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Effects of different cold sterilization techniques on physicochemical and flavor quality of low salt sliced bacon

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Abstract

The effects of irradiation, ultrahigh pressure and ultraviolet combined coating (UV-coating) on physicochemical, microbial, sensory and volatile flavor compounds of low salt sliced bacon under their optimal sterilization conditions were investigated to explore the most suitable treatment for this product. The results indicated that the sterilization effect of irradiation and ultrahigh pressure was better than that of UV-coating treatment, and the nitrite content of the three treatments was far lower than the Chinese standard limit. The effect of irradiation treatment on the structure of sliced bacon was considered to be the lowest, but it promoted fat oxidation and the formation of sulfur compounds, which in turn affected the flavor. The ultrahigh pressure treatment could improve the water-holding capability and taste feeling, meanwhile remain the color as well as the composition and relative content of the main aromatic compounds such as aldehydes, phenols and hydrocarbons closest to blank group. UV-coating treatment could significantly increase moisture content, block oxygen and raise color, while its sterilization effect was poor and the sour was heavier, easily to affect the edible quality of the product. Therefore, the ultrahigh pressure process was considered as the best according to the sterilization ability and flavor quality.

Keywords: cold sterilization; low salt; sliced bacon; physicochemical property; volatile flavor compound.

Practical Application: Cold sterilization is favored by consumers because of its less damage to food quality. In this study, the advantages and disadvantages of irradiation, ultrahigh pressure and UV-coating treatment on low-salt sliced bacon were reflected. Among them, the sulfide produced by irradiation and the sour taste introduced by the coating were the main factors affecting the sensory of the product. Relatively speaking, ultra-high pressure can ensure the sterilization effect while retaining the sensory and flavor composition of low-salt sliced bacon, which provides a certain reference for the application of cold sterilization in meat products.

1 Introduction

Bacon is one of the famous traditional cured meat products in China, which is usually made from pork tenderloins or hind legs through trimming, cutting, curing, drying, smoking and ripening (Deng et al., 2021). It is highly appreciated by consumers because of the unique flavor, convenient storage and transportation. In order to extend the shelf life of traditional bacon, a large amount of salt is added and the moisture content is reduced to inhibit the growth and reproduction of microorganisms. However, these procedures make bacon taste dry and hard, and meanwhile high content of salt not only increases the fermentation cycle and manufacture cost of bacon, but impels the human body to absorb excessive sodium thus the incidence of cardiovascular and kidney disease was highly improved (Rysová & Šmídová, 2021). In addition, with the social production and lifestyle changes, convenient and pre-packaged foods have become popular and widespread, traditional bacon needs to be innovated to meet the modern consumer market (Liu et al., 2021). Sliced bacon is easier to package, transport, store, and cook than traditional bacon block, but the slicing process enhances the area and time exposed to the air, accelerates fat oxidation, similarly increases the probability of microbial contamination. Currently, microorganisms are generally inactivated by high temperature and long time sterilization in the meat industry, which causes great loss of taste, color and nutrients. Therefore, the cold sterilization process without heat effect has gradually been favored by researchers around the world in recent years (Sun et al., 2021a; Zhao et al., 2022).

Nowadays, physical cold sterilization methods such as ultrahigh pressure, irradiation, and ultraviolet light treatment are widely applied in meat and have wild application prospects (Nema et al., 2022; Rosario et al., 2021; Singh et al., 2021). Among them, ultrahigh pressure sterilization has been proved to not only possess good sterilization effect, but also protect color by inactivating high iron myoglobin reductase in pork (Bak et al., 2012; Botsaris & Taki, 2015). For instance, kunnath et al. found that the color and acceptance of fresh pink perch sausage treated with 600 MPa for 10 min were significantly higher than those unsterilized samples on the 7th day of vacuum refrigeration, and maximum log reduction in microbial count was observed (Kunnath et al., 2015). In most cases, controllability, economy and continuity are considered as the main advantages of irradiation sterilization, but irradiation dose and sample thickness are the key factors restricting the sterilization effect. At present,

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irradiation technology is widely used in dried meat, spices and special purpose food. In cured meat products, irradiation has been shown to promote the degradation of nitrite and significantly reduce the total number of molds and colonies (De Mey et al., 2017). However, with the increase of irradiation dose, the fat oxidation, color deepening and irradiation odor of cured meat will be accelerated (Li et al., 2017). Ultraviolet light sterilization mainly works on the surface of samples, which has a good application value for agricultural by-products and meat products with a low degree of bacterial contamination, accorded with the study of Corrêa et al. that ultraviolet light was effective in reducing the levels of E. coli and S. aureus contamination on the surface of pork, beef and chicken (Corrêa et al., 2020). In this study, the physicochemical indexes and flavor quality of low salt sliced bacon were compared by three cold sterilization processes including ultrahigh pressure, irradiation and UV-coating under their respective optimal conditions to estimate the best method.

2 Materials and methods

2.1 Preparation of low salt sliced bacon samples

Chilled pork tenderloin with a fat-to-lean ratio of 3:7 to 4:6 was trimmed and scraped off the residual hair and dirt on the cortex, then cleaned, trimmed neatly along the edge, and divided into rectangular blocks of about 15 cm long and 3 cm wide. The blocks were rinsed in warm water at 30 °C for 2 min to remove oil and impurities on the surface, then taken out and drained. A total of 2.5% salt and 0.005% sodium nitrite according to meat weight was added for dry curing, the samples were refrigerated at 4 °C for 48 h and turned every 24 h during cured period. Thereafter, the bacon was preheated at 50 °C (humidity was 49%) for 1 h and then baked at 60 °C (humidity was 62%) for 18 h, finally smoked with cypress sawdust for 8 h (smoking temperature was 40-50 °C). The moisture content of the processed bacon was controlled at about 40%. The prepared bacon was cut into pieces of 8 cm in length, 3 cm in width and 3 mm in thickness before vacuum-packed. Every 6 slices of low salt sliced bacon were packaged in a high temperature cooking plastic bag (15 × 20 cm) without overlap. Except for the total number of colonies measured on the 30th day of cold storage, the other indicators were measured immediately after cold sterilization. The untreated samples were blank control named group A.

Irradiation sterilization process

The vacuum-packed samples were sent to Sichuan Runxiang Irradiation Technology Co., Ltd. within 12 hours and irradiated by a high energy electron accelerator (vf-proacc-10/20, 10 MeV, 20 kW) with a dose rate of about 260 $Gy \cdot s^{-1}$. The irradiation dose was set as 3 kGy and the irradiation temperature was 25.0 ± 1.0 °C. The absorbed dose of the sample was measured with a silver dichromate dosimeter, and the actual absorbed dose was about ± 5% of the set dose. The irradiation treated samples were named group B.

Ultrahigh pressure sterilization process

The samples were vacuum packed before treatment, and the parameters of the ultrahigh pressure sterilizer (HPP.L2-800/1, Tianjin Huatai Senmiao Biotechnology Co., Ltd, China) were set as follows: constant pressure was 400 MPa, pressure boost speed was 50 MPa/s, pressure release speed was 100 MPa/s, and processing time was 10 min (excluding the time of pressure rise and release). The pressure transmission medium was dioctyl malonate hydraulic oil. The oil temperature before treatment was 22 °C, it would rise during treatment, and then decrease to the initial temperature after treatment. When the treatment was completed, the surface oil of the package was cleaned with tap water (water temperature was about 10 °C). The ultrahigh pressure treated samples were named group C.

Coating combined with ultraviolet sterilization process

1.5% chitosan solution was prepared using chitosan as solute and 0.5% acetic acid as solvent, and 1.5% sodium alginate solution was prepared with sodium alginate and deionized water. Both the sodium alginate and chitosan solution were stirred in a water bath at 60 °C to be fully uniform. After the solution was cooled, the sodium alginate-chitosan complex solution (1:1, V/V) was prepared and allowed to stand for use. Nisin was dissolved in distilled water and configured into a mass fraction of 0.08% nisin solution, which was added to the sodium alginate-chitosan coating solution. At the same time, 2% glycerol was added as a plasticizer. The water bath was heated to make the solution transparent and uniform, and then cooled to room temperature for use. The coating and ultraviolet treatment were carried out in a sterile workbench. The sliced bacons were immersed in the coating solution for 2 min, then vacuum-packed and sterilized respectively for both front and back sides under ultraviolet light (TUV-F17T8 ultraviolet lamp, PHILIPS, USA) with 20 W power and 254 nm wavelength for 30 min. The UV-coating treated samples were named group D.

2.2 Physicochemical and microbial contamination determinations

Moisture content

Based on Chinese national standard GB 5009.3-2016 (National Health and Family Planning Commission of the People's Republic of China, 2016a), the samples were chopped and mixed evenly before determination, the capped weighing bottle was dried to constant weight and placed in a desiccator to cool down in advance, weighed and recorded as m_3 (g). About 2 g sample was weighted (accurate to 0.0001) in the weighing bottle, capped weighing was recorded as m_1 (g), then placed in a 105 °C drying oven, and the cap was obliquely put in the bottle edge during drying. The weighing bottle with cap was taken out every 2 h until the weight difference was less than 2 mg, the last weighting result was recorded as m_2 (g). The moisture content was calculated using Equation 1.

$$\text{moisture content}(\%) = \frac{m_1 - m_2}{m_1 - m_3} \times 100 \quad (1)$$

pH values

In terms of Chinese national standard GB 5009.237-2016 (National Health and Family Planning Commission of the

People's Republic of China, 2016b), 10 g sample was cut into pieces and put into a conical flask. After that, 90 mL distilled water was added and the mixture was shaken for 30 min. The supernatant was filtered in a beaker and the pH value was measured using a precision pH meter (PHS-2F, Shanghai Yidian science instrument Co., Ltd, China).

Residual nitrite content

In terms of the experimental procedure in Chinese national standard GB 5009.33-2016 (National Health and Family Planning Commission of the People's Republic of China, 2016c), the standard curve of sodium nitrite ($y = 0.0159x + 0.0016$, $R^2 = 0.9995$) was determined and fitted in advance. Therefore, the absorbance of the sample treatment solution was combined with the standard curve to obtain the nitrite content, and then the relative content was calculated according to the actual sampling weight.

Peroxide value (POV)

According to Chinese national standard GB 5009.227-2016 (National Health and Family Planning Commission of the People's Republic of China, 2016d), the representative fat part was fully broken and mixed, then placed in a jar, then three times the sample volume of petroleum ether was added and the mixture was well agitated. After standing for 12 h, the mixture was filtered and placed in a water bath below 40 °C, and the residue after vacuum evaporation was the determination sample. Approximately 2 g (the actual weight was recorded as m (g), accurate to 0.001) residue was placed in a 250 mL iodometric flask, 30 mL chloroform-glacial acetic acid mixture solution was added. After agitating, 1.00 mL saturated potassium iodide solution was accurately added, then the cap was tightly pressed, gently agitated for 0.5 min and placed in the dark for 3 min. A total of 100 mL deionized water was supplemented in the bottle, after agitating, 0.002 (c) mol/L sodium thiosulfate standard solution was immediately titrated the precipitated iodine, until the light yellow was observed, 1mL starch indicator was added, then the titration and agitation were continued until the blue color disappeared, the consumed volume was recorded as v (mL). Meanwhile, the volume consumed for the blank test was recorded as v_0 (mL). The peroxide value was calculated using Equation 2.

$$\mathrm{POV}\left(\mathrm{g}/100\mathrm{g}\right) = \frac{\left(v - v_0\right) \times c \times 0.1269}{m} \times 100 \quad (2)$$

Color differences

Three pieces sliced bacon samples (8 cm × 3 cm × 3 mm) of each treatment were randomly selected for determination. The lens of the carcass colorimeter (OPTO-LAB carcass colorimeter, MATTHAUS, Germany) was used to stick on the sample surface. The L* (brightness) value, a* (redness) value, and b* (yellowness) value of the samples were collected for comparing.

Total bacterial count

Total bacterial count was determined referring to Chinese food safety GB 4789.2-2016 (National Health and Family Planning Commission of the People's Republic of China, 2016e), 25 g broken and evenly mixed bacon sample was weighed in a sterile homogenizing cup filled with 225 mL normal saline. The homogenizing time was 2 min. The homogenizing liquid was diluted 10-fold for several times until an appropriate dilution was selected. Then 1 mL dilution and 15-20 mL AGAR medium were respectively added to sterile petri dish. After thorough mixing, petri dish was cultured at 36 °C for 48 h in a constant temperature incubator (DHP-80, Changzhou Maikenuo Instruments Co., Ltd, China). The number of colonies was converted according to the number of colonies and dilution.

2.3 Texture determination method

The texture instrument (TA XT plus, Stable Micro Systems, UK) was collocated with a P/0.5 probe with the following settings: the initial test speed was 2 mm/s, the middle test speed was 1 mm/s, the posterior test speed was 1 mm/s, the trigger force was 5 g, and the measurement interval was 5 s accompanied with 50% compression distance.

2.4 Sensory evaluation standard

Ten food postgraduates were selected as sensory evaluators and trained, in combination with the dynamic sensory techniques and quantitative descriptive analysis method, the evaluators were required to make a comprehensive description of the samples in terms that he could think of, then discussed and classified these terms, and established preliminary descriptive words and scores after simplification (Paglarini et al., 2020; Vidal et al., 2020). During sensory analysis, the evaluators were not allowed to be hungry and mentally exhausted. Smoking, chewing gum and eating food with strong smell were prohibited within one hour before the samples were analyzed. Clear water was provided for gargling before each sample was evaluated. Four groups of sliced bacon with different sterilization treatments (8 cm×3 cm×3 mm) were steamed at 100 °C for 15 min. Ten sensory evaluators scored and averaged the color, structure, aroma and taste of bacon. The specific scoring criteria were shown in Table 1. The scoring results were summarized and evaluated by radar chart as shown in Figure 1. The score for each evaluation indicator was calculated as the average of the scores given by 10 evaluators, and the comprehensive score was the average of the scores for all the evaluation indicators in the treatment group.

2.5 Determination of volatile compounds

As illustrated by Zhang et al. (2022), the volatile compounds were accumulated by solid phase microextraction (SPME). A total of 3 g chopped samples were placed in a 15 mL headspace bottle before sealing, then the aged extraction head (75 μm carboxeml/polydimethylsiloxane, Supelco, USA) was inserted into the headspace part and adsorbed for 40 min at 60 °C water bath. The adsorbed extraction head was transferred into the inlet of gas chromatography (GCMS-QP2020, Shimadzu, Japan), desorbed at 250 °C for 6 min, before the instrument started to collect data.

SH-Rxi-5SilMS capillary column (30M × 0.25 mm × 0.25 μm, Shimadzu, Japan) was used to separate volatile compounds. The splitless helium was selected as carrier gas with 1.19 mL/

Table 1. Sensory evaluation standard of low-salt sliced bacon.

Evaluation indicator	Grading	Score
Color	The color is ruddy and even, natural and soft, which can arouse appetite	5
	Ruddy color, slightly uneven, can arouse appetite	4
	Lighter or darker color, natural and even	3
	Lighter or darker color, uneven shade	2
	Unnatural color, dull and faded	1
	The color is abnormal and unacceptable	0
Tissue structure	Moderately soft and hard, tightly organized, elastic and chewy	5
	Soft and hard are moderate, the tissue is tighter, more elastic, and chewy	4
	Slightly softer or slightly harder, the tissue is tighter and more elastic	3
	Slightly soft or slightly hard, the tissue is loose and slightly elastic	2
	Very soft or hard, loose tissue, not chewy	1
	The tissue is very loose, inelastic, and chewy	0
Aroma	Strong aroma, natural and pure, obvious smoky taste	5
	Strong aroma, strong smoky taste	4
	Lighter aroma, less smoky, no peculiar smell	3
	Fragrance is mild. Smokey taste is not prominent, slightly peculiar smell	2
	Unnatural scent, or no noticeable scent	1
	Rancidity and peculiar smell are obvious	0
Taste	Moderate saltiness, delicate meat, even fat and thin, delicious	5
	The saltiness is more moderate, the meat quality is more delicate, the fat and thinness are more uniform, and it is more delicious	4
	Slightly salty or slightly bland, the taste is more acceptable and more delicious	3
	Too salty or too bland, the taste is average, acceptable	2
	Too salty or too bland, poor taste, not easy to accept	1
	Unacceptable smell and taste	0

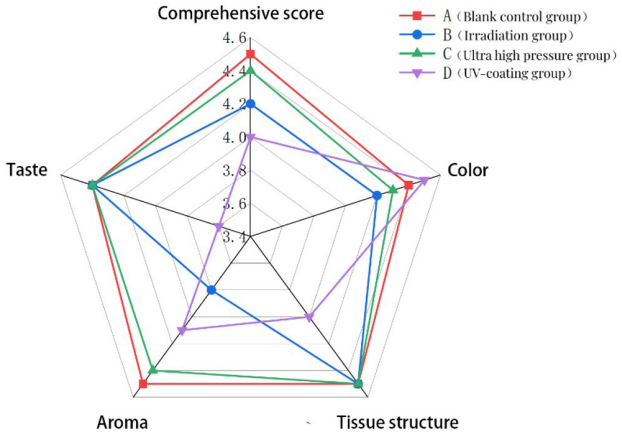


Figure 1. Sensory evaluation radar map of low salt sliced bacon after different cold sterilization treatments. The radar map consisted of five evaluation indicators of color, tissue structure, aroma, taste and comprehensive score, and different groups were distinguished by color. Among them, red represented the blank control group (A), blue represented the irradiation treatment group (B), green represented the ultrahigh pressure treatment group (C), and purple represented the UV-coating group (D). Extending outward from the center of the radar map indicated a higher score.

min of flow rate. The inlet temperature was 250 °C. The initial temperature was 35 °C and maintained for 3 min, then ramped to 130 °C at 4 °C/min and maintained for 2 min, finally ramped to 230 °C at 8 °C/min and maintained for 3 min.

EI ion source was used as ionization mode in the mass spectrometer with 35-450 m/z of scanning range. The interface and ion source temperatures were respectively 250 °C and 200 °C. The separated volatile flavor compounds were identified by searching the mass spectrometry data of the known compounds in the self-contained database, and the identification report was based on the matching degree of more than 800. The peak areas of all the flavor compounds were normalized to calculate relative content. Meanwhile, the retention indexes (RI) were identified through NIST database (USA) and confirmed in terms of available references.

2.6 E-nose modeling

The samples were chopped and mixed using an electric meat grinder (MM-DC25, Changhong Meiling Co., Ltd., China), a total of 1.0 g samples were collected in a 15 mL headspace bottle before sealing. After being placed at 25 °C for 30 min, the injection needle was manually inserted through septum to absorb the top air for electronic nose (PEN3; Airsense Analytics Inc., Germany) determination and analysis. Program parameters were set as follows: initial injection flow and carrier gas flow rate was 400 mL/min, sampling interval time was 1s, automatic cleaning time was 60 s, sensor zeroing time was 10 s, preparation time was 5 s, detection time was 70 s. The matched Winmuster software was used to calculate and model according to characteristic values reflected in different sensors. The response value of the sensor gradually increased during measurement, and tended to be flat after 50 seconds. Therefore, the data of 50-52 seconds

after the sensor signal was stabilized were selected for modeling and analysis.

2.7 Statistical analysis

All the determinations followed the principle of random and independent sampling. In addition to GC-MS analysis and sensory evaluation, the remaining indicators were subjected to three parallel experiments (n = 3), and the results were presented in the form of mean ± standard deviation. The test of significant difference was assessed by SPSS (Version 22.0, SPSS Inc., USA) using ANOVA with Duncan method at the 5% significance level ($P <. 05$) in all statistical analyses, which was marked with lowercase letters. The radar map of sensory evaluation was performed by Origin (Version 8.1, OriginLab Co., USA). The Winmuster software (Version 3.0, Airsense Analytics Inc., Germany) was used to establish a model in terms of collected data from electronic nose.

3 Results and discussion

3.1 Physicochemical indexes and microbial contamination after sterilization

As indicated in Table 2 that no significant difference was discovered in moisture content between the blank control group and the other three groups ($P >.05$), but the moisture content of group D was the highest, because the sodium alginate-chitosan composite coating contained moisture itself and had strong water absorption capacity as well as excellent film forming property, which could delay the water loss of sliced bacon (Liu et al., 2023). The moisture content of group C treated by ultrahigh pressure was slightly higher than that of the blank control, which was similar to the results of Zeng et al. (2022) that ultrahigh pressure treatment could reduce the moisture loss and improve the water holding capacity of the meat sample. Relatively speaking, irradiation had the least effect on the structure and moisture of meat products, so the moisture content was the closest to the blank control group. Due to acetic acid was used as the solvent in the preparation of the coating, the lowest pH value was observed in group D and was significantly lower than the other three groups ($P < .05$). The residual nitrite in the four groups were all low, far below the limit of 30 mg/kg in the Chinese food safety standard. Among them, the degradation of nitrite was accelerated by irradiation in group B, so the residual nitrite was significantly lower than that in blank control group. The residual nitrite in the coating group D was the highest, which may be associated with the conversion of NO_2^- to NO_3^- was reduced by isolating oxygen from the coating film during processing. In terms of color difference, the L* and a* values respectively represented the brightness and redness of the carcass. The redness and brightness of group D were significantly higher than those of the other three groups, which may be due to the minimum damage to sliced bacon caused by UV combined with coating treatment, meanwhile the reaction of oxygen and myoglobin was effectively prevented by coating film, allowing nitrite to penetrate evenly and develop color for a longer time, therefore more redness and brightness were displayed on the samples.

Compared with the blank control group, the brightness of the ultrahigh pressure treated group C was slightly higher and had the same redness level, this may be associated with the condensation and denaturation of proteins by high pressure, which converted ferrous myosin to metmyoglobin in muscle cells, thus counteracted part of the effect of nitrite coloration (Cartagena et al., 2019). The peroxide value (POV) can be used to measure the degree of fat oxidation. From Table 2, it was reflected that fat oxidation would be accelerated by the three cold sterilization processes to different degrees, among which group B was treated with irradiation and the oxidation degree was significantly higher than the other three groups, indicating that irradiation could accelerate fat oxidation faster compared with ultrahigh pressure and UV-coating processes. Since fat oxidation products have been shown to induce more intense fat and protein oxidation reactions (Li et al., 2019), stricter requirements on the oxygen barrier properties and vacuum degree of packages were necessarily adopted to preserve sliced bacon for a long time. Probably because of fat oxidation that occurred during air drying process of the coating as well as UV irradiation, the POV of the UV-coating group was slightly higher than that of the blank control group, but the antioxidant capacity during storage needs to be further studied. As far as the sterilization ability was concerned, the total number of colonies of three cold sterilization treatments were kept at a lower level after 30 days of refrigeration. No colonies were detected in the ultrahigh pressure and irradiation treatment groups, and only 1.00×10^2 cfu/g was detected in the UV-coating treatment group, which was significantly better than the blank control group. It showed that both ultrahigh pressure and irradiation had good overall sterilization ability, while ultraviolet process only applied on the surface of the samples as well as subtle omissions

Table 2. Changes of physicochemical indexes and microbial contamination of low-salt sliced bacon after different cold sterilization treatments.

Detection Indicator	A	B	C	D
Moisture content (%)	40.04 ± 0.02^{ab}	39.06 ± 0.00^{b}	42.92 ± 0.02^{a}	43.42 ± 0.01^{a}
pH	5.76 ± 0.03^{a}	5.80 ± 0.02^{a}	5.62 ± 0.02^{b}	5.40 ± 0.04^{c}
Residual nitrite content(mg/kg)	11.37 ± 0.26^{b}	9.23 ± 0.25^{c}	9.56 ± 0.30^{c}	12.6 ± 0.44^{a}
L*	46.33 ± 0.58^{b}	42.33 ± 0.58^{c}	47.00 ± 0.00^{b}	68.00 ± 0.00^{a}
a*	24.00 ± 0.00^{b}	22.00 ± 0.00^{c}	24.00 ± 0.00^{b}	28.33 ± 0.58^{a}
b*	12.00 ± 0.00^{b}	15.67 ± 0.58^{a}	11.33 ± 0.58^{bc}	10.67 ± 0.58^{c}
POV (g/100g)	0.023 ± 0.00^{d}	0.034 ± 0.00^{a}	0.029 ± 0.00^{b}	0.027 ± 0.00^{c}
Total number of colonies (CFU/g)	2.50×10^2	ND	ND	1.00×10^2

The different lowercase letters (a-d) showed statistically significant differences among the four samples ($P \leq 0.05$), and "ND" meant that No colonies were detected.

and heterogeneous coating film comprehensively resulted in insufficient bactericidal and bacteriostatic effects.

3.2 Texture profile analysis

As reflected in Table 3, the texture indexes are closely related to the moisture content and tissue status of samples, digitally embodying the taste feelings in sensory evaluation (Dong et al., 2018). The hardness and chewiness of the four groups were inversely proportional to the moisture content, and the resilience, cohesion and elasticity were proportional to the moisture content, which was consistent with the research results of Yalçın & Şeker (2016). Among them, group D showed the lowest hardness and the highest resilience because more water was retained thus making the myofibril more elastic and could buffer the external force. The moisture content of group C was also higher, so the hardness and chewiness were significantly lower while the resilience was significantly higher than those in the blank control group ($P < .05$), beneficial to express a better taste.

The texture indexes of group B were close to those of the blank control group, and no significant difference was found in hardness, resilience and chewiness ($P > .05$), illustrating that almost no loss to the sample structure and tissue status would be caused by irradiation treatment, meanwhile the taste of the sliced bacon could be retained to the utmost extent. Although Lv et al. (2018) discovered that the hardness, resilience and chewiness of clam meat increased with the irradiation in increased dose, and the higher the dose, the more pronounced the increase. However, in this study, it was not found the texture of sliced bacon was greatly changed after irradiation treatment. This may be due to the relatively low radiation dose of only 3 kGy, and meanwhile there existed certain difference between clam and pork structure. Moreover, the impact of irradiation on food quality needed to be further comprehensively judged by combining sensory evaluation as well as qualitative and quantitative research on volatile flavor compounds.

3.3 Sensory evaluation analysis

According to the results of sensory evaluation in Figure 1, the comprehensive score and aroma score of group A were the highest, whose taste and tissue structure score were not significantly different from those of group B and C, but higher than those of group D, demonstrating the edible quality of sliced bacon could be influenced by the three cold sterilization techniques to a certain extent. Specially, the taste, tissue structure and color score of group B were close to those of group A and C, but the aroma score of group B was the worst and far lower, which was related to the irradiation odor as well as the unpleasant odor generated from oxidation of fat and protein catalyzed by irradiation (Jia et al., 2021). As shown in Figure 1, the scores of group C in color, aroma, especially tissue structure and taste were the closest to those of group A, which may be attributed to that ultrahigh pressure treatment promoted the retention of water in muscle tissue and improved the taste of sliced bacon to a certain extent. The color score of group D was the highest, which was consistent with the redness and brightness measured in the physicochemical part. But the remaining indexes of group D were lower than the groups of A, B and C, especially in the taste and comprehensive score, which may be attributed to the use of acetic acid as a solvent in the preparation of the coating solution, and the obviously tasted acidity resulted in worse acceptance. Combining the results of each evaluation index with the comprehensive score, the treatment with ultrahigh pressure and UV-coating was respectively the best and worst in sensory evaluation among the three cold sterilization techniques.

3.4 GC-MS analysis

As shown in Table 4, according to the qualitative and quantitative analysis of volatile flavor compounds by GC-MS, 44,42,47 and 45 flavor compounds were identified in groups A, B, C and D, respectively. Among them, the least flavor compounds were discovered in group B, but the most in group C. The types and relative proportions of various compounds under different treatments were quite different, indicating that different cold sterilization techniques would cause certain differences in the volatile components of low salt sliced bacon. In terms of aldehydes that were mainly derived from the automatic oxidation of fat (Sun et al., 2021b), and the types and relative proportions of which in group B were the highest, indicating that the fat oxidation was aggravated by irradiation treatment in sliced bacon, in accordance with the tendency in peroxide value. A total of 7 aldehydes were detected in group B, accounting for 47.63%, of which hexanal and furfural accounted for the highest proportion. Hexanal was regarded to have grass aroma, while furfural was considered to possess wood and roast aroma, and the threshold of the two compounds was lower and the relative proportion was close, making the flavor of group B more plant fragrance (Guo et al., 2021; Merlo et al., 2021). The composition and relative proportion of aldehydes in group C were the most similar to those in the blank control group A, mainly concentrated in furfural and 5-methyl-2-furancarboxaldehyde, resulting in heavier wood and incense flavor. However, the relative proportion of 5-methyl-2-furancarboxaldehyde in group D was the highest among the four

Table 3. Changes of texture indexes of low-salt sliced bacon after different cold sterilization treatments.

Detection Indicator	A	B	C	D
Hardness (g)	4903.566 ± 164.358^{a}	4908.094 ± 196.247^{a}	3838.382 ± 162.141^{b}	2953.715 ± 23.738^{c}
Resilience (%)	17.938 ± 0.680^{c}	17.756 ± 0.579^{c}	20.355 ± 0.541^{b}	23.835 ± 0.080^{a}
Cohesion	0.673 ± 0.005^{b}	0.644 ± 0.014^{c}	0.686 ± 0.011^{ab}	0.699 ± 0.009^{a}
Springiness (%)	93.710 ± 1.240^{b}	91.433 ± 1.306^{c}	94.675 ± 2.119^{b}	96.095 ± 1.414^{a}
Chewiness	3079.559 ± 87.550^{a}	3282.292 ± 124.478^{a}	2328.924 ± 152.461^{c}	1529.174 ± 119.894^{d}

The different lowercase letters (a-d) showed statistically significant differences among the four samples ($P \leq 0.05$).

Table 4. GC-MS results of volatile substances in low-salt sliced bacon under different cold sterilization treatments.

Category	Volatile flavor compounds	[a]RI	[b]Identification	[c]Relative content%			
				A	B	C	D
Aldehydes	Hexanal	1072	MS, RI	—	22.72	—	3.49
	Heptanal	1175	MS, RI	—	1.75	—	—
	Octanal	1290	MS, RI	—	1.36	0.13	1.21
	Furfural	1458	MS, RI	31.46	19.64	34.99	27.67
	2-Furancarboxaldehyde, 5-methyl-	1566	MS, RI	4.88	—	4.93	8.35
	Benzaldehyde, 2-hydroxy-	1663	MS, RI	—	0.39	—	—
	Nonanal	1384	MS, RI	0.35	1.67	0.49	1.48
	Decanal	1492	MS, RI	—	0.10	—	0.12
	Amount			3	7	4	6
	Total aldehydes			36.69	47.63	40.53	42.32
Phenols	2-Methoxy-5-methylphenol	1789	MS, RI	5.64	4.26	6.11	9.77
	Phenol, 2-methoxy-	1858	MS, RI	15.90	15.87	17.04	26.27
	Creosol	1957	MS, RI	5.36	—	5.97	—
	Phenol	1995	MS, RI	3.28	2.18	3.32	5.11
	Phenol, 2-methyl-	1998	MS, RI	0.37	0.36	0.47	0.64
	Phenol, 4-ethyl-2-methoxy-	2020	MS, RI	0.56	0.46	—	1.17
	p-Cresol	2078	MS, RI	0.48	—	—	1.59
	Phenol, 3-methyl-	2099	MS, RI	—	0.49	0.73	—
	Phenol, 2-methoxy-4-propyl-	2103	MS, RI	0.03	—	0.03	0.09
	Eugenol	2155	MS, RI	0.08	—	0.09	0.16
	Phenol, 3,4-dimethyl-	2225	MS, RI	—	—	—	0.28
	Phenol, 2-methyl-5-(1-methylethyl)-	2225	MS, RI	—	0.08	0.05	0.10
	3-Allyl-6-methoxyphenol	2232	MS, RI	—	0.05	—	—
	trans-Isoeugenol	2336	MS, RI	0.03	—	0.05	0.10
	Amount			10	8	10	11
	Total phenols			31.72	23.75	33.87	45.27
Ketones	2-Hexanone, 6-hydroxy-		MS	—	—	0.90	—
	2-Cyclopenten-1-one, 2,3-dimethyl-	1521	MS, RI	—	0.54	—	0.97
	2-Butanone, 1-(acetyloxy)-	1526	MS, RI	—	—	2.18	—
	2-Furanone, 2,5-dihydro-3,5-dimethyl	1631	MS, RI	1.43	—	1.20	—
	2(5H)-Furanone, 5-methyl-	1658	MS, RI	—	—	—	0.17
	2(5H)-Furanone, 3-methyl-	1713	MS, RI	1.43	—	—	1.28
	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	1833	MS, RI	1.51	—	1.55	1.67
	2-Cyclopenten-1-one, 3-ethyl-2-hydroxy-	1891	MS, RI	0.14	—	0.16	—
	4-Methyl-5H-furan-2-one	1912	MS, RI	0.64	0.28	0.68	0.50
	Maltol	1968	MS, RI	0.21	—	0.35	—
	1,4-Methanoazulen-9-one, decahydro-1,5,5,8a-tetramethyl-, [1R-(1.alpha.,3a.beta.,4.alpha.,8a.beta.)]-		MS	0.02	—	0.02	0.03
	Amount			7	2	8	6
	Total ketones			5.37	0.82	7.03	4.63
Alcohols	3-Furanmethanol	1649	MS, RI	12.96	5.16	11.20	—
	2,3a-Dimethylhexahydrobenzofuran-7a-ol		MS	—	—	—	0.22
	Cedrol	2109	MS, RI	0.17	0.46	0.22	0.41
	Ethylene glycol - Adipate - Diethylene glycol		MS	0.10	—	0.05	0.07
	Amount			3	2	3	3
	Total alcohols			13.23	5.62	11.47	0.71
Esters	Diethyl Phthalate	2366	MS, RI	0.43	0.26	0.02	—
	Dibutyl phthalate	2678	MS, RI	0.08	—	—	—
	9-Hexadecenoic acid, eicosyl ester, (Z)-	3730	MS, RI	—	0.18	—	—
	Amount			2	2	1	0
	Total esters			0.51	0.44	0.02	0.00
Acids	Benzenesulfonic acid, 2,5-dimethyl-		MS	—	0.33	—	—
	Acetic acid	1730	MS, RI	—	—	—	0.22
	Amount			0	1	0	1
	Total acids			0.00	0.33	0.00	0.22
Ethers	Disulfide, dimethyl	1065	MS, RI	—	9.24	—	—
	2-Phenylethyl isopropyl ether		MS	—	0.36	—	—
	Amount			0	2	0	0
	Total ethers			0.00	9.60	0.00	0.00

RI: Retention Index; MS: Mass Spectrum. [a]Retention index was calculated through comparing with the C6-C20 n-alkanes data; [b]Identification method: MS was identified with NIST database; RI was confirmed with retention index of available references; [c]Relative content was calculated by normalizing the peak areas of all the flavor compounds. "-": not detected.

Table 4. Continued...

Category	Volatile flavor compounds	[a]RI	[b]Identification	[c]Relative content%			
				A	B	C	D
Hydrocarbons	Camphene	1083	MS, RI	—	0.39	—	—
	(+)-4-Carene	1149	MS, RI	—	0.36	—	—
	Cyclohexene, 1-methyl-5-(1-methylethenyl)-, (R)-	1200	MS, RI	—	1.08	—	—
	Disulfide, methyl 2-propenyl	1281	MS, RI	—	1.10	—	—
	Cyclopentane, (2-methyl-1-propenyl)-		MS	0.81	—	1.17	—
	Nonane, 5-methyl-5-propyl-		MS	—	0.56	—	—
	Cyclohexane, ethoxy-		MS	—	—	—	1.02
	3-Tetradecene, (E)-	1392	MS, RI	—	—	—	0.07
	1-Methyl-4-(6-methylhept-5-en-2-yl)cyclohexa-1,3-diene	1474	MS, RI	—	—	0.05	—
	(1R,4S,5S)-1,8-Dimethyl-4-(prop-1-en-2-yl)spiro[4.5]dec-7-ene	1475	MS, RI	—	—	0.05	0.05
	Octane, 3,6-dimethyl-		MS	—	0.10	—	—
	Nonane, 2-methyl-5-propyl-		MS	0.05	—	—	—
	Dodecane		MS	—	0.15	0.08	0.14
	(−)-α-Cedrene	1571	MS, RI	0.81	2.54	0.98	2.02
	Longifolene	1590	MS, RI	0.13	0.15	0.13	0.12
	(−)-β-Cedrene	1606	MS, RI	0.22	0.69	0.30	0.50
	cis-Thujopsene	1628	MS, RI	0.97	2.57	1.25	1.26
	2H-2,4a-Methanonaphthalene, 1,3,4,5,6,7-hexahydro-1,1,5,5-tetramethyl-, (2S)-	1608	MS, RI	—	—	0.06	—
	Spiro[5.5]undec-2-ene, 3,7,7-trimethyl-11-methylene-, (-)-	1686	MS, RI	0.13	—	0.22	0.17
	2-Isopropenyl-4a,8-dimethyl-1,2,3,4,4a,5,6,8a-octahydronaphthalene	1730	MS, RI	—	0.28	—	—
	Benzene, 1-methyl-4-(1,2,2-trimethylcyclopentyl)-, (R)-	1776	MS, RI	0.33	0.92	0.57	0.59
	2,3-Dimethoxytoluene	1806	MS, RI	0.19	0.18	0.19	0.29
	Pentadecane		MS	—	0.08	—	—
	Tridecane		MS	—	—	—	0.07
	Cedrene-V6		MS	0.10	—	0.13	0.09
	Di-epi-.alpha.-cedrene-(I)		MS	0.08	0.26	0.08	0.10
	(1R,4aR,8aR)-2,5,5,8a-Tetramethyl-4,5,6,7,8,8a-hexahydro-1H-1,4a-methanonaphthalene, rel-		MS	0.08	0.21	0.11	—
	1,1,4a-Trimethyl-5,6-dimethylenedecahydronaphthalene		MS	—	—	0.03	—
	(1R,5S)-1,8-Dimethyl-4-(propan-2-ylidene)spiro[4.5]dec-7-ene		MS	0.05	0.18	0.09	0.05
	(R)-3-Methylene-6-((S)-1,2,2-trimethylcyclopentyl)cyclohex-1-ene		MS	—	—	0.03	—
	Tetracosane		MS	0.06	—	—	—
	Hexatriacontane		MS	0.57	—	—	—
	Amount			15	18	18	15
	Total hydrocarbons			4.58	11.81	5.51	6.54
Others	Ethanone, 1-(2-furanyl)-	1506	MS, RI	7.60	—	—	—
	N-Methyl methacrylamide		MS	—	—	1.42	—
	1,4,3,6-Dianhydro-.alpha.-d-glucopyranose	2394	MS, RI	0.16	—	0.08	0.12
	3,4-Anhydro-d-galactosan		MS	0.05	—	—	0.03
	2,3-Anhydro-d-mannosan		MS	0.10	—	0.08	0.16
	Amount			4	0	3	3
	Total others			7.90	0.00	1.58	0.31

RI: Retention Index; MS: Mass Spectrum. [a]Retention index was calculated through comparing with the C6-C20 n-alkanes data; [b]Identification method: MS was identified with NIST database; RI was confirmed with retention index of available references; [c]Relative content was calculated by normalizing the peak areas of all the flavor compounds. "-": not detected.

treatments. The study of Karagöz et al. suggested that 5-methyl-2-furancarboxaldehyde mainly came from lignin decomposition, which could be further decomposed into acetic acid (Yang et al., 2021a), hence the small amount of acetic acid contained in the coating film may prevent its decomposition to some extent. Strecker degradation has always been considered as an important pathway for flavor formation, and the production of furfural and 5-methyl-2-furancarboxaldehyde during processing may be related to Strecker degradation of phenylalanine (Yang et al., 2021b). Since hexanal was known as the main product of lipid oxidation metabolism, ultrahigh pressure and UV-coating treatment were proven to promote Strecker degradation to a certain extent without strong promotion of lipid oxidation, which was consistent with the previous POV analysis.

Most of the phenols in smoke were produced through lignin decomposition, and phenols were the main source of smoke flavor (Saldaña et al., 2019). The types and relative proportions of phenols in group B were the lowest, with a total of 8 types, accounting for 23.75%, so the smoked flavor was the weakest. The types and relative proportions of phenolic compounds in group D were the highest, with a total of 11 types, accounting for 45.27%, showing a strong smoke flavor, which may be related to the lower threshold of phenolic compounds, and the protective effect of the coating on volatile flavor compounds (Abdel-Naeem et al., 2021). The composition and quantity of phenolic compounds in the ultrahigh pressure treatment group and the blank control group were relatively close, both of which were 10 types, accounting for 31.72% and 33.87% respectively.

Among them, such as phenol, 2-methoxy-phenol, 2-methoxy-5-methylphenol, creosol, etc., which accounted for a relatively high proportion and were very considerable for bacon products, the relative proportions of the aroma providing compounds were rarely different, proving that ultrahigh pressure had little effect on the degradation and formation of phenolic compounds, so the smoked flavors of A and C groups were the closest.

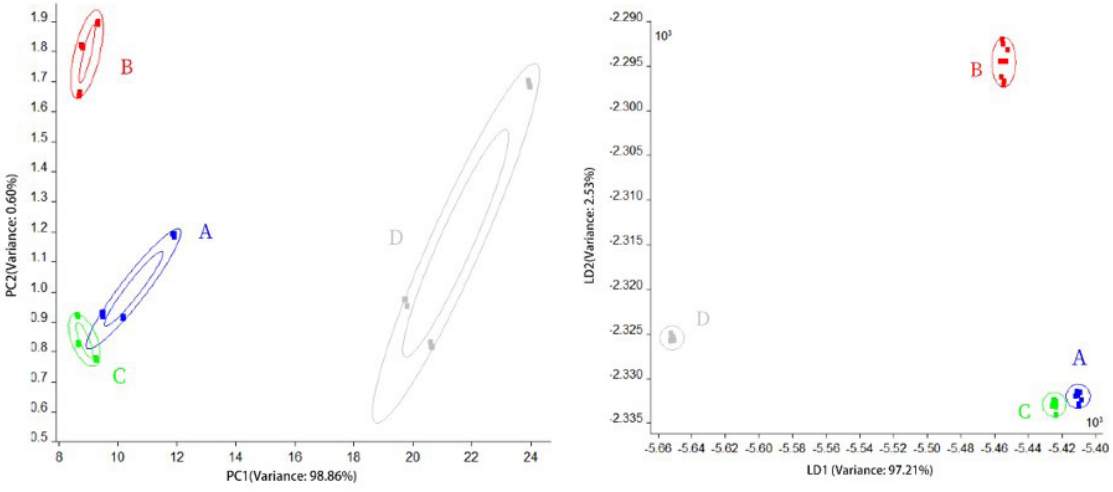
Ketones were mainly produced by Maillard reaction, degradation and metabolism of protein, fat and carbohydrate. Most of these compounds had unique fruit, woody and mushroom flavor (Merlo et al., 2021). The types and relative proportions of ketones in group C were the highest, with 8 types, accounting for 7.03%, followed by group A, with 7 types, accounting for 5.37%, then group D, with 6 types, a relative proportion of 4.63%, and group B, with only 2 types, accounting for 0.82%. Regardless of the type or relative content of ketones, group D was much lower than the other three groups, which may be due to the fact that irradiation tended to promote the decomposition of macromolecular compounds into aldehydes and hydrocarbons (Feng & Ahn, 2016; Kong et al., 2017). In addition, most of the ketones in the experiment belonged to furanone, indicating that there were cyclic carbon-carbon double bonds in the molecular formula, which were more susceptible to oxidative decomposition by irradiation.

Alcohols, acids and esters would accumulate with the processing of bacon. The same alcohols were detected in group A and C, the relative proportion was also relatively close, in which 3-furanmethanol was relatively high, 11.20% and 12.96% respectively, followed by cedrol. Due to the use of cypress for smoking, so cedrol was detected in the four groups without a high proportion. 3-Furanmethanol was regarded as the resource of sweet, caramel, and coffee aromas that could provide a pleasant flavor to meat products, and was an important aroma component (Zhao et al., 2017). Only two acids were detected in the experiment. Among them, 2,5-dimethyl-benzenesulfonic acid was only found in group B, which was most likely to be the product of hydrolysis and oxidation of higher fatty acids. Acetic acid was only detected in the UV-coating group, which was related to the introduction of acetic acid as a solvent during coating preparation. Esters were mainly produced by esterification between acids and alcohols. UV-Coating treatment could well prevent the esterification reaction, while ultrahigh pressure could promote the decomposition of esters to acids and alcohols, which was consistent with the results of Martínez-Onandi et al. (2016). Therefore, the content of esters in the two treatments was low, which may cause the loss of some ester-specific fruit aroma.

In this study, no ethers were detected in groups A, C and D, and only dimethyl disulfide and 2-phenylethyl isopropyl ether were detected in group B, which accounted for 9.60% and 0.36% respectively. Dimethyl disulfide was the main odor compound in irradiated meat products, with sulfur and cooked cabbage flavor (Jiang et al., 2022), it had a great influence on the product flavor, also resulted in the lowest aroma score in sensory evaluation. Hydrocarbons was one of the largest categories of compounds contained in the four treatments, mainly because a large number of unique compounds were produced by cypress fumigation, such as (−)-α-cedrene, (−)-β-cedrene, longifolene, cis-thujopsene were all important components of smoked bacon flavor. Because irradiation increased the content of hydrocarbons by accelerating the auto-oxidation of fat, group B appeared a stronger cypress aroma than the other three groups.

3.5 PCA and LDA analysis of E-nose model

As shown in Figure 2a, the variance contribution rates of PC1 and PC2 for the four groups were 98.86% and 0.60% respectively, and the cumulative contribution rate was 99.46%, indicating that a lot of information that could reflect the entire samples was contained in the PCA model, and the differences between the samples were mainly reflected in PC1. Each ellipse in the figure represented the data collection points of the samples under different cold sterilization



(a) **(b)**

Figure 2. (a) PCA model of low-salt sliced bacon after different cold sterilization treatments. (b) LDA model of low-salt sliced bacon after different cold sterilization treatments. The letters A-D represented different treatment groups, and each group was distinguished by different colors.

treatments. Except for the overlap between group A and C, the other samples were distributed in independent regions, indicating that no significant difference was found in the overall flavor between group A and C. It was in accordance with the result that the composition and relative content of the main aromatic compounds such as aldehydes, phenols, ketones, alcohols and hydrocarbons in group A and C were very close in GC-MS analysis. The difference in group B was mainly reflected in PC2, the relatively high proportion of aldehydes, ethers and hydrocarbons were regarded as the main reason. The overall flavor of group D was quite different from the other three groups. The difference was mainly reflected in PC1, which may be related to its relatively high proportion of phenols and relatively low proportion of alcohols and esters, therefore it could be significantly distinguished from the other three groups. In Figure 2b of LDA analysis, the contribution rates of LD1 and LD2 were 97.21% and 2.53%, with a total of 99.74%. No overlap was shown in LDA model and the trend was noticeable, illustrating that the LDA model could effectively distinguish the four treated samples. The difference between group A, B and D was the largest, and the difference between group A and C was the smallest, which was consistent with the results of PCA analysis. In summary, the flavor of low salt sliced bacon treated under different cold sterilization processes could be effectively distinguished through PCA combined with LDA.

4 Conclusions

The three cold sterilization techniques including irradiation, ultrahigh pressure and UV- coating had different effects on the physicochemical and edible quality of low salt sliced bacon. Irradiation treatment could promote the decomposition of nitrite and had an excellent sterilization effect. However, it would inevitably promote fat oxidation and the formation of irradiation odor. The superior sterilization effect was also proved by ultrahigh pressure treatment, meanwhile the color and flavor were maintained to the greatest extent consistent with the blank control group, furthermore the taste was improved. UV-coating treatment showed excellent water retention, oxygen resistance and auxiliary nitrite coloration abilities, but its sterilization effect was unstable and the sensory was influenced by coating. Based on the analysis of physicochemical indexes and sensory qualities, ultrahigh pressure was considered an ideal cold sterilization process for low salt sliced bacon.

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