min of microwave application to hummus placed in an open petri dish in a 2450 MHz home microwave device. Ahmed et al. (2019) studied the effects of high pressure treatment on the dielectric properties and microstructure of hummus obtained from a local market in Kuwait. The color L^*, a^*, and b^* values of unprocessed hummus samples were reported as 78.6 ± 0.11, 2.77 ± 0.01, and 27.0 ± 0.09, respectively. The lightness L^*, redness $+a^*$, and yellowness $+b^*$ values declined as the pressure increased, with the lowest values recorded at 600 MPa (L: 76.5 ± 0.14; a: 2.41 ± 0.02 and b: 26.6 ± 0.16).

3.2 | TBARS

The oxidative stability of processed lentil hummus samples was measured throughout storage; the TBARS values are listed in Tables 1–3. The TBARS values of hummus samples before treatment with MAPS and MATS were determined as 0.06 μg/g. After heat treatment processes, the TBARS values were found to be higher in MATS samples than in MAPS samples (Figure 3). Since heat can initiate the oxidation of lipids in oils (Konishi et al. 1995), an increase in TBARS values was detected after the process, as expected. Our findings revealed that the maximum generation of secondary oxidation products occurred on the 30th day of storage in the MAPS samples and on the 120th day of storage in the MATS samples. Typically, TBARS values rise during storage; however, this increase is not consistent (Alves et al. 2023; Asnaashari et al. 2015). The lid film of the packaging has low oxygen permeability, which helps to keep the TBARS value low. The film, which is made of nonpolar PET and PP, prevents moisture absorption during heat treatment. Patel et al. (2020) evaluated the performance of different packages containing ready-to-eat chicken pasta meals after MATS processing and in an accelerated shelf life process. They found that PET packaging with a double metal oxide coating exhibited a highly effective barrier against lipid oxidation, which was comparable to that of pouches made from aluminum foil.

The lentil hummus samples in our study contained 10.7% tahini and 8% soybean oil. Tahini comprises 57%–65% w/w oil, with a majority of this being unsaturated fatty acids like linoleic acid and oleic acid (Szpinak et al. 2022). Similarly, soybean oil contains a high concentration of polyunsaturated fatty acids; it includes 47% linoleic acid and 26% oleic acid (Prabakaran et al. 2018). Owing to the presence of polyunsaturated fatty acids in its composition, hummus is prone to lipid degradation (Papastergiadis et al. 2012). Results are given as malondialdehyde (MDA) equivalent. MDA is a prevalent secondary product of lipid oxidation. As oxidation progresses, hydroperoxides break down into MDA during storage. Oxidative rancidity is typically detected by measuring the concentration of MDA (Jung et al. 2016).

Since lipid autoxidation is a continuous and inevitable free radical chain reaction, it continues as long as there are compounds in the environment (Amaral et al. 2018). MDA values of MAPS and MATS samples decreased at the end of storage. The decrease in TBARS value can be explained by the decrease in primary and secondary oxidation products of lipid oxidation reactions with storage time (Gómez-Limia et al. 2021). On the 120th day of storage at 4°C, MAPS samples exhibited 0.12 μg/g MDA. Meanwhile, on the 180th day at 38°C, corresponding to 3-year storage at 23°C, MATS samples showed 0.22 μg/g MDA.

In the literature, there is no established TBARS value for hummus. Data and threshold values are generally only available for meat and fish products. In our study, the TBARS values obtained for lentil hummus samples are below the threshold TBARS values reported for other products in the literature. Campo et al. (2006) suggested a limit of approximately 2.0 mg of MDA per kg for oxidized beef acceptability. In contrast, McKenna et al. (2005) established an arbitrary threshold of 1.0 mg MDA/kg. Moreover, Hughes et al. (2014) reported that TBARS levels ranging from 2.60 to 3.11 mg MDA/kg in long-term aged beef striploins were still considered acceptable by consumers. Secci and Parisi (2016) established TBARS values for fish products, categorizing them as follows: values less than 0.58 mg/kg are considered not rancid, values between 0.58 and 1.51 mg/kg are deemed marginally rancid but acceptable, and values exceeding 1.51 mg/kg are classified as rancid and correlate with adverse sensory attributes.

3.3 | Vitamin C

The vitamin C content of lentil hummus samples before and after thermal processing is presented in Tables 1–3 and Figure 3. To enrich lentil hummus samples, 60 mg of liposomal-encapsulated vitamin C was added per 100 g of product. The amount of vitamin C detected in hummus samples before thermal processing was 34.95 mg/100 g for MAPS samples and 33.6 mg/100 g for MATS samples. After thermal processing, the amount of Vitamin C detected was 52.4 mg/100 g in MAPS samples and 50.5 mg/100 g in MATS samples. At the end of 120 days of storage at 4°C, 76.0% of the Vitamin C in MAPS-treated lentil hummus samples was retained. At the end of 180 days of storage at 38°C, 33.5% of the Vitamin C in MATS-treated lentil hummus samples was retained. The Vitamin C

used consisted of liposomal nano structures containing phosphatidylcholine. Various studies in the literature have utilized phosphatidylcholine liposomes for Vitamin C encapsulation. Marsanasco et al. (2016) used soy phosphatidylcholine-based liposomes to encapsulate Vitamin C, which was then added to chocolate milk for pasteurization. Their analyses demonstrated that the phosphatidylcholine-based liposomes exhibited a protective influence on heat-sensitive Vitamin C after pasteurization. In another set of studies, Marsanasco et al. (2015) and Marsanasco et al. (2011) incorporated liposomes derived from soy phosphatidylcholine into orange juice and pasteurized it. Their results indicated that these liposomal formulations were appropriate for applications in the food industry and yielded functional orange juice that maintained its bioactivity after pasteurization.

Kirby et al. (1991) utilized egg phosphatidylcholine for the encapsulation of ascorbic acid in liposomes. Their research suggested that these additives could be beneficial for enriching high-moisture foods and infant formulations. Sharma and Lal (2005) prepared microencapsulated ascorbic acid containing liposomes using the method described by Kirby et al. (1991). They enriched buffalo milk with this formulation and investigated its thermal stability after pasteurization and sterilization. They observed that the losses in Vitamin C were lower in pasteurization (63°C/30 min) compared to sterilization (121°C/15 min). Encapsulation of ascorbic acid in liposomes for high-moisture foods provided greater stability and better-controlled release characteristics compared to other techniques (Ramon and Danino 2008).

3.4 | pH and Microbiological Quality

The pH values of lentil hummus samples before and after thermal processing are listed in Tables 1–3. The pH value of the lentil hummus samples was 5.35 before the MAPS application and 5.72 after. During storage, the pH value of the lentil hummus samples tended to decrease. At the end of storage, the pH value of the samples was 5.41. Prior to the application of MATS, the pH value of the samples was 5.25, whereas after the application it increased to 5.42. Significant statistical differences were observed throughout the storage period. Toward the end of the storage period, the pH increased to 5.49. Amr et al. (2017) and Al-Qadiri et al. (2021) defined that the pH values of hummus samples subjected to gamma irradiation decreased during refrigerator storage. The WHO (2008) stated a pH value of 5.1 for hummus made with chickpeas. It has been recommended that hummus, which is intended to be consumed within 24 h after preparation, should have its pH value adjusted below 5 as a critical control point during production. Klug et al. (2018) reported a pH range of 4.9–5.1 for hummus with added broccoli. Canet et al. (2015) found that the pH value of chickpea gel, which has a similar composition to hummus, ranged from 5.98 to 4.31 depending on the amount of lemon juice added. Abidi and Yamani (2024) reported that the pH values of hummus samples obtained from restaurants in Amman, Jordan, ranged from 4.1 to 6.5. Makhloufi and Yamani (2024) reported that hummus made with chickpeas and other legumes did not show significant pH differences, with pH values ranging from 4.5 to 4.7. The difference in pH values depends mainly on the amount of lemon juice in hummus recipes. The predominant acid in lemon juice is citric acid, which is widely used in hummus to reduce pH levels. As a chelating agent, citric acid limits microbial growth by binding to divalent metal ions (Brul and Coote 1999). In hummus production methods that do not typically involve heat treatment, lowering the pH serves as a hurdle technology to extend shelf life. However, the resulting increase in sourness from acid-induced pH reduction is not always desirable. Hummus pasteurized and sterilized using MAPS and MATS methods can be produced in compliance with food safety standards, without the need to add excessive amounts of lemon juice that may negatively impact taste.

Aerobic plate counts and yeast and mold counts of lentil hummus samples were performed before processing, after processing, and during storage. Throughout the storage period, the microbiological quality of hummus remained preserved. Colony numbers were below the detection limit (10 CFU/g). These microbiological findings confirmed the effectiveness of the MAPS and MATS processing methods for hummus samples. Peng (2014) reported that, after a 16-day incubation of the MATS-processed tomato pouches at 35°C ± 1°C, no colonies below the detection limit (1 CFU/g) were detected in the treated samples.

3.5 | Weight Loss

The reduction in weight primarily results from the movement of moisture from inside the trays to the environment. It depends on the WVTR of the lidding film, which consists of an outer barrier of PET and an inner layer of polypropylene with the layers in between that cover the trays. The weight loss in MAPS-processed lentil hummus samples varied between 0% and 0.04% during 120 days of storage at 4°C. The weight loss in MATS-processed lentil hummus samples during 180 days of storage at 38°C ranged from 0% to 1.2%. A minimal alteration in weight (≤ 1.2%) was noted at both storage temperatures. The higher weight loss in MATS-processed samples may be due to the accelerated rate of water vapor loss due to low humidity and high temperature during storage. This weight loss was largely associated with the very low value of WVTR film. Sonar (2020) filled carrot puree into pouches containing PET and polyethylene and subjected them to pasteurization. He reported that the total weight loss during storage was less than 0.5% regardless of storage temperature (4°C, 8°C, and 13°C). Patel et al. (2020) studied the performance of ready-to-eat chicken pasta meals packaged with EVOH-based pouches, double metal oxide coated PET layer-based ultra-high barrier packaging, and aluminum (AL) foil-based pouches during the MATS processing and shelf life. They reported that, compared to EVOH pouches, PET pouches with double-layered metal oxide coating preserved a greater portion of the moisture in the product during storage.

4 | Conclusion

The MAPS and MATS processing methods allow for safe production without the need for excessive lemon juice or chemical preservatives, preserving both product quality and taste. MATS

samples had a greater color difference (ΔE) compared to MAPS samples. Samples containing tahini and soybean oil showed an increase in TBARS values after thermal processing due to lipid oxidation, with peak levels observed at different storage times for MAPS and MATS samples. Despite fluctuations in TBARS values during storage, the final values remained below the threshold typically reported for other food products. The addition of liposomal-encapsulated Vitamin C enhanced the ascorbic acid content of the hummus samples, with higher retention rates observed after thermal processing. The microbiological quality of the hummus samples remained stable throughout storage, with colony counts below the detection limit, confirming the effectiveness of the MAPS and MATS processing methods.

Author Contributions

Burcu Tenderis: methodology, investigation, writing – original draft, visualization, and project administration. **Shyam S. Sablani:** conceptualization, writing – reviewing and editing, supervision, and project administration. **Juming Tang:** conceptualization, methodology, writing – review and editing, funding acquisition, resources, supervision, and project administration. **Zhongwei Tang:** investigation. **Huimin Lin:** investigation. **Stewart Bohnet:** investigation.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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