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Storage quality of retort-pouched foods for patients with kidney disease

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Abstract Most kidney-friendly foods available in the market are freshly prepared and remain susceptible to microbial contamination, which leads to rapid spoilage. To address this issue, thermal sterilization is required, using packaging that can withstand high temperatures and pressures. Retort pouches, composed of multilayer plastic films, have been shown to possess high resistance to sterilization processes and enable the extended shelf life of ready-to-eat meals at ambient temperature, and maintaining product quality, including physical, chemical, and sensory attributes, throughout the storage period remains critical. This study investigated the quality and shelf-life of a kidney-friendly sour curry product containing egg white tofu mixed with fish and Chinese cabbage, packed in retort pouches and stored under accelerated conditions at 35, 45, and 55°C for 4 weeks. The results indicated that samples stored at 35°C had the highest values in lightness (L), redness (a), and yellowness (b*) of the curry broth. The total color difference (ΔE) increased throughout the 4-week storage period under accelerated conditions. However, samples stored at 55°C exhibited the highest hardness, cohesiveness, and chewiness values, and no growth of pathogenic or spoilage microorganisms was detected during the entire 4-week storage period under ambient conditions. Sensory evaluation using the difference from the control test revealed that consumers perceived noticeable color changes starting from the 2nd week of storage at 55°C. Therefore, color was identified as the primary indicator of quality deterioration, and the overall color change (ΔE) observed in egg white tofu mixed with fish at week 2 under accelerated storage at 55°C was designated as the product's critical point. This critical point signifies the moment when the quality of the egg white tofu begins to decline significantly, as indicated by consumer perception of color changes. Recognizing this threshold allows for better management of storage conditions to maintain product quality.

Keywords: Chronic kidney disease, Retort pouch, Sour curry, Shelf life

Introduction

Patients with chronic kidney disease (CKD) who undergo hemodialysis to remove excess fluid and waste products from the body often experience

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significant losses of proteins, vitamins, and minerals during the dialysis process. This loss leads to a high risk of malnutrition, especially protein deficiency. Therefore, it is essential for these patients to follow an appropriate renal diet that ensures adequate nutrient intake and helps reduce complications. Currently, commercially available renal-specific meals are typically freshly cooked and may still contain spoilage microorganisms. As a result, they require refrigeration and can only be stored for 1–2 days. This short shelf life poses challenges for manufacturers in terms of maintaining cold chain conditions during storage, transportation, and distribution. To address these issues, commercial sterilization is necessary. This process allows food to be preserved for 4–12 months without the need for refrigeration. However, sterilization requires the use of packaging that can withstand high temperature and pressure. Retort pouches, which are made from multilayer plastic films or laminated structures that include aluminum foil, have been shown to endure high-temperature sterilization processes effectively (Lee *et al.*, 2015). Currently, frequently pre-prepared foods, such as soups, boiled rice, and curries, are primarily sold in retort pouches. It has been reported by Shankar *et al.* (2002) that thermal processing of curries in retort pouches results in products with satisfactory sensory attributes and a shelf life of 24 months at room temperature. This indicates that the method of thermal processing used for these foods preserves their flavor and texture and allows them to be stored safely without refrigeration for an extended period. Kumar *et al.* (2017) developed The RTE foxtail millet halwa was prepared and subjected to a specific heat treatment process designed to ensure food safety by achieving a total lethality value, which helps eliminate harmful microorganisms. The value of 5.26 minutes suggests the duration required at a certain temperature to effectively achieve this level of safety.

This study aimed to develop a ready-to-eat meal for CKD patients with extended shelf life at ambient temperature. The approach involved thermal sterilization combined with retort pouch packaging. The goal was to produce a convenient, nutritionally appropriate food product that meets the lifestyle needs of consumers with CKD while also minimizing storage, transportation, and distribution challenges for food manufacturers.

Materials and methods

Raw materials

The ingredients used in this study included egg white tofu with fish meat, Chinese cabbage, and sour curry soup base, all obtained from Modish Food Design Co., Ltd., as well as 3 grams of lime powder, vitamin C (22.6 mg per 100 g), vitamin B_1 (0.71 mg per 100 g), sodium (309 mg of per 100 g), phosphorus (43.5 mg per 100 g) and potassium (158 mg per 100 g).

Equipment and instruments

The equipment and instruments used in this study included a four-digit precision analytical balance (Sartorius, model BSA224S-CW, Germany), variable volume pipettes (100–1,000 µL; Pipetman, model G, USA), and a horizontal water spray retort sterilizer. A data logger (Yokogawa, model FX1012, China) with a 2.5 cm thermocouple probe was used for temperature monitoring. The packaging material consisted of stand-up retort pouches with an aluminum foil layer (PET 12 µm/ON 15 µm/Al 9 µm/CPP 80 µm), measuring 140 × 180 × 40 mm, obtained from Paya Belle Corporate Co., Ltd., Thailand. Standard kitchen utensils such as bowls, plates, cutting boards, knives, and spoons were also utilized.

Experimental procedure

The sour curry, nutritionally formulated to be suitable for patients with chronic kidney disease by Modish Food Design Co., Ltd., was filled into retort pouches and thermally processed at 121°C for 34 minutes. The products were then stored under accelerated conditions at temperatures of 35°C, 45°C, and 55°C for a period of 4 weeks.

Quality evaluation of sour curry stored in retort pouched

Color Measurement: Color of the curry broth, Chinese cabbage, and fish tofu was measured using a colorimeter under D65 illumination in the CIELAB system. Values were recorded as L* (lightness), a* (redness), and b* (yellowness). Three samples were measured per replication. Overall color change (ΔE) was calculated relative to week 0 values using the following formula:

$$\Delta E = [\ (\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2\ ]^{2/1}$$

where ΔL*, Δa*, and Δb* are the differences in lightness, redness, and yellowness, respectively, between week 0 and weeks 1, 2, 3, or 4.

Texture Profile Analysis (TPA): Fish tofu cubes (1.5 × 1.5 × 1.5 cm) were analyzed for textural characteristics using a texture analyzer (TA-XTPlus, Stable Micro Systems, UK), adapted from Colmenero *et al.* (2010). A 50 mm cylindrical probe (P/50) compressed samples at a pre-test speed of 1.0 mm/s, a test speed of 1.0 mm/s, and a post-test speed of 5.0 mm/s, with 50% deformation. Parameters recorded included hardness, springiness, cohesiveness, and chewiness. Six samples were measured per replication.

pH measurement: Ten grams of homogenized sour curry were mixed with 90 mL of distilled water, and pH was measured using a pH meter according to the method by Agnihotri and Pal (1997). Each sample was measured three times per replication.

Lipid oxidation was assessed by determining 2-thiobarbituric acid (TBA) values. Optical density (OD) was measured, and TBA content was expressed as mg malonaldehyde per kg of sample.

Sensory evaluation using the difference from control test: Sensory difference testing was conducted using the Difference from Control Test. A score of 0 indicated no difference, while a score of 10 represented the highest degree of difference. Ten untrained panelists participated in the evaluation. Samples were placed in coded plastic cups labeled with randomly generated three-digit numbers and sealed tightly. Samples were served at room temperature. In this phase of the study, participants did not taste the samples but were instructed to assess only visual and olfactory attributes, including color and aroma. Evaluations were conducted at weeks 0, 1, 2, 3, and 4.

Microbiological analysis

Microbiological testing was carried out by the Asian Medical and Agricultural Research Center (AMARC) according to Thai Ministry of Public Health Notification No. 355 (B.E. 2556) on hermetically sealed foods. Analyses included total viable count (U.S. Food and Drug Administration, (2001), yeast and mold counts (AOAC, 2019), coliforms (U.S. Food and Drug Administration, 2013), *Staphylococcus aureus* in 25 g of sample (ISO 6888-3, 2003), *Salmonella spp.* in 25 g of sample (ISO 6579, 2007), *Clostridium botulinum* in 25 g of sample (U.S. Food and Drug Administration, 2001), and mesophilic and thermophilic anaerobic sporeformers (APHA, 2001). Assessments were performed at weeks 0 and 4.

Shelf-life estimation

Shelf-life was estimated on the degradation kinetics of selected quality indicators sensitive to product deterioration in retort pouch packaging. Shelf-life prediction was calculated using chemical kinetic modeling approaches.

Experimental design and data analysis

A completely randomized design (CRD) was used for all experiments, except for sensory preference testing, which employed a randomized complete block design (RCBD). Statistical analysis of variance (ANOVA) was conducted, and mean differences were compared using Duncan's new multiple range test. All data were analyzed using commercial statistical software.

Results

Quality evaluation of sour curry stored in retort pouched

The changes in color parameters of the sour curry product packed in retort pouches during accelerated storage at 35, 45, and 55 °C for 4 weeks were investigated. The results of lightness (L*), redness (a*), and yellowness (b*) are shown in Tables 1, 2, and 3, respectively.

Table 1. Lightness (L*) values of sour curry products packed in retort pouches during accelerated storage at 35, 45, and 55 °C

Sample	Storage Time (weeks)	Storage temperature (°C)		
		35	45	55
Egg tofu with fish meat	1^{NS}	50.18 ± 6.31^{a}	48.90 ± 3.15^{a}	49.04 ± 1.77^{a}
	2	48.62 ± 2.14^{aA}	46.58 ± 4.19^{abAB}	42.88 ± 4.19^{abC}
	3	44.90 ± 4.31^{aA}	43.44 ± 1.59^{acA}	36.35 ± 3.88^{cB}
	4	46.59 ± 4.47^{aA}	39.76 ± 4.31^{cB}	37.77 ± 1.45^{bcB}
Chinese cabbage	1^{NS}	47.79 ± 4.33^{a}	49.51 ± 2.71^{a}	44.91 ± 3.54^{a}
	2	49.12 ± 4.99^{a}	41.68 ± 7.38^{a}	42.78 ± 3.50^{a}
	3	49.48 ± 4.37^{a}	49.11 ± 3.14^{a}	40.51 ± 4.60^{a}
	4	51.69 ± 5.63^{a}	46.13 ± 7.17^{a}	38.83 ± 3.26^{a}
Sour curry broth	1^{NS}	29.96 ± 0.55^{a}	29.71 ± 1.21^{a}	29.36 ± 1.99^{a}
	2	28.38 ± 0.71^{b}	28.99 ± 0.51^{a}	25.30 ± 0.49^{bc}
	3	28.44 ± 0.41^{b}	27.59 ± 0.65^{b}	25.66 ± 1.14^{b}
	4	29.44 ± 0.53^{a}	27.26 ± 0.30^{b}	23.95 ± 1.06^{c}

$^{a, b, c}$ Different letters in the same column indicate significant differences ($p < 0.05$).
$^{A, B, C}$ Different letters in the same row indicate significant differences ($p < 0.05$).
^{ns} No significant difference in the same column ($p \geq 0.05$).
^{NS} No significant difference in the same row ($p \geq 0.05$).

L* values of the retort-pouched sour curry products gradually decreased during accelerated storage for 4 weeks (Table 1). Among the tested components, the product containing egg tofu mixed with fish meat, cabbage, and sour curry soup stored at 35 °C exhibited the highest L* values, followed by those stored at 45 °C and 55 °C, respectively.

Consequently, elevated storage temperatures result in lower L* values for product components. As shown in Table 2 (a* values) and Table 3 (b* values), the redness (a*) and yellowness (b*) of egg tofu with fish meat and sour curry soup decreased, particularly under high-temperature storage conditions during the 4-week accelerated storage. Sour curry soup stored at 35 °C had the highest a* and b* values, followed by samples stored at 45 °C and 55 °C, respectively.

Table 2. Redness (a*) values of sour curry products packed in retort pouches during accelerated storage at 35, 45, and 55 °C

Sample	**Storage Time (weeks)**	**Storage temperature (°C)**		
		35	45	55
Egg tofu with fish meat	1^{NS}	11.91 ± 2.65^{ns}	12.90 ± 0.87^{ns}	12.67 ± 2.07^{ns}
	2^{NS}	13.23 ± 0.87^{ns}	12.44 ± 1.91^{ns}	11.49 ± 1.03^{ns}
	3^{NS}	13.76 ± 1.97^{ns}	14.68 ± 1.29^{ns}	13.38 ± 1.93^{ns}
	4^{NS}	13.44 ± 1.77^{ns}	14.26 ± 2.59^{ns}	12.09 ± 1.28^{ns}
Chinese cabbage	1^{NS}	5.39 ± 0.75^{a}	4.88 ± 1.84^{ns}	4.95 ± 1.27^{c}
	2	3.17 ± 1.44^{bB}	3.96 ± 1.38^{nsAB}	5.42 ± 1.43^{bcA}
	3^{NS}	5.71 ± 2.26^{a}	4.70 ± 1.24^{ns}	6.87 ± 1.37^{ab}
	4	2.68 ± 0.82^{bC}	3.95 ± 1.03^{nsB}	7.22 ± 0.93^{aA}
Sour curry broth	1	26.29 ± 0.40^{nsA}	26.36 ± 0.78^{nsA}	24.85 ± 0.43^{aB}
	2	25.75 ± 0.86^{nsA}	26.36 ± 0.35^{nsA}	23.20 ± 0.95^{bcB}
	3^{NS}	24.58 ± 2.50^{ns}	25.79 ± 0.22^{nsb}	24.18 ± 1.07^{ab}
	4	26.93 ± 1.07^{nsA}	25.62 ± 0.38^{nsB}	22.99 ± 0.84^{cC}

$^{a, b, c}$ Different letters in the same column indicate significant differences ($p < 0.05$).
$^{A, B, C}$ Different letters in the same row indicate significant differences ($p < 0.05$).
^{ns} No significant difference in the same column ($p \geq 0.05$).
^{NS} No significant difference in the same row ($p \geq 0.05$).

Table 3. Yellowness (b*) values of sour curry products packed in retort pouches during accelerated storage at 35, 45, and 55 °C

Sample	**Storage Time (weeks)**	**Storage temperature (°C)**		
		35^{ns}	45^{ns}	55^{ns}
Egg tofu with fish meat	1^{NS}	29.79±1.74	29.33±0.42	28.80±2.34
	2^{NS}	30.80±1.49	30.02±1.98	28.64±3.55
	3	29.90 ± 3.10^{A}	30.54 ± 1.71^{A}	25.55 ± 4.72^{B}
	4^{NS}	29.97±3.05	28.49±4.39	26.24±3.12
Chinese cabbage	1	25.63 ± 1.66^{B}	25.36 ± 2.01^{B}	27.69 ± 0.59^{A}
	2	24.79 ± 2.83^{B}	27.64 ± 2.16^{AB}	$30.17 \pm 2.6\ 9^{A}$
	3^{NS}	27.25±1.88	29.05±1.43	30.05± 3.25
	4	25.08 ± 2.63^{B}	26.42 ± 1.74^{B}	29.67 ± 1.65^{A}
Sour curry broth	1^{NS}	37.07± 0.59	36.86±0.61	36.14±0.84
	2	36.59 ± 0.54^{A}	35.38 ± 0.60^{B}	33.61 ± 0.93^{C}
	3	36.94 ± 1.52^{A}	36.74 ± 0.41^{A}	34.86 ± 1.30^{B}
	4	37.89 ± 1.07^{A}	36.29 ± 0.78^{B}	33.32 ± 1.34^{C}

$^{A, B, C}$ Different letters in the same row indicate significant differences ($p < 0.05$).
^{ns} No significant difference in the same column ($p \geq 0.05$).
^{NS} No significant difference in the same row ($p \geq 0.05$).

In addition, maillard reactions may also contribute where interactions between sugars and amino acids can reduce color intensity in retort-processed products, resulting in a loss of redness at higher temperatures. In contrast, the redness of cabbage in the product tended to increase during storage, with samples stored at 55 °C showing the highest a* and b* values, followed by those stored at 45 °C and 35 °C, respectively. These findings are clearly demonstrated that storage temperature and duration significantly influenced the color quality of retort-pouched sour curry products. The overall color change (ΔE) of sour curry products during accelerated storage at 35, 45, and 55 °C for 4 weeks is presented in Tables 4 to 6

Table 4. ΔE Values of White Egg Tofu Mixed with Fish Meat in Sour Curry Product Packed in Retort Pouches during Accelerated Storage at 35, 45, and 55 °C

Storage Time (Weeks)	**Storage Temperature (°C)**		
	35^{ns}	45	55
1^{NS}	2.83 ± 1.29	3.45 ± 0.80^{c}	3.88 ± 0.83c
2^{NS}	3.44 ± 0.42	5.50 ± 2.17^{bc}	9.36 ± 5.35^{ab}
3	7.70 ± 0.40^{B}	9.18 ± 1.42^{abB}	16.37 ± 1.48^{aA}
4^{NS}	6.45 ± 3.59	12.93 ± 2.98^{a}	14.81 ± 1.29^{a}

$^{a, b, c}$ Values within the same column with different letters are significantly different ($p < 0.05$).
$^{A, B, C}$ Values within the same row with different letters are significantly different ($p < 0.05$).
^{ns} No significant difference within the same column ($p \geq 0.05$).
^{NS} No significant difference within the same row ($p \geq 0.05$).

The total color difference (ΔE) values of egg tofu with fish meat, cabbage, and sour curry soup in retort-pouched sour curry products showed a continuous increase throughout 4 weeks of accelerated storage (Table 4-6). The highest ΔE values were observed in samples stored at 55 °C, followed by those stored at 45 °C and 35 °C, respectively.

Table 5. ΔE Values of Chinese Cabbage in Sour Curry Product Packed in Retort Pouches during Accelerated Storage at 35, 45, and 55 °C

Storage Time (Weeks)	**Storage Temperature (°C)**		
	35^{ns}	45^{ns}	55^{ns}
1^{NS}	4.67 ± 0.63	3.37 ± 0.75	5.52 ± 2.89
2^{NS}	3.31 ± 2.41	10.14 ± 7.03	11.15 ± 2.81
3	2.87 ± 0.30^{B}	4.12 ± 0.98^{B}	13.69 ± 5.27^{A}
4^{NS}	2.87 ± 1.36	5.99 ± 7.43	14.07 ± 0.25

$^{a, b, c}$ Values within the same column with different letters are significantly different ($p < 0.05$).
$^{A, B, C}$ Values within the same row with different letters are significantly different ($p < 0.05$).
^{ns} No significant difference within the same column ($p \geq 0.05$).
^{NS} No significant difference within the same row ($p \geq 0.05$).

Table 6. ΔE Values of Sour Curry Broth in Sour Curry Product Packed in Retort Pouches during Accelerated Storage at 35, 45, and 55 °C

Storage Time (Weeks)	Storage Temperature (°C)		
	35[ns]	45[ns]	55[ns]
1[NS]	3.09 ± 0.25	3.24 ± 1.44	2.90 ± 2.19
2	3.52 ± 0.31[B]	3.85 ± 0.24[B]	7.27 ± 0.94[A]
3[NS]	4.35 ± 0.57	4.66 ± 0.74	6.54 ± 1.75
4	4.23 ± 0.96[B]	4.93 ± 0.25[AB]	8.63 ± 1.95[A]

[A, B] Values within the same row with different letters are significantly different ($p < 0.05$).
[ns] No significant difference within the same column ($p \geq 0.05$).
[NS] No significant difference within the same row ($p \geq 0.05$).

Table 7. Texture Values of White Egg Tofu Mixed with Fish Meat in Sour Curry Product Packed in Retort Pouches during Accelerated Storage at 35, 45, and 55 °C

Texture Values	Storage Time (Weeks)	Storage Temperature (°C)		
		35	45	55
Hardness (g_f)	1[NS]	2497.70 ± 149.24[b]	2707.42 ± 128.92b[c]	2525.81 ± 70.94[c]
	2	2620.55 ± 157.18[bB]	2560.17 ± 120.83[cB]	2870.29 ± 86.18[bA]
	3	2645.93 ± 100.80[bB]	2890.25 ± 172.01[abB]	3289.79 ± 205.36[aA]
	4[NS]	3028.89 ± 65.01[a]	2999.27 ± 198.76[a]	3178.55 ± 263.36[a]
Elasticity	1[NS]	0.93 ±0.0 1[a]	0.92 ± 0.02[a]	0.92 ± 0.01[a]
	2[NS]	0.93±0.0 0[a]	0.93 ± 0.02[a]	0.94 ± 0.02[a]
	3[NS]	0.92 ±0.03 [a]	0.91 ± 0.01[a]	0.94 ± 0.01[a]
	4[NS]	0.93±0.02 [a]	0.93 ± 0.02[a]	0.95 ± 0.01[a]
Cohesiveness (g_f.s)	1[NS]	1488.77 ± 153.31[b]	1661.93 ± 92.32[bc]	1483.06 ± 80.26[b]
	2[NS]	1607.87 ± 90.29a[b]	1550.15 ± 94.45[c]	1600.73 ± 105.01[b]
	3[NS]	1668.56 ± 102.04[ab]	1796.36 ± 71.69[b]	1838.56 ± 147.71[a]
	4	1763.27 ± 131.52[aC]	2024.74 ± 168.26[aA]	1972.46 ± 10.20[aB]
Chewing Force (g_f)	1[NS]	1389.94 ± 151.06[b]	1529.26 ±61.10[bc]	1369.55 ±69.41[b]
	2[NS]	1489.82 ± 79.06[b]	1438.73± 94.64[c]	1503.57 ±121.71[b]
	3	1387.62 ± 163.39[bC]	1612.05 ±38.29[bB]	1906.28 ±38.70[aA]
	4[NS]	1859.84 ± 142.45[a]	1876.12 ±72.05[a]	1903.41 ±17.50[a]

[ns] No significant difference within the same column ($p \geq 0.05$).
[NS] No significant difference within the same row ($p \geq 0.05$).
[a, b, c] Values within the same column with different letters are significantly different ($p < 0.05$).
[A, B, C] Values within the same row with different letters are significantly different ($p < 0.05$).

The evaluated parameters included hardness, cohesiveness, and chewiness are shown in Tables 7. The elasticity of egg tofu with fish meat in retort-pouched sour curry products stored at 35, 45, and 55 °C showed no statistically significant differences ($p \geq 0.05$). In contrast, hardness, cohesiveness, and chewiness tended to increase over the 4-week accelerated storage period. The highest values for hardness, cohesiveness, and chewiness were observed in samples stored at 55 °C, followed by those stored at 45 °C and 35 °C, respectively.

As the storage temperature increases, protein structure is progressively disrupted, resulting in firmer and more cohesive textures with greater chewiness. These findings indicated that storage temperature and duration significantly affect the hardness, cohesiveness, and chewiness of egg tofu with fish meat in retort-pouched sour curry products.

For the pH analysis of retort-pouched sour curry products during accelerated storage at 35, 45, and 55 °C for 4 weeks (Table 8), the pH values remained constant throughout the storage period, even under elevated temperatures and prolonged storage time. This stability may be attributed to the buffering capacity of key ingredients in the sour curry formulation, such as organic acids and spices, which help maintain the product's acidity during storage.

Table 8. pH Values of Sour Curry Product Packed in Retort Pouches during Accelerated Storage at 35, 45, and 55 °C

Storage Time (Weeks)	Storage Temperature (°C)		
	35^{ns}	45	55^{ns}
1	4.59 ± 0.05^{A}	4.58 ± 0.16^{aA}	4.53 ± 0.04^{B}
2	4.57 ± 0.03^{A}	4.48 ± 0.03^{bC}	4.53 ± 0.03^{B}
3	4.63 ± 0.05^{A}	4.50 ± 0.04^{bB}	4.63 ± 0.02^{A}
4^{NS}	4.60 ± 0.03	4.54 ± 0.07^{a}	4.65 ± 0.22

ns No significant difference within the same column ($p \geq 0.05$).
a, b, c Values within the same column with different letters are significantly different ($p < 0.05$)

Table 9. Presents the thiobarbituric acid (TBA) values of the sour curry product packed in retort pouches during accelerated storage at 35, 45, and 55 °C

Storage Time (Weeks)	Storage Temperature (°C)		
	35^{ns}	45^{ns}	55^{ns}
1^{NS}	0.23 ± 0.18	0.22 ± 0.14	0.13 ± 0.21
2^{NS}	0.22 ± 0.02	0.28 ± 0.02	0.20 ± 0.03
3^{NS}	0.19 ± 0.02	0.18 ± 0.06	0.12 ± 0.04
4^{NS}	0.22 ± 0.02	0.18 ± 0.10	0.22 ± 0.15

ns No significant difference within the same column ($p \geq 0.05$)
NS No significant difference within the same row ($p \geq 0.05$)

The thiobarbituric acid (TBA) values of retort-pouched sour curry products during accelerated storage at 35, 45, and 55 °C for 4 weeks are presented in Table 9. The results showed no significant increase in TBA values throughout the storage period. TBA measurement is a widely used method for assessing lipid oxidation in meat products (Abeyrathne *et al.*, 2021). Lipid oxidation can negatively impact product quality, leading to rancidity, color degradation, nutrient loss, and flavor deterioration.

Based on the results of the difference-from-control tests for color and odor of retort-pouched sour curry products stored under accelerated conditions at 35, 45, and 55 °C for 4 weeks (Tables 10 and 11), panelists were able to clearly detect changes in color as early as week 2 of storage at 55 °C. Consequently, "color" was identified as a key quality attribute and a potential indicator of product deterioration.

Table 10. Difference-from-control test for color of sour curry product during accelerated storage

Storage Time (Week)	Storage Temperature (°C)	Mean Difference from Control	Difference from Blind Control Mean	*p*-Value
1	Blind Control	2.00		
	35	2.00	0.00	1.00
	45	2.10	0.10	0.990
	55	2.80	0.80	0.156
2	Blind Control	1.50		
	35	2.90	1.40	0.230
	45	290.	1.40	0.230
	55	5.70	4.20	0.000*
3	Blind Control	2.20		
	35	3.40	1.20	0.210
	45	4.50	2.30	0.000*
	55	7.30	5.10	0.000*
4	Blind Control	2.70		
	35	2.50	0.20	0.977
	45	4.10	1.40	0.081
	55	8.10	5.40	0.000*

* Significantly different from the blind control ($p < 0.05$)

Table 11. Difference-from-control test for odor of sour curry product during accelerated storage

Storage Time (Week)	Storage Temperature (°C)	Mean Difference from Control	Difference from Blind Control Mean	*p*-Value
1	Blind Control	.250		
	35	.280	0.30	0.795
	45	.250	0.00	1.000
	55	3.40	0.90	0.083
2	Blind Control	3.20		
	35	.350	0.30	0.933
	45	4.50	1.30	0.119
	55	.500	1.80	0.210
3	Blind Control	3.70		
	35	4.30	0.60	0.440
	45	5.10	1.40	0.015*
	55	6.30	2.60	0.000*
4	Blind Control	3.60		
	35	3.70	0.10	0.982
	45	4.60	1.00	0.016*
	55	5.60	2.00	0.000*

* Significantly different from the blind control ($p < 0.05$)

Microbiological analysis

Microbiological analysis of retort-pouched sour curry products after thermal sterilization (Tables 12 and 13) revealed that total viable counts, yeasts and molds, as well as hazardous pathogenic microorganisms such as *Staphylococcus aureus*, *Salmonella* spp., and *Clostridium botulinum*, were either at very low levels (<10 CFU/g or <3 MPN/g) or undetectable.

Table 12. Microbial counts of sour curry product packed in retort pouch after thermal sterilization

Microorganism type	Sour curry product after sterilization
Total plate count	10>CFU/g
Yeasts and molds	10>CFU/g
Coliforms	>3 MPN/g
Staphylococcus. Aureus	Not detected in 25 g
***Salmonella* spp.**	Not detected in 25 g
Clostridium botulinum	Not detected in 25 g
Thermophilic anaerobic sporeformer	Not detected in 25 g
Mesophilic anaerobic sporeformer	10>CFU/g

Table 13. Microbial counts of sour curry product packed in retort pouch after sterilization during 4 weeks of accelerated storage

Microorganism type	Storage Temperature (°C)		
	35	45	55
Total plate count	10>CFU/g	10>CFU/g	10>CFU/g
Yeasts and molds	10>CFU/g	10>CFU/g	10>CFU/g
Coliforms	>3 MPN/g	>3 MPN/g	>3 MPN/g
Staphylococcus. Aureus	Not detected in 25 g	Not detected in 25 g	Not detected in 25 g
***Salmonella* spp.**	Not detected in 25 g	Not detected in 25 g	Not detected in 25 g
Clostridium botulinum	Not detected in 25 g	Not detected in 25 g	Not detected in 25 g
Thermophilic anaerobic sporeformer	Not detected in 25 g	Not detected in 25 g	Not detected in 25 g
Mesophilic anaerobic sporeformer	10>CFU/g	10>CFU/g	10>CFU/g

Shelf-life estimation

Based on sensory evaluation of retort-pouched sour curry products during accelerated storage, Lee and Krochta (2002) noted that storage conditions can be adjusted to accelerate reactions and obtain results more rapidly. In this study, storage temperatures of 35, 45, and 55 °C were used for accelerated testing. Difference-from-control tests indicated that color was the most sensitive quality attribute for detecting product deterioration, with consumers clearly perceiving changes in appearance as early as week 2 of storage. Consequently, the total color difference (ΔE) of the soup at week 2 under storage at 55 °C was defined as the critical point indicating product deterioration. From this study, consumer acceptance began to decline when ΔE reached 7.27.

The kinetic model used to estimate the shelf life of retort-pouched sour curry products at 30 °C is expressed as: $\Delta Et - \Delta E_0 = kt$

Where: ΔE_0 is the initial ΔE value on day 0

ΔEt is the ΔE value at the critical point (7.27)

k is the reaction rate constant for ΔE at 30 °C, calculated using the Arrhenius model.

Using this model, the kinetic equation for ΔE at 30 °C was determined to be $\Delta E_t - \Delta E_0 = 1.3221\ t$, and the estimated shelf life of the retort-pouched sour curry product was 5.50 weeks.

Discussion

This study is comprehensively evaluated the physicochemical, microbiological, and sensory stability of sour curry products packed in retort pouches under accelerated storage conditions at 35, 45, and 55 °C for four weeks. Color parameters (L*, a*, b*) of egg white tofu with fish meat, Chinese cabbage, and sour curry broth decreased significantly with increasing temperature and storage time, particularly at 55 °C, due to heat-induced pigment degradation and Maillard reactions. This reduction in lightness could be attributed to non-enzymatic browning reactions. This reduction in lightness could be attributed to thermal degradation of natural pigments and non-enzymatic browning, as recent evidence indicates that naturally occurring food pigments are highly susceptible to heat- and storage-induced degradation (Pandiselvam *et al.*, 2023). Total color difference (ΔE) values exceeded the perceptibility threshold (ΔE > 3) within 2–4 weeks of storage, with the most notable deterioration observed at 55 °C. These color changes may be attributed to pigment degradation, such as the breakdown of carotenoids, as well as non-enzymatic browning through Maillard reaction induced by heat. The decline in lightness and color stability aligns with recent findings showed that carotenoids and other natural pigments are highly susceptible to thermal processing and storage conditions, undergoing degradation, isomerization, and oxidative cleavage during heat treatment (Syawalluddin *et al.*, 2024; Moura *et al.*, 2023; Zhang *et al.*, 2025). Moreover, a positive correlation between reaction rate and temperature which intensifies interactions between reducing sugars and amino groups can further contribute to the observed color alterations (as supported by recent kinetic and mechanistic studies of the Maillard reaction under elevated thermal processing conditions) (Tangduangdee *et al.*, 2023; Nehme and Bou-Maroun, 2025; Sruthi *et al.*, 2024). This finding aligns with recent studies showing that color changes in processed foods occur rapidly under elevated temperatures and are recognized as critical quality parameters influencing consumer acceptability and shelf-life (Pandiselvam *et al.*, 2023; Jiang *et al.*, 2025). Regarding odor, panelists detected significant sensory differences after storage at high temperatures — consistent with observations that thermal processing and storage can degrade aroma precursors (lipid oxidation and volatile loss), altering aroma profiles in heat-treated food matrices (Jiang *et al.*, 2025), which can negatively affect consumer acceptance and overall product quality. Therefore, the total color difference (ΔE) of the egg tofu with fish meat at week 2 under storage at 55 °C was proposed as the critical point for evaluating product deterioration. This parameter can be considered an appropriate quality standard for estimating the shelf life of retort-pouched sour curry products, in line with established food science principles regarding sensory changes in heat-processed foods (Maskan, 2001; Ganachari *et al.*, 2025). The initial pH of the sterilized product was 4.37 ± 0.01, classifying it as an acidified food (pH < 4.6), which enhances its microbiological safety by inhibiting the growth of *C. botulinum.* During storage, pH values remained stable across all tested temperatures, reflecting the buffering capacity of sour curry ingredients and contributing to the product's chemical stability. Bindu *et al.* (2007) reported that retort processing can reduce product color, while Correia and Mittal (1991) demonstrated that thermal processing in food manufacturing can result in nutrient degradation as well as losses in aroma and taste. Therefore, the absence of a significant increase in TBA values indicates that the product effectively resisted lipid oxidation, supporting its chemical stability and high-temperature storage capability.

Texture profile analysis increased hardness, cohesiveness, and chewing force during storage. These increases can be attributed to the irreversible heat-induced denaturation of ovalbumin present in the egg white component of the tofu (Kuang *et al.*, 2023), which promotes gel formation (Mine, 1995). Heat treatment also alters the native protein structure, leading to protein aggregation (Su *et al.*, 2025) and the development of a three-dimensional protein network, especially at higher temperatures, likely due to protein aggregation and water loss. Thiobarbituric acid (TBA) values remained low and unchanged, indicating minimal lipid oxidation and effective antioxidant preservation from spices in the formulation. This observation is consistent with the findings of Ganachari *et al.* (2025) who reported that foods with a well-developed buffer system can effectively resist pH changes during heat processing and storage. Microbiological tests confirmed the absence of pathogens and spoilage organisms throughout storage, complying with Thai Ministry of Public Health standards (Department of Health, 2013). Shelf-life estimation based on the zero-order kinetic model of ΔE change ($\Delta Et - \Delta E_0 =$

1.3221t) predicted a shelf life of 5.50 weeks at 30 °C. This model provides a practical tool for determining end-point quality in retort-pouched sour curry products under ambient conditions. In summary, the retort-pouched sour curry exhibited favorable stability in pH, lipid oxidation, and microbiological safety, while color and texture parameters were more susceptible to degradation during accelerated storage. Optimization of processing and formulation strategies to mitigate these changes is essential for maintaining product quality and consumer acceptance throughout its shelf life. Kim *et al.* (2013) stated that storing at 25° C slightly promoted lipid oxidation at the end of storage but did not affect protein deterioration. On microbial analysis, the aerobic and anaerobic bacteria were not detected from all cooking times during 4 wk storage at 4° C, but those bacteria were detected starting on 3 wk of storage in Chuncheon Dakgalbi stored at 25° C

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Conflicts of interest

The authors declare no conflict of interest.

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