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Impact of Packaging Conditions on Quality and Microbial Safety of Dry-Cured Ham During Storage

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ABSTRACT - This study investigated the effects of three packaging conditions-aerobic packaging (AP), vacuum packaging (VP), and modified atmosphere packaging (MAP) on the physicochemical properties, color attributes, and microbial safety of dry-cured ham over a 6-month storage period. AP exhibited the highest lipid oxidation, as evidenced by markedly elevated thiobarbituric acid (TBA) values, while showing the greatest protein degradation, as reflected in the volatile basic nitrogen (VBN) content. VP resulted in the lowest oxidative changes and the most stable pH during ripening. MAP demonstrated a progressive salt accumulation pattern and superior water activity stability. In terms of color, VP significantly enhanced redness during storage, whereas AP showed the greatest lightness but diminished redness over time. Microbial analyses revealed that MAP supported the highest counts of both total plate count (TPC) and lactic acid bacteria (LAB) at 6 months, suggesting a modified anaerobic environment facilitating microbial proliferation. These findings indicate that VP is the most effective strategy for preserving the oxidative stability and color integrity of dry-cured ham, whereas MAP requires careful optimization to balance microbial and chemical qualities during extended storage.

Keywords: Dry-cured ham, Packaging, Quality traits, Storage stability

Dry-cured ham is a non-heat-treated, ready-to-eat (RTE) meat product manufactured by treating pork with salt, nitrite, and spices, followed by extended drying and aging processes. Its distinctive flavor and texture arise from complex biochemical reactions such as proteolysis, lipolysis, and Maillard reactions occurring throughout processing[1,2]. As consumer interest grows, the Korean dry-cured ham market has expanded substantially, highlighting the need for standardized manufacturing and storage protocols[3].

Starter cultures are increasingly used in dry-cured ham to improve quality consistency and microbiological safety. *Lactobacillus pentosus* lowers pH through lactic acid production, inhibiting pathogens and spoilage flora while contributing to flavor via protease activity[4]. *Staphylococcus carnosus* enhances color stability and typical dry-cured flavor through lipase and protease action and also slows lipid oxidation[5,6]. Co-inoculation of these strains is known to improve product quality and shorten processing time in fermented meats[7], but their application to Korean domestic pork neck (Boston butt) has been little studied.

Packaging is crucial for maintaining quality and extending the shelf life of dry-cured ham during distribution. Slicing increases exposed surface area, which accelerates lipid oxidation, color deterioration, and microbial contamination[8,9], so selecting an appropriate packaging system is essential for both safety and quality. The main commercial systems are aerobic packaging (AP), vacuum packaging (VP), and modified atmosphere packaging (MAP). AP is inexpensive and allows direct visual inspection but the oxygen-rich headspace promotes lipid oxidation and aerobic microbial growth, reducing storage stability[10]. VP removes oxygen and effectively limits oxidative and aerobic spoilage, but can cause slice adhesion and moisture condensation, impairing appearance[8,11]. MAP adjusts gases typically using the antimicrobial properties of CO_2 and the inert, oxygen-displacing role of N_2 to prolong shelf life while maintaining product appearance[12].

Several studies have investigated the effects of packaging on the quality of sliced dry-cured ham. García-Esteban et al.[8]. reported superior textural retention in MAP, with the

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highest lightness (L*) stability at 20% CO_2. Salazar et al.[9] found that MAP better preserved color and antioxidant content, whereas VP more effectively suppressed lipid oxidation. León et al.[3] compared that both VP and MAP (N_2:CO_2=70:30) yielded lower TBARS values than AP, with MAP providing the best protective effect against discoloration and VP more limiting protein degradation[3].

Despite the previous literature[13-16], studies systematically evaluating the combined influence of packaging method and starter culture inoculation on the quality and microbiological safety of dry-cured ham manufactured from domestic Korean pork neck are extremely limited. Furthermore, comprehensive assessments covering physicochemical parameters, and microbiological indicators throughout an extended storage period are scarce. Therefore, the objective of this study was to evaluate the effects of three packaging methods on the physicochemical and microbiological quality changes during storage in dry-cured ham. The results of this study are expected to provide scientific evidence for selecting optimal packaging systems and establishing microbiological safety criteria for dry-cured ham produced in Korea.

Materials and Methods

Raw materials and preparation of starter cultures

Twenty pork neck (Boston butt) cuts were obtained from ten commercially raised crossbred pigs (Landrace× Yorkshire×Duroc, LYD) within 12 h post-mortem, with carcasses. Visible subcutaneous fat and connective tissue were removed before use. Two starter culture strains, *Lactobacillus pentosus* (4.0×10^9 CFU/g) and *Staphylococcus carnosus* (6.0×10^9 CFU/g), were used.

Manufacture of dry-cured ham

Dry-cured ham was manufactured following the method described by Kang et al.[14] with modifications. Per kilogram of meat, a curing mixture consisting of 50 g NaCl, 0.10 g $NaNO_2$, 0.5 g sodium erythorbate, and 5 g commercial spice blend was uniformly applied along with the mixed starter cultures. Dry-salting was performed at 0-4°C and 60-70% relative humidity (RH) for 2 weeks, followed by aging at 2-5°C and 70-80% RH for an additional 2 weeks. After desalting with cold water, the surface was dried at 35°C for 2 h and then cold-smoked at 30°C for 30 min. Samples were subsequently dried at 16°C and 70% RH for 3 months, yielding the final dry-cured ham product.

Packaging and storage conditions

After completion of the drying process, the dry-cured ham was sliced to approximately 3 mm thickness and assigned to one of three packaging treatments: AP (C; polyethylene/nylon film, no gas flush), VP (T1; oxygen permeability < 5 cm^3/m^2/24 h), and MAP (T2; N_2:CO_2=70:30, v/v). The headspace gas composition of T2 packages was verified at the time of packaging using a gas analyzer (CheckPoint, PBI Dansensor, Ringsted, Denmark). The MAP samples were packaged using a gas composition of 30% CO_2 and 70% N_2. Although residual O_2 was not directly measured during storage, gas retention stability was ensured by using a high-barrier film (OTR<20 mL/m²·day) and immediate sealing after flushing. All packaged samples were stored at 10±1°C for 6 months.

Physicochemical analyses

pH was determined by homogenizing 3 g of sample with 12 mL of distilled water at 6,451×g for 1 min (Ultra Turrax HMZ-20DN, Poonglim Tech, Seoul, Korea) and measuring the supernatant with a calibrated pH meter (S220, Mettler-Toledo, Schwerzenbach, Switzerland)[14]. Salinity (%) was measured directly from the same homogenate using a digital salt meter (SB-2000PRO, HM Digital, Seoul, Korea)[14]. Moisture content was determined gravimetrically after drying at 105°C for 24 h[17]. Water activity (a_w) was measured at 25°C using a bench-top water activity meter (LabMaster-a_w, Novasina, Lachen, Switzerland)[14].

Meat color was measured on the freshly cut surface of each sample using a colorimeter (CR-400, Konica Minolta, Tokyo, Japan) with illuminant D65 and a 10° standard observer. CIE L* (lightness), a* (redness), and b* (yellowness) values were recorded as the mean of five measurements per sample.

Lipid oxidation was assessed by the thiobarbituric acid reactive substances (TBARS) method. Ten grams of sample were homogenized with 50 mL of 20% trichloroacetic acid (TCA) solution and filtered; 5 mL of the filtrate was mixed with 5 mL of 0.02 M 2-thiobarbituric acid (TBA) reagent, heated at 90°C for 30 min, cooled, and absorbance measured at 532 nm. Results were expressed as mg malondialdehyde (MDA) equivalents per kg sample[14].

Volatile basic nitrogen (VBN) was determined by the Conway microdiffusion method. Ten grams of minced sample were mixed with 90 mL of distilled water, homogenized, and filtered; 1 mL of filtrate was placed in the outer chamber of a Conway dish with 1 mL of saturated K_2CO_3 solution. Boric acid (1 mL, 1%) with indicator was placed in the inner chamber. After sealing and incubation at 37°C for 120 min, the inner solution was titrated with 0.02 N H_2SO_4, and VBN was expressed as mg N per 100 g sample[17].

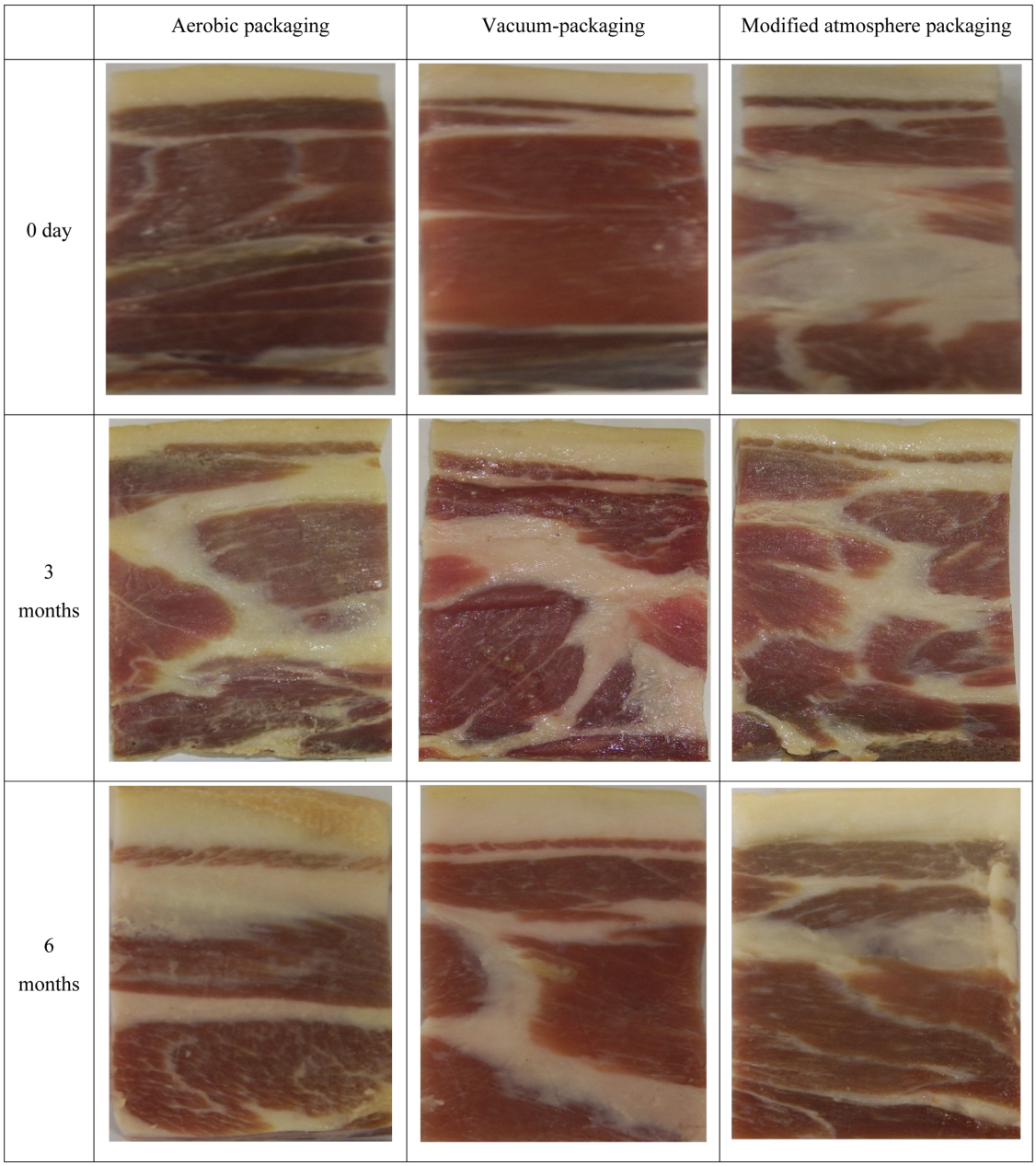

Fig. 1. Color of the dry-cured ham with different packaging at 10°C for 6 months.

Microbiological analyses

Total plate count (TPC) and lactic acid bacteria (LAB) count were determined immediately after packaging. Ten grams of sample were aseptically homogenized with 90 mL of 0.1% peptone water (Thermo Scientific Oxoid, Basingstoke, UK) using a homogenizer (BagMixer 400, Interscience, Saint-Nom-la-Bretèche, France) for 2 min. Serial decimal dilutions were plated on plate count agar (PCA; Difco, Detroit, MI, USA) for TPC and incubated at 35°C for 48 h, and on de Man, Rogosa and Sharpe agar (MRS) for LAB with incubation at 30°C for 72 h under anaerobic conditions. Colony counts were expressed as log CFU/g[14]. Microbiological analyses were conducted at 0, 3, and 6 months of storage.

Statistical analysis

The experiment was arranged in a completely randomized design with a 3×3 factorial arrangement of three packaging treatments (C, T1, T2) and three storage periods (0, 3, and 6 months), with five replicates per treatment. Data were analyzed using the PROC MIXED procedure of SAS (version 9.4, SAS Institute Inc., Cary, NC, USA). Means were separated by Tukey's honestly significant difference (HSD) test at α=0.05.

Results and Discussion

Physicochemical properties

Salt content

Salt content in dry-cured ham showed significant variation across packaging treatments and ripening duration ($P<0.05$; Table 1). Under aerobic conditions, salt content increased substantially from 4.33% at 0 months to a peak of 6.17% at 3 months, subsequently declining to 4.50% at 6 months. This transient elevation might be attributed to moisture loss during early aerobic ripening followed by partial redistribution of water and salt within the meat matrix. Vacuum-packaged samples maintained relatively stable salt levels (5.50-6.17%), with a peak at 3 months and a return to initial values by 6 months. In contrast, MAP showed a consistent progressive increase from 5.17% to 6.17%, suggesting a more uniform salt diffusion profile under modified gas

Table 1. Change of physicochemical profile in dry-cured ham with different packaging during aging

Item	Months of ripening			SEM
	0	3	6	
Salt content				
Aerobic packaging	4.33^{cC}	6.17^{aA}	4.50^{bC}	0.113
Vacuum-packaging	5.50^{bA}	6.17^{aA}	5.50^{bB}	0.057
Modified atmosphere packaging	5.17^{cB}	5.83^{bB}	6.17^{aA}	0.170
SEM*	0.113	0.170	0.057	
pH				
Aerobic packaging	5.24^{cA}	5.34^{bA}	7.13^{aA}	0.057
Vacuum-packaging	5.01^{bC}	5.05^{aB}	4.97^{bB}	0.023
Modified atmosphere packaging	5.06^{aB}	4.83^{cC}	4.97^{bB}	0.010
SEM	0.020	0.027	0.043	
Moisture content				
Aerobic packaging	45.00^{aA}	44.83^{a}	37.13^{bB}	1.220
Vacuum-packaging	44.59^{A}	42.05	43.03^{A}	0.820
Modified atmosphere packaging	40.34^{bB}	42.85^{a}	42.95^{aA}	0.780
SEM	0.647	1.093	1.080	
Water activity				
Aerobic packaging	0.88^{bB}	0.89^{aA}	0.80^{c}	0.001
Vacuum-packaging	0.89^{aA}	0.88^{bB}	0.81^{c}	0.001
Modified atmosphere packaging	0.87^{bB}	0.89^{aA}	0.81^{c}	0.003
SEM	0.007	0.000	0.010	
TBA (mg MDA/kg)				
Aerobic packaging	0.99^{cB}	2.73^{bB}	5.85^{aA}	0.313
Vacuum-packaging	0.37^{cC}	2.75^{bB}	3.41^{aC}	0.070
Modified atmosphere packaging	1.06^{cA}	3.05^{bA}	4.55^{aB}	0.250
SEM	0.282	0.154	0.198	
VBN (mg /100g)				
Aerobic packaging	29.59^{cC}	55.90^{bA}	57.40^{aA}	2.213
Vacuum-packaging	32.11^{bB}	27.53^{cB}	35.93^{aB}	0.760
Modified atmosphere packaging	35.09^{aA}	28.00^{bB}	35.00^{aB}	1.357
SEM	0.883	2.027	1.420	

*SEM, Standard error of the mean.
[a-c] Means are significantly different ($P<0.05$) within the same row.
[A-B] Means are significantly different ($P<0.05$) within the same column.

conditions. These results are consistent with those reported by Ruiz-Ramírez et al.[15], who described salt redistribution as a dynamic process highly influenced by the surrounding atmosphere and water migration during curing. The higher salt retention in MAP at 6 months may be linked to reduced moisture loss due to the gas barrier properties of the packaging.

pH

Significant differences in pH were observed among packaging treatments throughout the storage period ($P<0.05$). Aerobically packaged ham showed a pronounced alkaline shift, rising from 5.24 to 7.13 by 6 months, likely reflecting advanced proteolytic activity and accumulation of basic nitrogen compounds under aerobic conditions. The higher pH value (7.13) in AP may reflect proteolytic activity and basic compound production by aerobic bacteria. This observation implies potential spoilage initiation, even though sensory deterioration was not visually detected.

In contrast, both VP and MAP maintained relatively acidic pH values throughout ripening (4.83-5.06), consistent with the suppression of aerobic spoilage microorganisms and stimulation of acidogenic LAB. The significantly higher pH in AP at 6 months is consistent with elevated VBN values (57.40 mg/100 g), confirming that aerobic conditions accelerate protein catabolism and ammonia generation. These findings align with the work of Lorenzo et al.[1], who reported that reduced oxygen availability in vacuum-sealed systems inhibits oxidative proteolysis and helps maintain acidic pH conducive to cured meat stability.

Moisture content and water activity

Moisture content and water activity (aw) are key determinants of microbial stability and texture in dry-cured ham. Aerobic packaging resulted in the most pronounced moisture loss, declining from 45.00% to 37.13% by 6 months, while VP (44.59-43.03%) and MAP (40.34-42.95%) exhibited smaller moisture reductions, indicative of superior moisture retention under reduced oxygen conditions. These results are in agreement with Bermúdez et al.[18], who showed that oxygen-limiting packaging retards evaporative moisture loss during aging.

Despite these differences, water activity (aw) values at 6 months were comparable across all packaging treatments (0.80-0.81). The initial aw range of 0.87-0.89 across groups reflects an intermediate moisture status before extended ripening-induced dehydration. Notably, aw levels below 0.85 at terminal storage are generally considered inhibitory to most spoilage and pathogenic bacteria, supporting the microbial safety of all treatment groups[16].

Lipid oxidation (TBA) and protein degradation (VBN)

Lipid oxidation, assessed by TBA reactive substances (TBARS), increased significantly in all treatment groups over the storage period. AP exhibited the highest TBA values, reaching 5.85 mg MDA/kg at 6 months, followed by MAP (4.55 mg MDA/kg) and VP (3.41 mg MDA/kg). The substantially elevated TBARS in AP reflects the pro-oxidative role of atmospheric oxygen in promoting polyunsaturated fatty acid peroxidation. The protective effect of vacuum packaging against lipid oxidation is well established and has been confirmed in previous studies on dry-cured meat products.[19] MAP demonstrated intermediate oxidative stability, likely due to the modified gas mixture partially restricting oxygen availability.

Protein degradation, measured as VBN, showed divergent trends depending on packaging. AP displayed the highest VBN increase (57.40 mg/100g at 6 months), suggesting active proteolysis and deamination under aerobic conditions. VP and MAP showed lower and more stable VBN values (35.93 and 35.00 mg/100g, respectively), consistent with inhibited aminolysis under oxygen-restricted atmospheres. The elevated VBN in AP also corresponds with the concurrent rise in pH, indicating that alkaline nitrogenous compounds-particularly ammonia and biogenic amines-were more abundantly generated under aerobic ripening. These results corroborate the findings of García-González et al.[8], who demonstrated that oxygen availability is a primary driver of both lipid and protein oxidation in cured meat.

Color profile

Color is one of the most critical quality attributes influencing consumer acceptability of dry-cured ham. As shown in Table 2, significant differences in lightness (L*) were observed across packaging conditions and over time. MAP exhibited the highest initial L* value (49.14) but showed a progressive decline to 43.85 by 6 months, potentially indicating surface browning or Maillard-type reactions under modified atmosphere. Aerobic packaging demonstrated intermediate initial lightness (43.18) but increased significantly to 50.69 at 3 months before declining slightly. This transient brightness under aerobic conditions might reflect accelerated surface dehydration. VP showed the lowest and most stable L* values throughout storage, which might be attributed to the absence of oxygen-driven surface desiccation. Differences in lightness among packaging conditions have been previously documented by Gou et al.[20].

Redness (a*) also showed significant differences between packaging treatments. VP maintained and progressively enhanced redness from 12.12 to 18.10 over 6 months, a pattern consistent with the stabilization of myoglobin in a

Table 2. Change of color profile in dry-cured ham with different packaging during aging.

Item	Months of ripening			SEM
	0	3	6	
Lightness (*L**)				
Aerobic packaging	43.18^{cB}	50.69^{aA}	49.30^{bA}	1.403
Vacuum-packaging	40.74^{bC}	38.43^{cC}	44.82^{aB}	1.330
Modified atmosphere packaging	49.14^{aA}	44.82^{bB}	43.85^{cB}	1.337
SEM*	0.257	2.053	1.337	
Redness (*a**)				
Aerobic packaging	14.85^{aA}	7.21^{cC}	11.55^{bB}	0.873
Vacuum-packaging	12.12^{bB}	12.85^{bA}	18.10^{aA}	0.870
Modified atmosphere packaging	11.65^{C}	11.87^{B}	11.82^{B}	0.803
SEM	0.140	1.143	1.263	
Yellowness (b*)				
Aerobic packaging	6.44^{bB}	6.86^{bC}	7.16^{aC}	0.740
Vacuum-packaging	6.34^{bB}	6.07^{bB}	7.98^{aB}	0.410
Modified atmosphere packaging	8.37^{aA}	7.62^{cA}	8.06^{bA}	0.363
SEM	0.080	0.560	0.880	

*SEM, standard error of the mean.
$^{a-c}$ Means are significantly different (P<0.05) within the same row.
$^{A-C}$ Means are significantly different (P<0.05) within the same column.

Table 3. Change of total plate count and lactic acid bacteria count in dry-cured ham with different packaging during aging.

Item	Months of ripening			SEM
	0	3	6	
Total plate count				
Aerobic packaging	6.15^{cC}	6.29^{b}	6.42^{aC}	0.023
Vacuum-packaging	6.31^{bA}	6.30^{b}	6.56^{aB}	0.023
Modified atmosphere packaging	6.28^{bB}	6.28^{b}	6.68^{aA}	0.013
SEM*	0.027	0.013	0.020	
Lactic acid bacteria count				
Aerobic packaging	5.11^{cB}	5.28^{b}	5.41^{aC}	0.013
Vacuum-packaging	5.27^{bA}	5.27^{b}	5.55^{aB}	0.017
Modified atmosphere packaging	5.26^{bA}	5.26^{b}	5.61^{aA}	0.013
SEM	0.010	0.013	0.020	

*SEM, Standard error of the mean.
$^{a-c}$ Means are significantly different (P<0.05) within the same row.
$^{A-C}$ Means are significantly different (P<0.05) within the same column.

metmyoglobin reduction under anaerobic conditions. AP showed an initial high redness value (14.85) that decreased sharply to 7.21 at 3 months before partial recovery (11.55 at 6 months), indicating early myoglobin oxidation to metmyoglobin under oxygen exposure, followed by subsequent dehydration-associated pigment concentration. MAP maintained the most stable redness throughout storage (11.65-11.87), suggesting that the modified gas composition effectively buffered myoglobin oxidation. The superior red color retention in VP aligns with findings from Toldrá and Reig[1)], who reported that vacuum-sealed dry-cured products maintain more appealing myoglobin states.

Yellowness (b*) increased across all packaging treatments over time, reflecting progressive fat yellowing and pigment

alteration during extended ripening. MAP consistently produced the highest b* values, possibly due to the accumulation of secondary lipid oxidation products under elevated CO_2 conditions. The overall upward trend in b* aligns with observations by Pérez-Alvarez et al.[21], who associated yellowing in cured meats with secondary carotenoid degradation and lipid peroxidation by-products.

Microbial safety

Total plate count and lactic acid bacteria

Microbial counts in dry-cured ham serve as critical indicators of both product safety and quality. In the present study, TPC increased significantly across all packaging groups between 0 and 6 months, with MAP recording the highest final count (6.68 log CFU/g), followed by VP (6.56 log CFU/g) and AP (6.42 log CFU/g). Under anaerobic conditions, *Lactobacillus* spp. tend to dominate the microbial community, which explains the relatively higher TPC observed in MAP and VP compared to AP. LAB counts followed a trend similar to TPC, with MAP yielding the highest value (5.61 log CFU/g) at 6 months, followed by VP (5.55 log CFU/g) and AP (5.41 log CFU/g). Previous data showed that TPC and LAB of VP had lower than those of AP and MAP[22]. *Lactobacillus* spp. can grow efficiently under anaerobic conditions at low temperatures, competitively excluding other spoilage. The presence of *Lactobacillus* spp. promotes lactic acid production through fermentation, thereby lowering pH and suppressing other spoilage bacteria sensitive to acidic conditions, including meat-borne pathogens[23]. The LAB dominance observed in MAP samples is therefore considered microbiologically favorable rather than detrimental. While MAP conditions promoted the growth of LAB over spoilage-related aerobic bacteria, the total microbial counts still increased during prolonged storage. Thus, MAP can be considered relatively microbiologically stable but not entirely resistant to microbial changes or quality deterioration.

Packaging conditions markedly affected the quality and safety of dry-cured ham during 6 months of ripening. Aerobic packaging accelerated oxidative and proteolytic deterioration, leading to elevated pH, TBARS, and VBN values, alongside diminished redness stability. In contrast, vacuum packaging effectively inhibited lipid and protein oxidation, maintained color integrity, and limited moisture loss, confirming its superior ability to preserve the physicochemical and microbial quality of the product. Modified atmosphere packaging provided intermediate oxidative protection and favored the proliferation of lactic acid bacteria, contributing to microbiological stability under low water activity (<0.85). Collectively, these findings demonstrate that vacuum packaging represents the most suitable method for maintaining compositional stability, color quality, and safety of dry-cured ham during extended storage.

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국문요약

본 연구는 세 가지 포장 조건(함기 포장(AP), 진공 포장(VP), 공기치환 포장(MAP))이 건식 숙성 햄의 이화학적 특성, 색도, 및 미생물 안전성에 미치는 영향을 6개월 저장 기간 동안 조사하였다. 산화 및 단백질 분해 측면에서, 함기 포장(AP)은 TBA 값이 가장 높아 지질 산화가 가장 심하게 진행되었으며, VBN 함량 역시 가장 높아 단백질 분해도 가장 두드러졌다. 반면 진공 포장(VP)은 산화 변화가 가장 적고 저장 기간 동안 pH가 가장 안정적으로 유지되었다. 공기치환 포장(MAP)은 염분이 점진적으로 축적되는 경향을 보였으며, 수분 활성도(water activity)가 가장 안정적으로 유지되었다. 색도 측면에서, 진공 포장(VP)은 저장 중 적색도(redness)를 유의하게 향상시킨 반면, 함기포장(AP)은 명도(lightness)가 가장 높았지만 적색도는 시간이 지남에 따라 감소하였다. 미생물학적 측면에서, 공기치환포장(MAP)은 6개월 시점에서 일반 생균수(TPC) 및 젖산균(LAB) 수가 가장 높게 나타나, 변형된 혐기적 환경이 미생물 증식을 촉진한 것으로 판단된다. 결론적으로, 진공 포장은 산화 안정성과 색도 유지 측면에서 가장 효과적인 포장 방법으로 평가되며, 공기치환 포장은 장기 저장 시 미생물 및 이화학적 품질의 균형을 위한 추가적인 최적화가 필요한 것으로 나타났다.

Conflict of interests

The authors declare no potential conflict of interest.

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