IMPACT OF PARTIAL FREEZING WITH MODIFIED ATMOSPHERE PACKAGING ON PORK'S QUALITY
/
气调微冻对猪肉品质的影响

Huaming HOU [1,3], Dengming LI [2], Rui ZHANG [1], Wei NIU [1], Qingliang CUI [1,3], Yisheng CHEN *[2]
[1] College of Agricultural Engineering, Shanxi Agricultural University, Taigu 030801 / China;
[2] College of Food Science and Engineering, Shanxi Agricultural University, Taigu 030801 / China;
[3] Dryland Farm Machinery Key Technology and Equipment Key Laboratory of Shanxi Province, Taigu 030801 / China
Tel: +86-18404966321; E-mail: chenyisheng@sxau.edu.cn
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ABSTRACT
To preserve the original quality of fresh pork and prolong its shelf life, this study aimed to seek a no ionic residue efficient storage method. The partial freezing with modified atmosphere packaging (PF-MAP, -1°C, 75%O_2+20%CO_2+5%N_2) method was proposed and it was used to preserve fresh pork, and the storage effects with methods of refrigeration with MAP (R-MAP, 4°C), partial freezing with vacuum package (PF-VP, -1°C), refrigeration with vacuum package (R-VP, 4°C), partial freezing (PF, -1°C) and refrigeration (R, 4°C) were compared. The results indicated that after 8 days of storage, the total volatile basic nitrogen (TVB-N) content and total viable count (TVC) of pork under PF-MAP and R-MAP were much below the safety threshold limits, while the TVB-N content and TVC of the pork under PF-VP, R-VP, PF, R exceeded the safety limits. The drip and stewing losses of PF-MAP pork were lowest, which were 0.98% and 27.54%, respectively. The hardness and shear force of PF-MAP pork were 37.78 N and 38.38 N, respectively, which were significantly higher than other methods. The color of PF-MAP pork was bright, with a pH value of 6.08, an intense pork aroma, and perceived freshness. After 12 days of storage, the TNB-N content and TVC of PF-MAP pork remained significantly lower values, while the TVC of R-MAP pork approached the safety limit. After 20 days of storage, the TVB-N content and TVC of PF-MAP pork were 10.92 mg/100 g and 4.84 lg CFU/g, respectively, significantly lower than the threshold limits. Its drip loss, stewing loss, hardness, shear force, pH, and color (L, a*, b* values) were all satisfactory, resembling fresh pork in color and aroma. In conclusion, PF-MAP can better maintain the quality of fresh pork.*

摘要
为保持鲜猪肉品质，延长其货架期，该研究旨在寻求一种无离子残留的高效贮藏方法，提出了一种气调包装微冻猪肉的贮藏方法，测量其贮藏效果，并与气调冷藏、真空微冻、真空冷藏、微冻、冷藏方法的贮藏效果相比较。结果表明，贮藏 8 天时，气调微冻和气调冷藏猪肉的挥发性盐基氮（TVB-N）含量和菌落总数（TVC）远低于安全限量，而冷藏、微冻、真空冷藏和真空微冻猪肉的 TVB-N 含量和 TVC 已超过安全限量，气调微冻猪肉的汁液流失率和蒸煮损失率最低，分别为 0.98% 和 27.54%。气调微冻猪肉的硬度和剪切力均显著高于其他贮藏方法下的猪肉，分别为 37.78 N 和 38.38 N。气调微冻猪肉的色泽鲜亮，pH 值为 6.08，香气浓且感官上最为新鲜。贮藏 12 天时，气调微冻猪肉的 TNB-N 含量和 TVC 仍显著低于安全限量，而气调冷藏猪肉的 TVC 已达到安全限量。贮藏 20 天时，气调微冻猪肉的 TVC-N 含量和 TVC 分别是 10.92 mg/100 g 和 4.84 lg CFU/g，仍显著低于安全限量，其汁液流失、蒸煮损失、硬度、剪切力、pH 和色度 L、a*、b*值皆较好，色泽与新鲜猪肉相近，仍保有猪肉香气。综上可知，气调微冻方法能较好地保持鲜猪肉的品质。*

INTRODUCTION
The Rongchang pig is a superior pig breed in China, hailed as the "treasure of China," with advantages such as easy feeding, good meat quality, and high reproductive performance *(Leng et al., 2023).* However, developments in the intensive processing industry have resulted in a demand to preserve Rongchang pork. In the past, pork in China was mainly distributed as fresh or frozen meat. Fresh meat is not suitable for storage, and freezing can cause severe damage to the quality of the meat. Chilled fresh meat has become increasingly popular in recent years. Although chilling improves the quality of meat for eating, it is limited by the growth of

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[1] *As A.P. Ph.D. Eng. Huaming HOU; Yisheng CHEN, Prof. Ph.D. Eng.; Dengming LI, M.S. Eng.*

spoilage-related microbes during storage, which means it can only be stored for a maximum of 4-5 days *(Zhao et al., 2022)*. An efficient and safe method for preserving chilled fresh meat must be developed to extend the shelf life of chilled fresh pork, maintain its high quality, and ensure food safety.

Preservation by partial freezing refers to storing food slightly below its freezing point after rapid pre-cooling, resulting in a fresh appearance *(Hoang et al., 2016)*. After pre-cooling, the food can pass rapidly through the maximum ice crystal generation zone, thus avoiding damage to tissue and cell structure caused by ice crystals. Partial freezing technology allows some formation of ice crystals by water in the food, which effectively inhibits the activity of endogenous enzymes and the growth of spoilage-associated bacteria, thus maintaining the food quality *(Cao et al., 2023)*. Research has demonstrated that subjecting marine, meat, and meat products to partial freezing leads to a preserved state of freshness, significantly prolonging their shelf life by 1.5 to 4 times compared to conventional refrigeration methods *(Tao et al., 2023)*. The formation of uniform small ice crystals causes minimal damage to muscle fibers, thus making the procedure suitable for storing partially freezing fresh meat *(Guo et al., 2023)*. After partial freezing, there is no need to add protective ice blocks during short-term storage and transportation, thus reducing costs. Modified atmosphere packaging (MAP) involves the sealing of food in an artificially mixed gas environment using packaging materials to retard food spoilage, inhibit the growth of microorganisms and enzyme reactions in the food, and extend the shelf life of the product *(Liu et al., 2024)*. Common gasses used in MAP include O_2, CO_2, and N_2. O_2 can inhibit the reproduction of anaerobic bacteria, thus maintaining the fresh red color of the meat. In contrast, CO_2 can inhibit mold development and growth of aerobic bacteria, and N2, besides its bacteriostatic effect, helps maintain the meat products' original texture, color, and taste *(Abdullah et al., 2024)*. Research has demonstrated that MAP has bacteriostatic capabilities and preserves meat products' tenderness, color, water retention, and other characteristics. It also slows down the oxidation process of proteins and lipids in meat while maintaining the integrity of cellular structures *(Śmiecińska et al., 2023)*.

Therefore, this study investigates the impact of combining MAP technology with partial freezing to preserve fresh Rongchang pork and maintain its storage quality. The present study measured and compared the alterations in the quality of fresh Rongchang pork during storage using various methods, including refrigeration, partial freezing, vacuum refrigeration, and vacuum partial freezing. These findings serve as a valuable reference for advancing preservation and processing techniques for fresh pork.

MATERIALS AND METHODS

Storage Experiment Design and Freezing-Point Determination

Six types of storage conditions were investigated. These were refrigeration (4°C, denoted as A), partial freezing (-1°C, denoted as B), vacuum refrigeration (4°C, denoted as C), vacuum partial freezing (-1°C, denoted as D), R-MAP (75%O_2+20%CO_2+5%N_2, 4°C, denoted as E), and PF-MAP (75%O_2+20%CO_2+5%N_2, -1°C, denoted as F). Fresh pork was used as the blank control (CK). The experimental indicators included the total volatile basic nitrogen (TVB-N), total viable count (TVC), drip-loss rate, cooking-loss rate, hardness, shear force, pH, and color and aroma components. Measurements were conducted at four-day intervals to assess variations in pork quality across various storage conditions until the conclusion of the storage period. Monitoring of pork under a specific storage condition was stopped when the safety indicators (TVB-N, TVC) surpassed the safety limits.

The freezing point of Rongchang fresh pork was determined in advance to determine the partial freezing temperature. After removing the fat and connective tissue, the pork was cut into small pieces measuring 5 × 5 × 5 cm. A calibrated thermometer probe (JM222, Tianjin Jiming Instrument Co., Ltd., China) was inserted into the geometric center of the piece of meat, followed by placing the meat in a -18°C freezer (BCD-607WKPZM(E), Midea Group Co., Ltd., China). The temperature was recorded every 20 s until the temperature at the center of the pork reached -18°C. A temperature-change curve was plotted, and when a platform period appeared in the temperature change, the temperature of this platform period was taken as the freezing point of the pork. This measurement was conducted three times and averaged *(Li et al., 2020)*.

The fresh Rongchang pork was sliced on a sanitized workstation, and the fresh pork quality markers were recorded. The pork was packaged in PE preservation boxes (Haoduohe Blister Packaging, China) for the refrigeration and partial freezing procedures. In contrast, for MAP treatment, the pork was packed using a MAP machine (BZJ-300, Wenzhou Dajiang Packaging Machinery Co., Ltd., China). The pork was packed using a vacuum-packaging machine (DZ520/2D, Yuanda Intelligent Packaging Machinery Co., Ltd., China) for vacuum treatment. The packaged pork was then stored in constant-temperature refrigerators (KB(E6), KAIGEN Biotechnology Co., Ltd., Germany) for refrigeration (4°C) and partial freezing (-1°C).

Safety Analysis of Stored Pork

Marketable pork is required to meet the safety standards of specific indicators. To meet these standards, the research team measured two common indicators used in pork inspection and quarantine: the TVB-N content and the TVC. The TVB-N content in Rongchang pork was determined using a fully automatic Kjeldahl apparatus (K9860, Hanon Group, China). The lean meat portion was minced using a food processor (DEM-JS200, Guangdong Deerma Technology Co., Ltd., China). A 10 g sample and 75 mL of distilled water were introduced to a distillation tube, shaken, and allowed to digest for 30 minutes. Next, 1 g of MgO was added, and the liquid was distilled using the Kjeldahl apparatus. In parallel, the distilled ammonia was absorbed in a 250 mL conical bottle containing 2 drops of methyl red-bromocresol green mixed indicator, 10 mL boric acid solution (20 g/L), and a standard hydrochloric acid solution (0.01 mol/L) was added after the mixture had reacted for 6 minutes until it turned pink. The amount of standard hydrochloric acid solution used was noted. Distilled water was used as a blank control. The TVC-N content was calculated using the following formula *(Zhang et al., 2024)*:

$$X = \frac{(V_1 - V_2) \times c \times 14}{m} \times 100 \quad (1)$$

where X is the content of TVB-N in the sample, in mg/100 g or mg/100 mL; V_1 is the volume of standard hydrochloric acid solution consumed by the sample, in mL; V_2 is the volume of standard hydrochloric acid solution consumed by the blank group, in mL; c is the concentration of standard hydrochloric acid solution, in mol/L; m is the mass or volume of the sample, in g or mL.

Before determining the TVC, all Petri dishes, physiological saline, and culture media were sterilized using a vertical pressure steam sterilizer (JC100D, Deqiang Purify, China). In a laminar flow cabinet (SWP-2, Kenton Instrument Co., Ltd., China), 25 g of pork and 225 mL of sterile physiological saline were placed in a sterile homogenization bag (Type 400, BKMAN LAB, China). A 1:10 sample homogenate was produced after homogenizing the material for one to two minutes using a homogenizer (SCIENTZ-11, Ningbo Scientz Biotechnology Co., Ltd., China). Three appropriate dilution gradients were selected for plate coating out of ten serial dilutions of the homogenate produced. Aliquots of 1 mL of the homogenate were placed in sterile Petri dishes containing 15-20 mL of plate-count agar and evenly spread. The petri dish was then placed in a sterile constant-temperature incubator (HWS-500H, Ningbo Yanghui Instrument Co., Ltd., China) for 48±2 h, followed by plate counting.

Commodity Value of Stored Pork

Drip loss during pork storage has an impact on the commodity value. As a result, pork's drip and cooking loss rates were measured during storage. To determine the drip-loss rate, moisture on the surface of chilled fresh meat packaging was wiped off, and the meat and packaging were weighed using an analytical scale (JA2003, Sunny Hengping Instrument Co., Ltd., China) and recorded as m_1. The package was then opened and the liquid inside the package was absorbed with absorbent paper for the second weighing, recorded as m_2. Finally, the sample was removed from the packaging, and the mass of the packaging was weighed and recorded as m_3. The drip loss rate was calculated by the following formula *(Yao et al., 2024)*:

$$Drip\ loss\ (\%) = \frac{m_1 - m_2}{m_1 - m_3} \times 100 \quad (2)$$

To determine the stewing loss rate, the refrigerated raw meat was taken out of its packing and weighed, noted as m_1. Afterwards, it was immersed in a water bath (J-HH-2A, Shanghai LNB Instrument Co., Ltd, China) set at a temperature of 75°C for 20 minutes. It was then extracted, allowed to cool until the surface was devoid of moisture, and subsequently reweighed, documented as m_2. The stewing loss rate was determined using the following formula *(Gao et al., 2023)*:

$$stewing\ loss\ rate\ (\%) = \frac{m_1 - m_2}{m_1} \times 100 \quad (3)$$

Organoleptic Properties of Stored Pork

The color, aroma, taste, and texture of pork represent intuitive indicators of its quality. Therefore, the color, aroma components, pH value, shear force, and hardness of the pork during storage were measured. The color of the chilled fresh meat was measured using a colorimeter (NR10QC, Hunan Lichen Instrument Technology Co., Ltd., China). Following the calibration process, the colorimeter's test port was positioned correctly in alignment with the sample, and results were documented once they reached a stable state. Three measurements were conducted for each sample, and the mean value was calculated *(Che et al., 2023)*.

The aroma components of the chilled fresh meat were measured using an electronic nose (C-Nose, Bosin Tech, China). One gram of chopped and evenly mixed sample was placed in a 15 mL headspace vial, sealed with a polytetrafluoroethylene pad, and left at room temperature for 30 min. Electronic nose detection was examined using the headspace suction method, with each sample being measured three times *(Zhang et al., 2022)*.

The pH value of the chilled fresh meat was measured using a portable pH meter (PH828+, SIGMA TECHNOLOGY, China). Following the calibration process, the pH meter probe was put into the sample, and measurements were taken once the values became stable. Three measurements were taken for each sample, and the mean value was calculated.

The texture analyzer (TA-300W, CZMLD, China) was used to measure the shear force and hardness of the chilled fresh meat. When measuring the shear force, after measuring the cooking-loss rate, the meat sample was cut into strips of 1 × 1 × 3 cm and measured using a V-notch probe, using the parameters of deformation rate of 40%, trigger load of 3.8 N, test speed of 60 mm/min, and return speed of 100 mm/min*(Feng et al., 2023)*. When measuring the hardness, the cooked meat sample was cut into cubes of 1 × 1 × 1 cm and measured using a TA9 probe, with the parameters of deformation rate of 40%, trigger load of 3.8 N, test speed of 60 mm/min, return speed of 60 mm/min, and cycle number of 2 *(McGuinness et al., 2024).*

Statistical Analysis

The raw data was organized and analyzed using Excel software. The measurement findings were presented as the average value plus or minus the standard deviation. The Origin2021 software was utilized for generating statistical graphs, while SPSS version 25.0 (IBM Corp., Armonk, NY, USA) was used for significance tests and correlation analysis.

RESULTS AND ANALYSIS

Freezing Point of Pork

Figure 1 shows a progressive reduction in the core temperature of the pork as the storage time increased. After 28 minutes, a platform phase was observed, with a temperature of -0.8°C, suggesting that the pork had reached its freezing point. As a result, the temperature for storing partially frozen items was adjusted to -1°C.

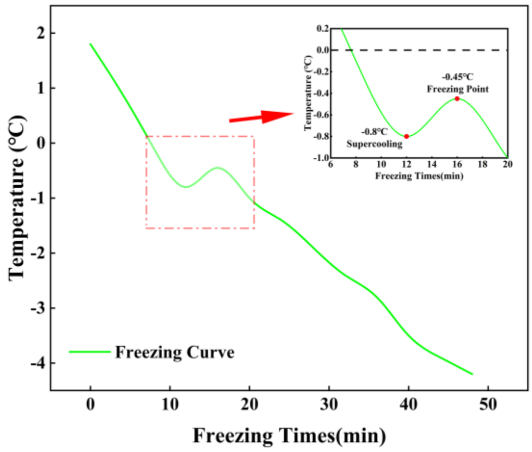

Fig. 1 - Freezing Curve of pork

Changes in TVB-N Content and TVC in Pork under Different Storage Conditions

TVB-N and TVC are essential indicators of meat freshness. A higher TVB-N content indicates greater amino acid degradation *(Zhang and Zhao, 2023)*, while TVC reflects the degree of bacterial contamination in the meat. National meat safety standards stipulate that the TVB-N content of fresh pork should not exceed 15 mg/100 g *(Cai et al., 2024)*, and the TVC should not exceed 6 lg CFU/g *(Xu et al., 2018)*. As shown in Figure 2, as the storage time increased, both the TVB-N content and TVC of the pork in all groups tended to increase. On the eighth day, the level of TVB-N in the vacuum-packed and partially frozen pork surpassed the safe limit. Furthermore, the TVC of the pork in the vacuum-refrigerated and refrigerated groups exceeded the limit. On the twelfth day, the amount of TVB-N in the pork stored in a R-MAP environment was still below the acceptable limit, however its TVC value was above the limit. On the 20th day, the pork in the PF-MAP group had TVB-N levels of 10.92 mg/100 g and TVC levels of 4.84 lg CFU/g, which were still within the acceptable limits for freshness. This is possibly due to the effective protection of the protein structures in the meat by the MAP treatment *(Hou et al., 2023)* and inhibition of bacterial growth in the partial-freezing environment.

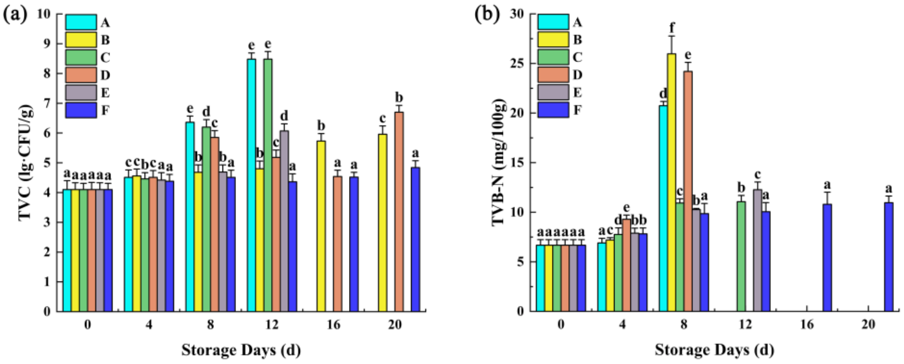

Fig. 2 - Changes of TVC and TVB-N content of pork during storage:
(a) Changes of TVC; (b) Changes of TVB-N content

Changes in Drip Loss Rate and Stewing Loss Rate of Pork under Different Storage Conditions

The drip loss and stewing loss rates are essential indicators of meat quality as they reflect the water-holding capacity of the meat. The annual economic losses caused by drip loss are immeasurable *(Eom et al., 2024)*. The higher the stewing loss rate, the smaller the water-holding capacity and the poorer the eating quality *(Qin et al., 2022)*. Figure 3a shows that as storage time extended, the drip-loss rate of pork in all groups increased gradually. During the first eight days of storage, drip loss rates in the refrigerated, vacuum-packed, PF-MAP, and R-MAP pork groups were low and gradually increased. After eight days, the drip loss was found to be lowest in the PF-MAP pork, with the slowest rate of rise, followed by the R-MAP pork. By day 20, the drip loss rate in the PF-MAP pork was 1.7%. As shown in Figure 3b, during the first four days of storage, the stewing-loss rate of the pork in all groups showed an upward trend, with a slower rate of increase in the vacuum-partial frozen, vacuum-refrigerated, and PF-MAP groups. From day 8, the stewing-loss rate of the PF-MAP pork was found to be the lowest, with the slowest increase rate. The R-MAP pork's stewing-loss rate tended to decline from days 8 to 12, and by day 12, it was nearly identical to that of the PF-MAP group. The partial freezing pork with MAP had a reasonably low stewing-loss rate of 29.76% till day 20. This is because some of the moisture in the pork created tiny ice crystals in the partially frozen environment, which caused the least damage to the pork's cells and tissue.

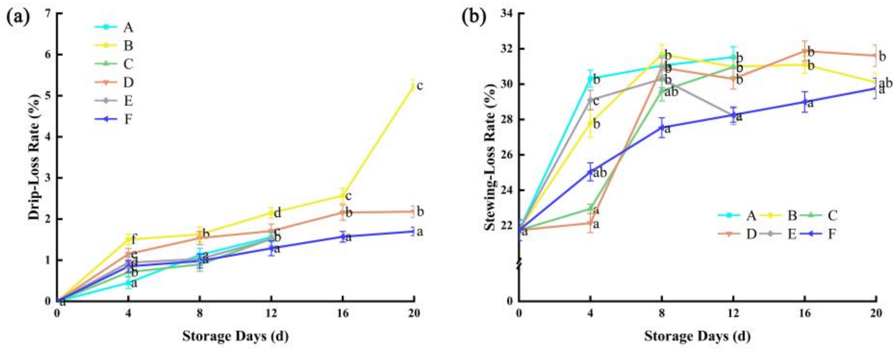

Fig. 3 - Changes in drip loss and stewing loss of pork during storage:
(a) changes of drip loss; (b) changes of stewing loss

Changes in Pork Color under Different Storage Conditions

Meat color is the most intuitive indicator of pork quality. Within a certain range, higher *L** values, larger *a** values, and smaller *b** values indicate fresher meat *(Bohrer and Boler, 2017)*. Oxidation of proteins and lipids in pork increases the *b** value. As the storage time increased, the *L**, *a**, and *b** values in all the pork groups tended to increase. Figure 4a shows the color of the pork after 12 days of storage. The *L**, *a**, and *b** values of all the refrigerated pork groups are higher than the color values of the fresh pork. Among them, the R-MAP group's *L*, a*,* and *b** pork values were highest, showing a bright red-yellow color. This indicates that while MAP treatment enhanced the color of the pork, it did not significantly slow down the oxidation of proteins and lipids, as well as the growth of microbes. Figure 4b depicts the hue of the pork after a storage period of 20 days. The *L**, *a**, and *b** values of all the partially frozen pork groups were greater than the color values of the fresh pork. Among them, the *L** and *a** values of pork in the PF-MAP group were the highest, and its *b** value was closest to the *b** value of the fresh pork. This indicates that partial freezing effectively delayed the color change caused by protein and lipid oxidation and microbial erosion in pork. Thus, PF-MAP treatment improves the color of stored pork.

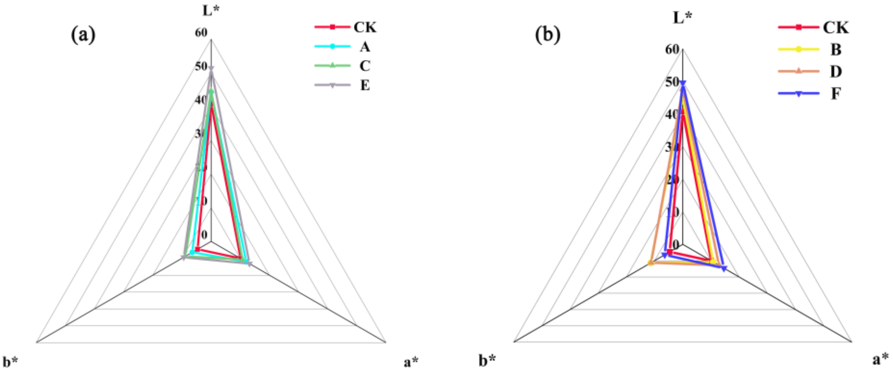

Fig. 4 - Colorimetric radar chart of pork under different storage conditions during storage:
(a) Color comparison of pork under different refrigeration conditions after 12 days of storage;
(b) Color comparison of pork under different frozen storage conditions after 20 days of storage

Changes in Aroma Components of Pork under Different Storage Conditions

From Figure 5a, it can be observed that the principal components 1 and 2 of the volatile compounds in fresh pork accounted for a combined percentage of 86.6%, and their distribution is relatively uniform with no significant differences. Figure 5b indicates that after eight days of storage, there was a substantial difference in the volatile components between the vacuum and fresh-pork groups, while other groups showed no significant differences compared to the fresh-pork group. In Figure 5c, after 12 days of storage, the volatile components of the MAP- partial freezing group showed no significant difference from those of fresh pork, while other groups showed some differences. Figure 5d indicates that after 20 days of storage, there were substantial differences in the volatile components of all the partial-freezing groups compared to fresh pork. However, the vacuum-partial and PF-MAP groups showed no significant differences in their volatile components. At this stage, both of these groups had lost their commodity value, suggesting that the freshness of the PF-MAP group fell somewhere between that of chilled fresh meat and spoiled meat. Furthermore, the pork in the PF-MAP group was in the transitional phase towards becoming spoiled meat. These findings indicate that using PF-MAP treatment can effectively slow down the degradation of volatile compounds in chilled fresh pork, hence maintaining the natural aroma of the pork.

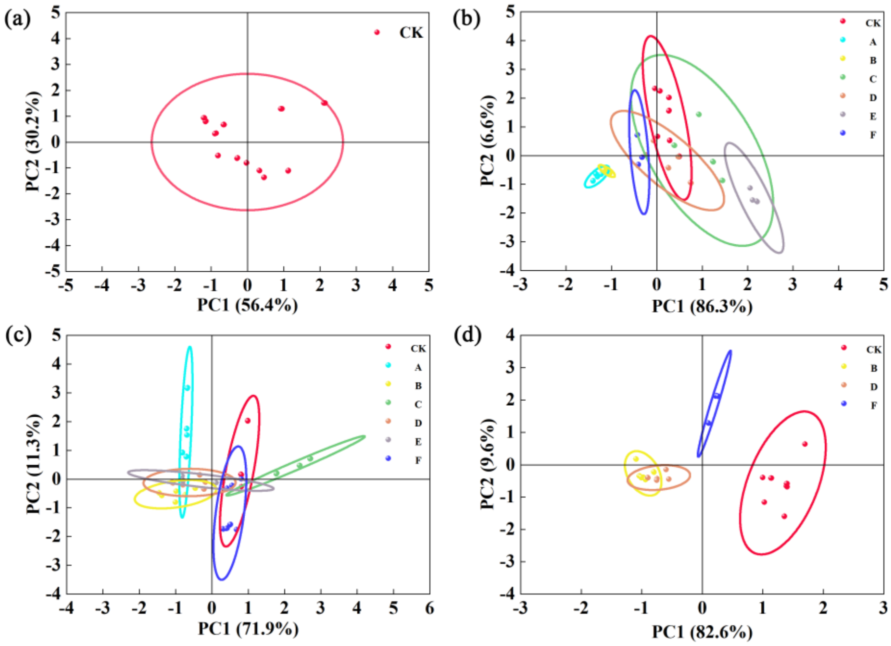

Fig. 5 - Principal component analysis (PCA) of the pork aroma during storage:
(a) PCA of the fresh pork aroma; (b) PCA of the pork aroma after 8 days of storage;
(c) PCA of the pork aroma after 12 days of storage; (d) PCA of the pork aroma after 20 days of storage

The main flavor-associated substances in pork are usually ribose and dicysteine. As shown in Figure 6, with the extension of storage time, the total amount of volatile components in chilled pork gradually decreased, indicating the continuous consumption of volatile flavor substances and thus reduced aroma. Figure 6a shows that the main volatile components in the fresh pork were nitrogen oxides, alkanes, sulfides, alcohols, aromatic compounds, and sulfur organic compounds. Figure 6b illustrates the volatile components in the various pork groups after four days of storage. The detected levels of W3S, W1C, W3C, and W5C in each group did not differ significantly from those of the fresh pork, while the remaining six components differed. The detected levels of W5S, W6S, W1S, W1W, and W2W in the pork in the PF-MAP and vacuum-partial-freezing groups were increased, with the vacuum treatment restricting the overall increase. The levels of volatile components in other groups displayed a declining pattern. Figures 6c and 6d display the levels of volatile components in all the groups that underwent partial freezing on days 16 and 20 of storage. The total concentration of volatile compounds in each partially frozen group was significantly lower than in the fresh pork.

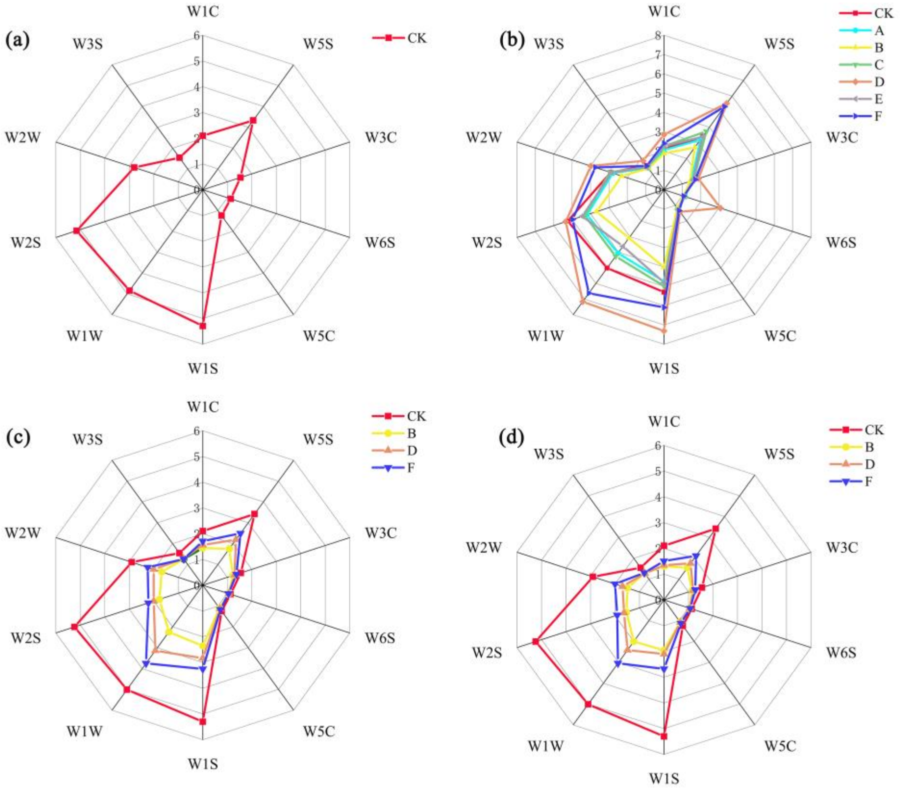

Fig. 6 - Radar plots of pork volatile components during storage

(a) Radar plots of the fresh pork volatile components; (b) Radar plots of the pork volatile components after 4 days of storage; (c) Radar plots of the pork volatile components after 16 days of storage;
(d) Radar plots of the pork volatile components after 20 days of storage

Furthermore, there were variations between the groups, particularly in the levels of W1S, W1W, W2S, and W2W. The total volatile component content in the PF-MAP group was significantly higher than in the vacuum-partial and partial-freezing groups. These findings suggest that fluctuations in the concentrations of W5S, W6S, W1S, W1W, and W2W during storage are linked to the freshness of chilled pork. Furthermore, using PF-MAP treatment is advantageous in preserving the volatile constituents of chilled fresh pork.

Changes in Pork pH under Different Storage Conditions

The pH value of pork is used as a reference index for measuring the freshness of the meat, as it affects the meat's color, tenderness, water retention, flavor, and shelf life. Generally, the pH value of primary fresh meat ranges from 5.18 to 6.12, while secondary fresh meat is between 6.13 and 6.16, with pH values above 6.17 indicating spoilage *(Laack et al., 2001)*. As shown in Figure 7, the pH values of the pork in each group generally showed an upward trend. In the first 12 days, the observed fluctuations in the pH values in all groups may be due to changes in the lactic acid content. After 12 days, the pH values began to increase, attributed to the breakdown of proteins and nitrogen-containing compounds in the meat by microorganisms and endogenous enzymes, leading to the formation of alkaline substances. During storage, the pH value of MAP-partially frozen pork remained relatively low with a slow increase.

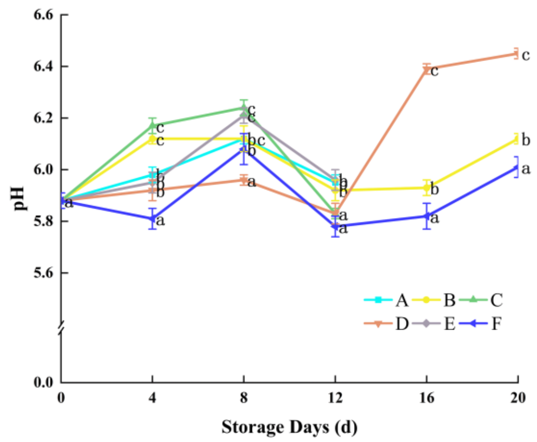

Fig. 7 - Changes in pH of pork during storage

In contrast, the vacuum-refrigerated and partially frozen groups had higher pH values. After 12 days, the pH values of the vacuum-partially frozen pork increased rapidly. After 20 days of storage, the pH value of the MAP-partially frozen pork was 6.01. Therefore, vacuum treatment is not conducive to maintaining the pH of pork, while the combination of MAP and partial freezing can better maintain the pH.

Changes in Pork Hardness and Shear Force under Different Storage Conditions

Hardness and shear force are important indicators reflecting the freshness and tenderness of pork. Within a certain range, greater hardness indicates freshness, and lower shear force indicates tenderness *(LeMaster et al., 2024)*. Figure 8a demonstrates that as the duration of storage extended, the meat's hardness in all groups tended to decline. During storage, the hydrolysis of myofibrillar proteins and the breakdown of peptide bonds between amino acids allow the collagen protein cross-linkages to break, which leads to a loss in hardness. Throughout the storage period, the pork in the PF-MAP group maintained a consistently high level of hardness, which was much greater than the hardness observed in the other groups.

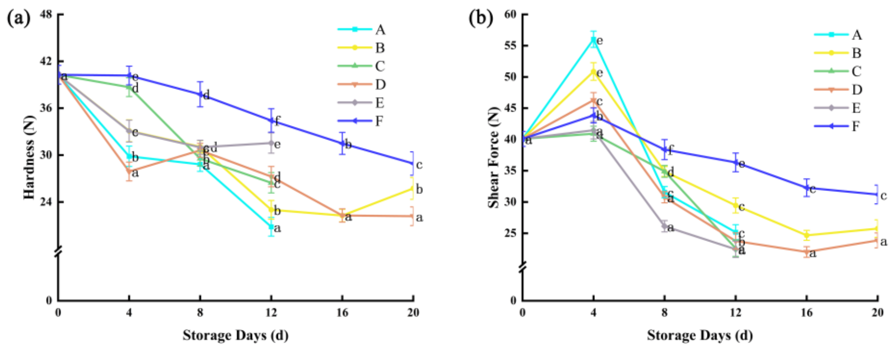

Fig. 8 - Changes in hardness and shear force of pork during storage:
(a) Changes in hardness of the pork; (b) Changes in shear force of the pork

Furthermore, the hardness of the pork in this group reduced gradually over time. The hardness of the pork in the partial-freezing group ranked second, while the pork in the vacuum-partial-freezing group showed the fastest decrease in hardness. After 20 days of storage, the hardness of the pork in the PF-MAP group was 28.92 N. As shown in Figure 8b, the shear force of the pork in each group first tended to increase and then decrease, possibly due to the after-ripening of the chilled fresh meat leading to an increase in shear force, followed by the growth of ice crystals and microbial proliferation causing damage to muscle fibers, resulting in a decrease in the shear force. Over the initial four days of storage, the pork in the R-MAP, R-VP, and PF-MAP groups had low shear force values, suggesting excellent flesh tenderness. Over 4 days, the shear force of the pork in the PF-MAP group gradually declined but remained at a relatively high level, which was significantly higher than the other groups.

In contrast, the shear force in the other groups decreased quickly. After 20 days of storage, the shear force of the pork in the PF-MAP group was 31.2 N. Therefore, PF-MAP storage can reduce damage to the fiber structures of pork muscle, inhibit microbial proliferation, and help maintain the hardness and tenderness of the pork.

CONCLUSIONS

To prolong the shelf life of fresh pork, this study proposed and researched the effect of partial freezing with modified atmosphere packaging on the quality of fresh pork, and comparing with the methods of refrigeration with MAP, partial freezing with vacuum package, refrigeration with vacuum package, partial freezing, and refrigeration. The results showed that the effect of PF-MAP was the best, which could significantly inhibit the increase of TVB-N content and TVC in fresh pork, better retaining the juice, color, flavor, hardness and tenderness of fresh pork, and the storage period could reach more than 20 days. In conclusion, the storage method of PF-MAP can better maintain the quality of fresh pork, which can be used to solve the problem of short shelf life of fresh pork and provide a reference for the research and development of fresh pork storage technology.

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