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Original Research Article

Shelf Life Study of Preconditioned Zanthoxylum Armatum-Flavored Rabbit Meat Slices

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Abstract: Rabbit meat, as a high-quality white meat with high protein, low fat, and low cholesterol, ranks among the world's leading in terms of production and sales scale in China. To meet the demand of the prepared food track, a preconditioned Zanthoxylum armatum-flavored rabbit meat slice was developed. The effects of three refrigeration temperatures (1℃, 4℃, and 7℃) on total volatile basic nitrogen (TVB-N), total bacterial count, coliforms, pH value, sensory quality, and color of rabbit meat slices during storage were investigated. The results showed that both storage time and temperature had significant effects on the quality of rabbit meat slices. With the extension of storage time, TVB-N content, total bacterial count, and coliforms increased continuously, pH value first decreased and then increased, and sensory quality deteriorated gradually; the higher the temperature, the faster the deterioration rate. Regarding color parameters, the decreases in L* (lightness) and b* (yellowness) values intensified with increasing temperature, while a* (redness) value first decreased and then increased, followed by abnormal reddening in the late storage period. Based on Chinese national standards and sensory thresholds, a shelf-life model was established by combining the Arrhenius model with kinetics, using TVB-N as the core indicator. The predicted shelf lives were 12.1 days for the 1℃ group, 10.5 days for the 4℃ group, and only 9.5 days for the 7℃ group.
Keyword: Rabbit Meat, Shelf Life, Total Volatile Basic Nitrogen (TVB-N), Total Bacterial Count, Coliforms.

1 INTRODUCTION

1.1 Research Purpose

As a high-quality white meat resource, rabbit meat exhibits prominent advantages in its nutritional composition under modern healthy dietary concepts. Every 100 g of rabbit meat contains 19.7 g of protein, which is higher than the average value of livestock meats (18.3 g) and roughly equivalent to that of well-known lean pork (20.2 g), beef (20.0 g), and chicken (20.3 g). Its fat content is only 2.2 g and cholesterol content is 59 mg, both significantly lower than those of common red meats. Additionally, the amino acid composition of rabbit meat is highly consistent with human nutritional requirements, making it a high-quality protein source suitable for fitness enthusiasts, adolescents in the growth period, and post-operative rehabilitation patients to supplement protein (Bae *et al.*, 2024).

Preconditioned meat products refer to ready-to-eat or ready-to-cook meat products that use livestock meat, poultry meat, or their by-products as the main raw materials. These products undergo preprocessing such as cutting, trimming, marinating, seasoning, tenderizing, tumbling, or shaping, followed by storage and circulation through refrigeration, freezing, or modified atmosphere packaging. Consumers can consume them with simple heating. Thanks to their advantages of convenience and standardization, prepared foods have become an important choice for catering consumption and home dining (Peng, 2025) (Zhang *et al.*, 2024). Combining traditional flavors with modern food processing technology has become a key path for innovation and differentiated competition in the current meat product market.

Therefore, developing a Zanthoxylum armatum-flavored preconditioned rabbit meat chop can not only effectively alleviate the inherent fishy odor of rabbit meat through flavor modification and improve palatability but also fully exert the excellent nutritional characteristics of rabbit meat, such as high protein, low fat, low cholesterol, and rich mineral content (Mota-

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Rojas *et al*., 2024), thereby catering to the market's diverse demands for convenience, health, and flavor innovation. The development of such products holds significant practical significance and industrial development value for promoting the transformation of the rabbit meat industry from raw material-oriented to high-value-added intensive processing.

1.2 Experimental Purpose

Rabbit meat slices prepared with a proprietary formula were vacuum-packaged in nylon-polyethylene vacuum bags, with each bag containing 100 g of the sample. The packaged samples were stored under refrigeration at 1℃, 4℃, and 7℃ respectively, and the changes in their quality indicators were monitored throughout the storage period.

2 MATERIALS AND METHODS

2.1 Experimental Materials

The raw material used in the experiment was rabbit meat slices marinated with a proprietary formula. Hydrochloric acid, absolute ethanol, and boric acid were purchased from Chengdu Kelong Chemical Co., Ltd.; magnesium oxide was obtained from Tianjin Zhiyuan Chemical Reagent Co., Ltd.; sodium chloride was purchased from Shanghai Macklin Biochemical Co., Ltd.; bromocresol green was supplied by Tianjin Kemiou Chemical Reagent Co., Ltd.; plate count agar (PCA) and violet red bile agar (VRBA) were obtained from Beijing Aoboxing Biotechnology Co., Ltd. All reagents were of analytical grade (AR).

2.2 Experimental Methods

2.2.1 Determination of Total Volatile Basic Nitrogen (TVB-N)

The content of total volatile basic nitrogen (TVB-N) was determined according to the first method (Automatic Kjeldahl method) specified in GB 5009.228-2016 National Food Safety Standard - Determination of Total Volatile Basic Nitrogen in Foods.

2.2.2 Determination of Total Bacterial Count

The total bacterial count was measured in accordance with GB 4789.2-2022 National Food Safety Standard - Microbiological Examination of Foods - Determination of Total Bacterial Count.

2.2.3 Determination of Coliforms

Coliforms were determined using the second method (Coliform plate count method) described in GB 4789.3-2025 National Food Safety Standard - Microbiological Examination of Foods - Enumeration of Coliforms.

2.2.4 Determination of pH Value

Accurately weigh 5 g of the minced sample into a beaker, add 45 mL of primary water, and homogenize at 5000 r/min for 2 min using a homogenizer. After filtration, the pH value of the filtrate was measured with a pH meter, and the reading was recorded after the value stabilized.

2.2.5 Sensory Evaluation

Ten panelists with professional knowledge of food sensory evaluation were selected to assess the eating quality of the rabbit meat chops. The evaluation criteria are shown in Table 1: six aspects including color, texture, appearance, taste, odor, and overall acceptability were scored on a scale of 0 to 10. The total sensory score was calculated by weighting the individual scores as follows: color (10%), texture (20%), appearance (10%), taste (20%), odor (20%), and overall acceptability (20%).

To ensure the consistent initial state of samples within the same batch, all rabbit meat chops were cooked using an electric oven with uniform specifications. The process parameters were set as follows: upper and lower heating mode; after preheating to 180°C, the samples were placed in the middle layer of the oven and heated for 15 minutes.

Table 1: Sensory Evaluation Criteria Table for Formula Optimization of Rabbit Meat Rips

Sensory Indicators	Evaluation Criteria	Sensory Score
Color 10%	Good color, presenting golden yellow.	7~10
	Average color, presenting pale yellow or dark brown.	4~6
	Poor color, appearing white or scorched black.	0~3
Mouthfel 20%	Moderate hardness, chewy.	7~10
	Relatively moderate hardness, feels hard or somewhat soft when chewing.	4~6
	Unsuitable hardness, too hard or too soft/mushy.	0~3
Appearance 10%	Complete shape, compact texture, slight burnt aroma.	7~10
	Average shape, relatively compact texture, slight burnt smell.	4~6
	Poor shape, coarse texture, significant burnt smell.	0~3
Taste 20%	Distinctive flavor of cooked rabbit meat, moderate taste.	7~10
	Relatively distinctive flavor of cooked rabbit meat, taste is somewhat strong or light.	4~6
	Slight flavor of cooked rabbit meat, taste is very heavy or very light.	0~3
Aroma 20%	Possesses the inherent meat aroma of rabbit, no off-flavors or burnt smell.	7~10
	Inferior inherent meat aroma of rabbit, slight off-flavors or burnt smell.	4~6
	Poor aroma or heavy off-flavors, impure flavor.	0~3
Overall Acceptability 20%	Product is easily accepted, desire to eat.	7~10
	Product is relatively easy to accept, some desire to eat.	4~6
	Product is unacceptable, no desire to eat.	0~3

2.2.6 Color Determination

A colorimeter was used to measure the color parameters of the samples. Prior to measurement, the colorimeter was calibrated with standard black and white plates. Subsequently, the color of the samples was determined, and the L*, a*, and b* values were recorded respectively. Among these parameters, L* represents lightness, a* denotes red-green hue, and b* indicates yellow-blue hue. For each sample, measurements were performed at 5 identical locations, and the average value was calculated as the final result.

2.2.7 Data Analysis

The experimental results were expressed as "mean ± standard deviation (SD)". Data analysis was performed using IBM SPSS Statistics 27.0 software, with the significance level set at p 5. Data collation was completed using Microsoft Excel 2021 software, and graph plotting was conducted with Origin 2021 software.

3 RESULTS AND DISCUSSION

3.1 Changes in TVB-N during Storage

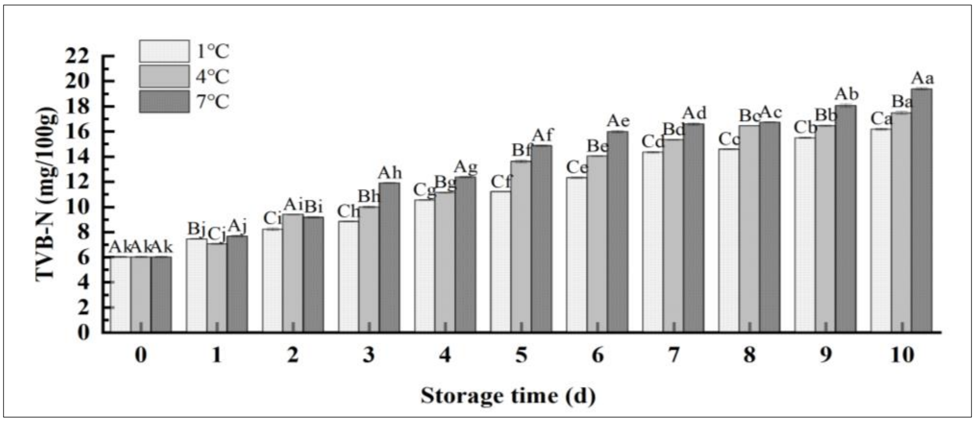

Figure 1: Changes in TVB-N during Storage

Note: a) Different lowercase letters indicate significant differences within each treatment group (p < 05), and different uppercase letters indicate significant differences among different treatment groups ($p < 0.05$).

The TVB-N content of rabbit meat slices showed a continuous upward trend with the extension of refrigerated storage time, and the higher the storage temperature, the faster the increase rate. As shown in Figure 1, the TVB-N content in each group increased significantly (p < 05) with the prolongation of storage time, reaching 16.17, 17.47, and 19.38 mg/100 g on day 10, respectively. Among them, the TVB-N content in the 7℃ group was significantly higher than that in the 1℃ and 4℃ groups. This result indicates that low temperature can effectively inhibit the reproduction of microorganisms and the activity of endogenous proteases, delay protein decomposition and the formation of ammonia compounds(Qian *et al*., 2023), thereby slowing down the accumulation of TVB-N, which plays an important role in maintaining the freshness of rabbit meat slices.

4.3.2 Changes in Total Bacterial Count during Storage

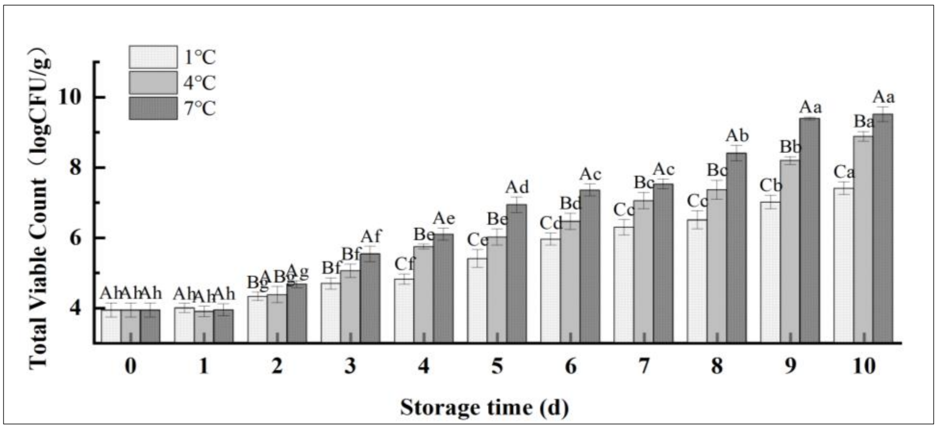

Figure 2: Changes in Total Viable Count during Storage

Note: a) Different lowercase letters indicate significant differences within each treatment group (p < 05), and different uppercase letters indicate significant differences among different treatment groups ($p < 0.05$).

The total viable count of rabbit meat slices showed a continuous increasing trend with the extension of refrigerated storage time, and the higher the storage temperature, the faster the growth rate. As shown in Figure 2, there were no significant differences among the groups at the initial stage of storage, indicating consistent initial contamination levels. With the prolongation of storage time, the total viable count in each group increased significantly, reaching 7.40, 8.88, and 9.51 log CFU/g on day 10, respectively. Among them, the total viable count in the 7℃ group was significantly higher than that in the 1℃ and 4℃ groups. This result indicates that low temperature can effectively inhibit the growth and reproduction of microorganisms, delay the increase of total viable count, and play an important role in maintaining the microbial safety of rabbit meat slices.

4.3.3 Changes in Coliforms Count during Storage

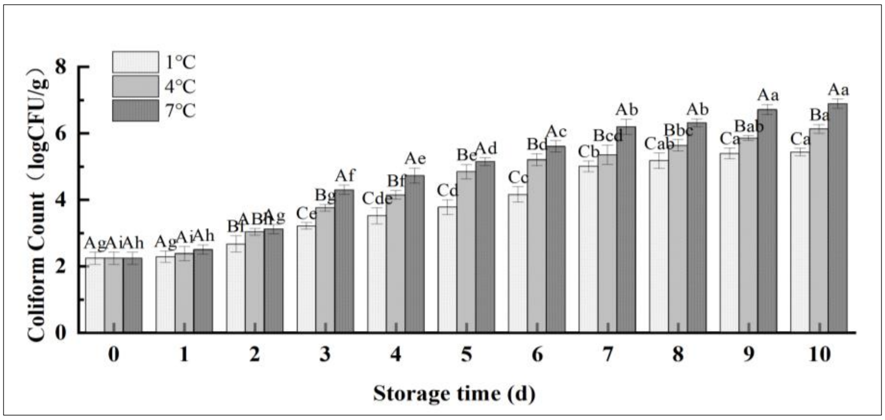

Figure 3: Changes in Coliform Group during Storage

Note: a) Different lowercase letters indicate significant differences within each treatment group (p < 05), and different uppercase letters indicate significant differences among different treatment groups ($p < 0.05$).

As shown in Figure 3, the coliforms count of rabbit meat slices showed a continuous increasing trend with the extension of refrigerated storage time, and the higher the storage temperature, the faster the growth rate. At the initial stage of storage, there were no significant differences among the groups, indicating consistent initial contamination levels. With the prolongation of storage time, the coliforms count in each group increased significantly ($p < 0.05$), reaching 5.43, 6.13, and 6.89 log CFU/g on day 10, respectively. Among them, the coliforms count in the 7℃ group was significantly higher than that in the 1℃ and 4℃ groups. This result indicates that low temperature can effectively inhibit the growth and reproduction of coliforms, delay the increase of their count (Zhang *et al*., 2024), and play an important role in maintaining the hygienic safety of rabbit meat slices.

From the perspective of variation characteristics under different storage temperatures, the coliforms count in the 1℃ group showed the slowest growth rate, while the 7℃ group exhibited the fastest growth rate. During the first 2 days of storage, the coliforms count in each group increased relatively slowly with no significant differences. Starting from day 3, the growth rate of the 7℃ group accelerated significantly, and the differences between the 7℃ group and the 1℃ and 4℃ groups gradually expanded. At the same storage time, the coliforms count increased significantly with the rise of temperature; at the same temperature, the coliforms count increased significantly with the extension of storage time. These results indicate that both temperature and time are key factors affecting the growth of coliforms in rabbit meat slices.

4.3.4 Changes in pH Value during Storage

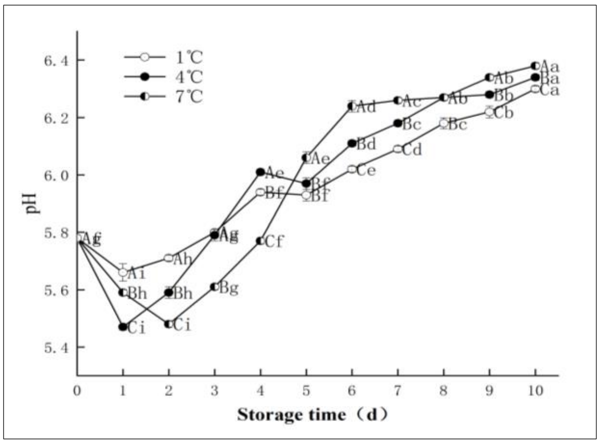

Figure 4: Changes in pH During Storage

Note: a) Different lowercase letters indicate significant differences within each treatment group (p < 05), and different uppercase letters indicate significant differences among different treatment groups (p < 0.05).

Starting from day 2, the pH value of the rabbit meat chops in each group entered a stage of continuous increase, and the higher the temperature, the faster the increase rate. The differences among the groups gradually expanded with the extension of storage time. The pH value of the 1℃ group showed the flattest upward trend, gradually increasing from 5.71 on day 2 to 6.30 on day 10; the 4℃ group increased from 5.48 to 6.34; the 7℃ group had the fastest increase rate, rising from 5.59 to 6.38. At the end of storage, the pH value of the 7℃ group was significantly higher than that of the 1℃ group. The recovery of pH value at this stage is mainly due to the decomposition of nitrogen-containing substances such as proteins and polypeptides by microorganisms during their growth and reproduction (Blachier & Kong, 2025), producing alkaline metabolites such as ammonia and amines, which neutralize the acidic substances in the system (Kang *et al*., 2026). In addition, higher storage temperatures accelerate the metabolic activities of microorganisms and the hydrolytic effect of endogenous proteases (Xie *et al*., 2025)(Bhaskar & Mahendrakar, 2007)(Zhang *et al*., 2025), promoting the faster accumulation of alkaline substances. Therefore, the recovery amplitude and rate of pH value in the 7℃ group were significantly higher than those in the 1℃ and 4℃ groups, which is consistent with the variation law reported by Agunbiade *et al*., (Agunbiade *et al*., 2010). Overall, temperature and storage time jointly regulate the changes in the pH value of rabbit meat chops by affecting the process of glycogen glycolysis and microbial metabolic activities (Guo *et al*., 2024) (Yi *et al*., 2025) (Lin *et al*., 2022).

4.3.5 Changes in Sensory Quality during Storage

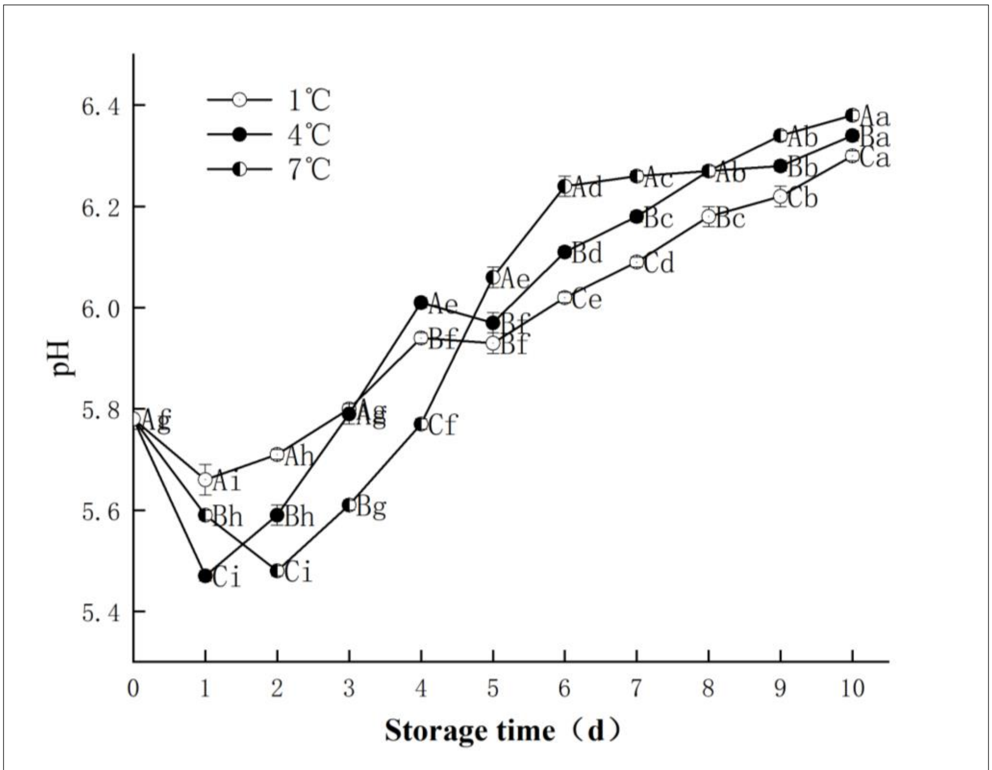

Figure 5: Changes in Sensory Properties during Storage

Note: a) Different lowercase letters indicate significant differences within each treatment group (p < 05), and different uppercase letters indicate significant differences among different treatment groups (p < 0.05).

Sensory quality showed a continuous deterioration trend over time, and storage temperature had a significant impact on its change rate. As shown in Figure 5, the sensory scores of rabbit meat chops in the 1℃, 4℃, and 7℃ groups all gradually decreased with the extension of storage time. Among them, the 1℃ group showed the flattest downward trend, the 7℃ group had the most drastic decline, and the 4℃ group had a variation range between the two. At the initial stage of storage (days 0-2), there were no significant differences in sensory scores among the three groups, all maintaining between 8.84 and 9.42, indicating that the impact of temperature on the sensory quality of rabbit meat chops was not obvious during short-term storage. From day 3 onwards, the differences among the groups gradually expanded: the sensory score of the 7℃ group was significantly lower than that of the 1℃ group, and the 4℃ group also began to lag behind the 1℃ group. This indicates that increasing temperature accelerates the deterioration process of sensory quality (Wang *et al*., 2024) (Li *et al*., 2026).

4.3.6 Changes in Color during Storage

Table 2: Changes in L* Value during Storage

Storage time（d）	L*		
	1℃	4℃	7℃
0	53.53±0.46^{Aa}	53.53±0.46^{Aa}	53.53±0.46^{Aa}
1	53.11±0.58^{Aa}	54.17±0.59^{Aa}	51.25±1.11^{Bb}
2	50.77±0.32^{Bb}	52.73±0.88^{ABa}	53.38±1.19^{Aa}
3	49.52±0.49^{ABc}	50.62±0.55^{Ab}	48.43±0.62^{Bc}
4	48.33±0.73^{Ac}	46.76±2.12^{ABb}	43.96±0.11^{Bd}
5	48.42±1.51^{Ac}	46.07±0.48^{Bc}	41.72±0.33^{Ce}
6	46.66±0.77^{Ad}	44.35±0.50^{Bd}	41.58±1.52^{Ce}
7	44.43±0.36^{Ae}	42.16±0.28^{Be}	40.26±0.65^{Cf}
8	42.57±0.77^{Af}	39.81±0.66^{Bf}	39.16±0.52^{Bf}
9	40.67±0.75^{Ag}	40.55±0.24^{Af}	39.25±0.27^{Bf}
10	40.13±0.27^{Ag}	39.74±0.45^{ABf}	39.06±0.24^{Bf}

Note: a) Different lowercase letters indicate significant differences within each treatment group (p < 05), and different uppercase letters indicate significant differences among different treatment groups ($p < 0.05$).

During the refrigerated storage of rabbit meat slices, as shown in Table 2, the L* value showed an overall continuous decreasing trend with the extension of storage time, and storage temperature had a significant impact on the change rate of L* value. With the progress of storage time, the L* value of each group gradually decreased, among which the 7℃ group had the largest decrease amplitude, the 1℃ group had the smallest, and the 4℃ group was between the two. This indicates that the higher the temperature, the faster the deterioration rate of L* value of rabbit meat slices.

In terms of inter-group differences, starting from day 1 of storage, the L* value of the 7℃ group was 51.25, which was significantly lower than that of the 1℃ and 4℃ groups ($p < 0.05$). On day 2, the L* value of the 7℃ group temporarily recovered to 53.38 and then decreased rapidly. After day 3, the differences in L* values among the three groups continued to expand: the 7℃ group was consistently significantly lower than the 1℃ group (p .05), and the 4℃ group also gradually lagged behind the 1℃ group, reflecting the protective effect of low temperature on color stability (Dimov *et al*., 2025)(Feng *et al*., 2025). By day 10 of storage, the L* value of the 1℃ group decreased from the initial 53.53 to 40.13; the 4℃ group decreased to 39.74; the 7℃ group decreased to 39.06. This change is closely related to myoglobin oxidation, microbial proliferation, and protein denaturation during storage (Zhao & Kong, 2010).

Table 3: Changes in a* Value during Storage

Storage time（d）	a*		
	1℃	4℃	7℃
0	4.33±0.20^{Aa}	4.33±0.20^{Abc}	4.33±0.20^{Ade}
1	4.15±0.10^{Aab}	3.77±0.22^{Ac}	4.11±0.39^{Aef}
2	3.90±0.18^{Ab}	2.26±0.42^{Bd}	3.69±0.31^{Afg}
3	3.18±0.15^{Adef}	2.31±0.48^{Bd}	3.34±0.52^{Agh}
4	2.79±0.29^{ABg}	2.43±0.29^{Bd}	3.18±0.26^{Ah}
5	3.05±0.08^{Befg}	3.76±0.54^{Bc}	4.70±0.29^{Ad}
6	2.93±0.11^{Bfg}	5.08±0.91^{Ab}	5.57±0.18^{Ac}
7	3.39±0.06^{Bcd}	6.00±0.54^{Aa}	5.95±0.07^{Abc}
8	3.31±0.10^{Bcde}	6.25±0.43^{Aa}	6.40±0.23^{Aab}
9	3.46±0.09^{Bc}	6.62±0.13^{Aa}	6.63±0.12^{Aa}
10	3.51±0.06^{Bc}	6.76±0.10^{Aa}	6.75±0.08^{Aa}

Note: a) Different lowercase letters indicate significant differences within each treatment group (p < 05), and different uppercase letters indicate significant differences among different treatment groups ($p < 0.05$).

As a core indicator reflecting the color freshness of meat products, the change law of a* is significantly different from that of L*. As shown in Table 3, under the refrigeration conditions of 1℃, 4℃, and 7℃, the a* value of rabbit meat chops did not show a single decreasing trend but presented a phased change characteristic of first decreasing and then increasing. Moreover, storage temperature had an extremely significant regulatory effect on the change amplitude and inflection point of the a* value (p < 05).

During days 0-4 of storage, the a* values of the three groups of rabbit meat chops all decreased to varying degrees (Cheng *et al*., 2009). Among them, the 4℃ group showed the most obvious decrease, dropping from the initial 4.33 to 2.43 on day 4; the 1℃ and 7℃ groups had relatively gentle decreases, falling to 2.79 and 3.18, respectively. The decrease at this stage is mainly attributed to the conversion of oxymyoglobin to metmyoglobin in fresh rabbit meat, leading to the weakening of the red tone on the meat surface (Bai *et al*., 2022).

Starting from day 5, the a* value of each group reversed and continued to increase, and the higher the temperature, the greater the recovery amplitude. The 4℃ and 7℃ groups showed an extremely strong upward trend: by day 10 of storage, the a* value of the 4℃ group reached 6.76, and that of the 7℃ group reached 6.75, both significantly higher than the initial values; while the 1℃ group had the smallest recovery amplitude, only 3.51 on day 10, which was significantly lower than the 4℃ and 7℃ groups (p < 05).

Higher temperatures can accelerate the massive proliferation of psychrophilic microorganisms such as Pseudomonas (Wu *et al*., 2024)(Orkusz *et al*., 2024). The reductive substances such as hydrogen sulfide produced by their metabolism can reduce metmyoglobin to myoglobin (Guo *et al*., 2024), and the pigment substances of the microorganisms themselves can also cause abnormal redness on the meat surface. In contrast, the low temperature of 1℃ can effectively inhibit the excessive proliferation of microorganisms, delay this abnormal color change, and better maintain the stability of the natural red tone of rabbit meat.

Table 4: Changes in b* Value during Storage

Storage time （d）	b*		
	1℃	**4℃**	**7℃**
0	$14.77±0.40^{Aa}$	$14.77±0.40^{Aa}$	$14.77±0.40^{Aa}$
1	$14.56±0.41^{ABa}$	$15.01±0.53^{Aa}$	$14.15±0.25^{Bab}$
2	$15.09±0.23^{Aa}$	$14.55±0.37^{Aa}$	$14.75±0.16^{Aa}$
3	$13.64±0.35^{Bb}$	$15.03±0.85^{Aa}$	$13.94±0.61^{ABb}$
4	$14.62±0.16^{Aa}$	$13.49±0.35^{Bb}$	$11.10±0.40^{Cd}$
5	$13.57±0.55^{Ab}$	$12.06±0.23^{Bc}$	$12.48±0.41^{Bc}$
6	$12.85±0.22^{Ab}$	$10.38±0.44^{Bd}$	$11.14±0.73^{Bd}$
7	$12.99±0.54^{Ab}$	$9.47±0.53^{Ce}$	$10.39±0.14^{Be}$
8	$11.47±0.51^{Ac}$	$9.15±0.20^{Be}$	$9.82±0.15^{Bef}$
9	$10.43±0.47^{Ad}$	$9.20±0.16^{Be}$	$9.45±0.20^{Bf}$
10	$10.85±1.09^{Acd}$	$9.11±0.17^{Be}$	$9.30±0.23^{Bf}$

Note: a) Different lowercase letters indicate significant differences within each treatment group (p < 05), and different uppercase letters indicate significant differences among different treatment groups (p < 0.05).

As shown in Table 4, under the refrigeration conditions of 1℃, 4℃, and 7℃, the b* value of rabbit meat chops showed an overall fluctuating decreasing trend. The higher the storage temperature, the faster the decrease rate of b* value and the greater the final decrease amplitude, and the significant differences among groups gradually became prominent with the extension of storage time (p < 0.05). At the initial stage of storage (days 0-3), the b* values of the three groups of rabbit meat chops were in a relatively stable fluctuating state, without showing obvious linear change characteristics, and the differences among groups only appeared at local time points. For example, on day 3 of storage, the b* value of the 4℃ group was 15.03, which was significantly higher than 13.64 of the 1℃ group and 13.94 of the 7℃ group. Starting from day 4, the b* values of each group began to show a regular decrease, and the regulatory effect of temperature on the decreasing trend became more significant. Among them, the 4℃ group showed the most drastic decrease: the b* value dropped rapidly from 15.03 on day 3 to 9.47 on day 7, then continued to decrease slightly, and dropped to 9.11 on day 10; the 7℃ group had the second largest decrease, with a b* value of 9.30 on day 10; the 1℃ group showed the flattest decrease, maintaining a relatively high b* value throughout the storage period, reaching 10.85 on day 10, which was significantly higher than the 4℃ and 7℃ groups (p < 0.05).

The decrease in b* value is essentially closely related to the process of lipid oxidation: higher temperatures can accelerate the activity of lipoxygenase and microbial proliferation, promoting the oxidative decomposition of unsaturated fatty acids (Xu *et al*., 2025), leading to a reduction in yellow tone-related substances in meat products. At the same time, microbial metabolism consumes part of the pigment precursors, further exacerbating the decrease in yellowness value. In contrast, the low temperature of 1℃ effectively delays the lipid oxidation process by inhibiting enzymatic oxidation and microbial growth, thereby maintaining the relative stability of the b* value of rabbit meat chops.

Combined with the aforementioned change laws of L* and a* values, it can be seen that under the refrigeration condition of 1℃, the color indicators (L*, a*, b*) of rabbit meat chops all showed the optimal stability, which is highly consistent with the results of sensory quality analysis.

4.3.7 Kinetic Model and Shelf-Life Prediction

The Pearson correlation coefficients between changes in various indicators of rabbit meat slices during storage and sensory evaluation are shown in Table 5. A larger Pearson correlation coefficient indicates a higher correlation. Except for the a* value under the storage condition of 1°C, the Pearson correlation coefficients between all other indicators and sensory evaluation were highly significant.

Table 5: Pearson correlation coefficient between various indicators and sensory evaluation during storage period

Temperature (℃)	Total viable count	Coliform count	TVB-N	pH	L*	a*	b*
1	-0.971**	-0.951**	-0.948**	-0.965**	0.975**	0.27	0.959**
4	-0.981**	-0.921**	-0.928**	-0.889**	0.922**	-0.813**	0.900**
7	-0.995**	-0.964**	-0.964**	-0.912**	0.928**	-0.859**	0.946**

According to Table 5, TVB-N and total viable count were selected as the core indicator indices. Referring to the kinetic laws of food spoilage, zero-order and first-order reaction models were fitted.

Kinetic equations:

Zero-order: $C = C_0 + kt$

First-order: $lnC = lnC_0 + kt$

Where:
C is the measured value of the indicator; C0 is the initial value; k is the rate constant (d^{-1}); t is time (d).

Because chemical kinetic equations can directly reflect the relationship between physicochemical quality changes of food and time, they are widely used in food science. To more accurately predict the shelf life of pre-conditioned Tengjiao pepper-flavored rabbit meat slices, this chapter uses chemical kinetic equations to establish a shelf-life prediction model. The formulas for the zero-order and first-order chemical kinetic equations are as follows:

Table 6: Kinetic parameters of total viable count and TVB-N in raw prepared meat at different temperatures

Indicator	Temperature (℃)	Zero order		First order	
		k (d^{-1})	R^2	k (d^{-1})	R^2
Total viable count (lg CFU/g)	1	0.34	0.98	0.06	0.99
	4	0.49	0.98	0.08	0.99
	7	0.56	0.97	0.09	1.00
TVB-N (mg/100g)	1	1.02	0.97	0.10	0.99
	4	1.15	0.98	0.11	0.99
	7	1.34	0.99	0.12	1.00

As shown in Table 6, the coefficients of determination (R^2) of the first-order kinetic model for total viable count and TVB-N under storage conditions of 1, 4, and 7°C were all greater than 0.98, significantly higher than those of the zero-order model, indicating that both microbial proliferation and protein decomposition in raw pre-conditioned meat during storage follow first-order reaction kinetics. Although the increase in total viable count showed a stronger correlation with sensory deterioration, and the fit of the first-order model was slightly better than that for TVB-N, the Chinese national standard sets a mandatory limit only for TVB-N in raw meat: 15 mg/100 g for first-grade fresh meat and ≤25 mg/100 g for second-grade fresh meat. Therefore, TVB-N was determined as the core indicator for shelf-life prediction. The Chinese national standard does not impose a unified mandatory requirement for total viable count, which was used as an auxiliary reference indicator for sensory spoilage. Combined with the spoilage characteristics of raw meat, 7 log CFU/g was set as the shelf-life endpoint.

$$lnk = lnk_0 - \frac{Ea}{R} \cdot \frac{1}{T1}$$

The Arrhenius equation was used to describe the effect of temperature on the deterioration rate:
Where: Ea is the activation energy (kJ/mol), and T is the absolute temperature (K).
The activation energy and Q_{10} parameters were obtained by fitting the first-order rate constants, and the results are shown in Table 7.

Table 7: Activation energy and Q_{10} values of toltal viable count and TVB-N

Indicator	Ea (kJ/mol)	Q_{10} (1~4℃)	Q_{10} (4~7℃)	R^2
TVB-N	30.35	1.43	1.40	0.99
Total viable count	40.08	1.62	1.57	0.99

As shown in Table 7, the activation energy of total viable count (40.08 kJ/mol) was higher than that of TVB-N (30.35 kJ/mol), indicating that microbial growth in raw pre-conditioned meat was more sensitive to temperature changes, and an increase in temperature promoted microbial proliferation more strongly than protein decomposition. The R^2 values of all models were greater than 0.99, indicating an excellent fit. The Q_{10} values were all greater than 1, consistent with the low-temperature storage law of food that higher temperatures accelerate the rate of quality deterioration.

Using total viable count of 7 log CFU/g and TVB-N of 15 mg/100g as the shelf-life endpoints, the shelf life was predicted using the first-order kinetics and Q_{10} model, and the relative errors were calculated. The results are shown in Table 8.

Table 8: Experimental and predicted shelf life

Indicator	Temperature (℃)	actual shelf life (d)	predicted shelf life (d)	relative error
TVB-N	1	12.50	12.10	0.03
	4	10.80	10.50	0.03
	7	9.80	9.50	0.03
Total viable count	1	9.30	8.20	0.12
	4	7.10	7.20	0.01
	7	6.30	6.20	0.02

As shown in Table 8, the established Q_{10} model exhibited high prediction accuracy within the low-temperature range of 1–7°C: the relative error of total viable count prediction was ≤12%, and that of TVB-N was ≤3%, both within the acceptable range for food shelf-life prediction. Notably, the prediction errors at 4°C and 7°C were only 1%–2%, indicating that the model is more suitable for the actual cold chain distribution temperature range and can achieve rapid and accurate shelf-life prediction for raw pre-conditioned meat products.

4. CONCLUSION

This study systematically investigated the effects of different refrigeration temperatures on the storage quality of rabbit meat slices, monitoring changes in physicochemical, microbiological, sensory, and color indicators. The results showed that temperature and storage time jointly determine the rate of product deterioration. Refrigeration at 1°C yielded the best results, significantly inhibiting microbial proliferation, reducing TVB-N accumulation, stabilizing pH, and delaying sensory and color deterioration, thereby achieving the longest shelf life. Higher temperatures accelerated spoilage and shortened shelf life. At 7°C, quality deterioration was the most rapid: pH first decreased and then increased, L* and b* values continuously decreased, and a* values abnormally increased in the later stage, collectively reflecting exacerbated myoglobin oxidation, microbial metabolism, and lipid oxidation under high temperature. Considering all indicators, 1°C is recommended as the optimal storage temperature to maximize the freshness, safety, and marketability of rabbit meat slices. The Q_{10} prediction model based on TVB-N had an error of only 3%, demonstrating high accuracy and compliance with national standards, and can be effectively used for rapid prediction and quality control of the cold chain shelf life of raw pre-conditioned meat products. This study defines suitable refrigeration parameters for rabbit meat slices, providing scientific support for cold chain storage and transportation, shelf-life management, and quality assurance of rabbit meat products.

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